EMPIRICAL MODEL OF SHEAR FORCE CAPACITY AND STIFFNESS OF SHEAR-TENSION SCREW CONNECTIONS IN TIMBER-CONCRETE COMPOSITE STRUCTURES

ANIS HANIM BINTI GHAZALI

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By

ANIS HANIM BINTI GHAZALI

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Name of Student: Anis Hanim Binti Ghazali

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 : 9/8/2022

Approved by:

(Signature of Supervisor)

Name of Supervisor : Dr. Mohd Amirul Bin Mohd Snin

Date : 9/8/2022

Approved by:

(Signature of Examiner)

Name of Examiner : Assoc. Prof. Ts. Dr. Fatimah De'nan

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ABSTRAK

Sistem kayu-konkrit komposit (TCC) adalah teknik pembinaan untuk kerja pemulihan lantai kayu dan pembinaan baharu seperti bangunan bertingkat dan jambatan pendek. Sistem ini menggabungkan kekuatan tegangan rasuk kayu dan kekuatan mampatan papak konkrit, yang bertindak secara komposit. Oleh itu, prestasi mekanikal yang mencukupi untuk struktur komposit ini mesti dipastikan dengan penggunaan penyambung yang mempunyai rintangan dan kekukuhan yang mencukupi. Kajian penyelidikan ini akan menilai kesan pembentukan sambungan skru yang berbeza, terutamanya bagi tegangan dan mampatan. Kesan sambungan skru pada tegangan-ricih dan mampatan-ricih akan dianalisa dengan memplot kapasiti daya ricih dan kekukuhan terhadap parameter yang diketahui. Nilai kuasa dua R yang berkaitan dengan garis arah aliran akan dipaparkan pada graf untuk mentafsir data. Nilai R^2 lebih daripada 0.5 menunjukkan bahawa pembolehubah bersandar mempengaruhi pembolehubah tidak bersandar. Dalam kajian ini, model empirikal baharu untuk mengira kapasiti daya ricih dan kekukuhan sambungan TCC adalah berdasarkan skru jenis condong, khususnya dalam tegangan-ricih dicadangkan dan dibandingkan dengan model yang diperolehi oleh Gelfi et al. (2002), Moshiri et al. (2014), dan Symons et al. (2010). Perbandingan model-model tersebut adalah berdasarkan nilai min, sisihan piawai, pekali varians dan regresi. Perbandingan antara model baharu yang dicadangkan dengan model lain dilaporkan dan dibincangkan secara kritikal. Berdasarkan pemerhatian, model empirikal baharu kapasiti daya ricih dan kekukuhan mempunyai nilai R^2 masing-masing, 0.9364 dan 0.5118. Nilai R^2 yang diperoleh daripada kedua-dua plot model empirikal baharu adalah lebih tinggi daripada plot model lain. Ini menunjukkan bahawa model empirikal baharu boleh meramalkan kapasiti daya ricih dan kekukuhan dalam TCC dengan lebih baik.

ABSTRACT

Timber-concrete composite (TCC) systems are a construction technique used in rehabilitation works of existing timber floors and for new construction such as multi-story buildings and short-span bridges. The system combines high tensile strength of timber beams and high compressive strength of concrete slabs, which act compositely together. Therefore, adequate mechanical performance to these composite structures must be assured using shear connectors characterized by sufficient resistance and stiffness. This research study will evaluate the effect of different formations of screw connections, mainly in shear-tension formation and shear-compression formation. The effect of screw connection on shear-tension and shear-compression will be analyzed by plotting the shear force capacity and stiffness graph against the known parameters. The R-squared value related to the trendline will be displayed on the graphs to interpret the data. The value of R^2 greater than 0.5 indicates that the dependent variable highly influenced the independent variable. In this paper, a new empirical model to calculate the shear force capacity and stiffness of timber-concrete composite (TCC) joints made with inclined screws, specifically in shear-tension is proposed and compared to models derived by Gelfi et al. (2002), Moshiri et al. (2014), and Symons et al. (2010). The models will be compared based on their mean, standard deviation, coefficient of variance, and regression value. A comparison between the new proposed model with the other models is reported and critically discussed in terms of both shear force capacity and stiffness. It was observed that the new empirical model of the shear force capacity and stiffness has R^2 values of 0.9364 and 0.5118, respectively. The value of R^2 obtained from plots of both empirical models was higher than that obtained from other model plots. The finding indicates that the new empirical model can better predict shear force capacity and stiffness in TCC connection.

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LIST OF ABBREVIATIONS

CLT	Cross Laminated Timber
IBS	Industrial Building Systems
LVL	Laminated Veneer Lumber
NLT	Nail Laminated Timber
TCC	Timber-Concrete Composite
TTC	Timber-Timber Composite
EC5	Eurocode 5
MLR	Multiple Linear Regression
SLS	Serviceability Limit State
ULS	Ultimate Limit State
EYM	European Yield Model
LWAC	Lightweight Aggregate Concrete
CoV	Coefficient of Variation

NOTATION LIST

Latin

D	diameter of the fastener
E_c	Young’s modulus of concrete
E_t	Young’s modulus of timber
$F_{ax,Rk}$	Axial withdrawal capacity of the fastener from Eurocode 5
$F_{V,Rk}$	Shear force capacity from Eurocode 5
F_s	Shear force capacity in Symons et al.’ s model
$f_{h,c}$	Embedment strength for concrete
$f_{h,t,\theta}$	Embedment strength of timber
K_{ser}	Stiffness at serviceability state from Eurocode 5
K_u	Stiffness at ultimate limit state
K_s	Stiffness at serviceability state
$K_{s,40}$	Stiffness at serviceability state (40% of maximum shear force capacity)
$K_{s,60}$	Stiffness at ultimate limit state
$K_{S,80}$	Stiffness at 80% of the maximum shear force capacity
L_c	Fastener length embedded within the concrete
L_t	Embedded length of the screw within the timber
L_{span}	Length of the beam
L_S	Length of screw
l_c	Distance of hinge from timber-concrete or timber-timber interface
l_t	Effective length fastener in timber
$M_{y,Rk}$	Yield moment of the fastener
$M_{y,t}$	Yield moment of timber

$M_{y,Rk}$	Yield moment of the fastener from Eurocode 5
M_y	Yield moment of screw
$P_{\max}$	Maximum shear force capacity
V	Shear force capacity
V_u	Shear force capacity in Gelfi et al.'s model

<u>**Greek**</u>

β	The ratio between the embedment strength of the members from Eurocode 5
β_i	The coefficient for unknown parameters in MLR analysis
$\hat{\beta}_l$	Predicted coefficient of parameter
λ	Stiffness coefficient
θ	Inclination angle
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_t	Compressive strength of slab member
σ_c	Compressive strength of beam member

CHAPTER 1

INTRODUCTION

1.1 Introduction

The evolution of the timber-concrete composite (TCC) system started in Germany approximately 100 years ago. At the same time, interest in TCC flooring has grown in the past 20-30 years (Moshiri, 2013). TCC structures, also known as one-way spanning elements, are horizontal elements that sustain a load in just one direction and are subjected to uniaxial bending (Ogrin et al., 2021). It combines timber beams and concrete slabs, forming a composite material. TCC system relies on the high tensile strength of timber and high compressive strength of concrete members, which act compositely together. Thus, the system performs better in the flooring system than in the timber-timber system. Timber and concrete possess brittle behavior under compression and tension, with the shear connections being the dominant contributor towards ductility (Moshiri et al., 2014). Therefore, the design parameters of TCC are highly dependent on factors such as the strength, stiffness, deflection, and configuration of the shear connection. According to previous research, the material properties of timber, concrete, and fasteners were found to influence the shear force capacity and stiffness of a TCC structure.

The study on the shear connection has been focused on determining the strength characteristics required to estimate the fastener's load-carrying capacity and distribution and preventing brittle failure mechanisms in the timber element. The stiffness within the linear range of response of shear connections influences the stiffness of the composite system and is consistent with the natural characteristics and behaviours of the material. Previous studies show inclined fasteners enhance stiffness and strength more than vertically inserted fasteners. A screw connection is the type of fastener investigated in this research paper. A screw is the most used fastener type due to its higher load-bearing capacity and provides ease in installation. The slip between timber and concrete at TCC connections and the stiffness of laterally loaded fasteners significantly influence a composite beam’s overall behavior, including stiffness, displacement, load bearing capability, and internal force distribution. The connection system is a critical component in the conception, design, and performance of TCC systems. Mechanical performance and composite action in TCC components are dependent on adequate strength, stiffness, and ductility of shear connections.

Initially, the TCC structures are designed according to Eurocode 5. Eurocode 5 is an integral part of the aimed European harmonization for product and design standards for a building structure (Sandhaas et al., 2018). Push-out tests are only recommended by Eurocode 5 for determining the shear force capacity and stiffness of unconventional connections. It was found that fewer studies have been conducted utilizing analytical closed-form equations to forecast shear force capacity and stiffness of TCC connections as input parameters for designing a partially composite floor. Eurocode 5, for instance, proposes equations for calculating slip modulus for screws and dowels that are restricted to vertically inserted fasteners. Therefore, this research paper will analyze the effect of slip modulus and shear force capacity relative to different forms of screw inclination in TCC structure. Before performing the analysis, a set of data samples are collected from published papers to study the effect of various formations of screw connection in TCC. The research study was also extended by developing a new predictive model of shear force capacity and stiffness for inclined screws, particularly in shear-tension.

1.2 Problem Statement

This research was carried out to analyze the influence of the various forms of screw connections in timber-concrete structures related to the slip modulus and shear force capacity of such systems. With reference to Eurocode 5 and other previously published works, it was found that there is a limitation seen in those models, which was the failure to consider the local characteristic of the screw embedded within the concrete on the behaviour of connection between timber and concrete. According to Mohd Snin (2021), Clause 7.1 of EC5 Part 1-1 states that the slip modulus of timber-concrete composite (TCC) connections can be calculated to be twice that of a timber-timber connection, for which there is a power law formula based on the density of the timber. This provision was included in the first version of EC5, which was approved by CEN (2004). From the clause, the local deformations within the concrete side of the connection are neglected. Clause 2.2.2(2) of EC5 further suggests that the slip stiffness of the connections can be taken as 2/3 of that at serviceability for the ultimate limit state condition. Furthermore, Clause 5.3 (2) of EC5 prohibits friction and adhesion between the timber and concrete from being accounted for in the case of timber-concrete composite connection.

It is noted that only a few numbers of previous research studies have attempted to assess the mechanical properties of screw-based timber-concrete composite shear connectors. The screw formation in TCC was found to have a significant effect on the mechanical properties of the connection. The analysis of the screw connection's strength in parallel formation (shear-tension and shear-compression) was discussed in this paper. There is also a need to optimize a new predictive model of shear force capacity and stiffness for inclined screws due to the absence of appropriate methods in the case of an inclined screw connection.

1.3 Aim and Objectives

This research study investigates the effect of different formations of the screw connections in a timber-concrete composite structure to analyze the impact of shear force capacity and stiffness of the screw connections in a TCC structure. Several review objectives are listed below to achieve this goal:

RO 1: To establish a set of databases for the screw connection in different formations (shear-tension and shear-compression) on timber-concrete composite (TCC) structure from previously published works.

RO 2: To analyze the database using a statistical tool (MS Excel).

RO 3: To evaluate the effect of material properties on the shear force capacity and stiffness of TCC structure.

RO 4: To develop a predictive shear force capacity and stiffness model for shear-tension screw connections in the TCC structure.

1.4 Limitation of Study

These findings of the experimental study program are limited to the short-term behavior of screw connections in timber-concrete composite structures. Dynamic cyclic and long-term impacts and behaviour under fire and changing moisture conditions were not considered. The long-term behavior of a timber-concrete composite is defined by the reaction of its three components: concrete, timber, and shear connections. The combination of these components results in mechano-sorption, drying shrinkage, creep, thermal strain, and hygroscopic strains, contributing to the complexity of TCC design (Ceccotti, 2002). These components also exhibit varying time-dependent behavior that is affected by environmental parameters such as moisture content, temperature, stress level, and relative humidity. TCC long-term experimental testing is time-consuming and costly. Such experiments are critical for validating an approximation design procedure and calibrating the existing analytical and numerical models. The shear force capacity and slip modulus are analyzed on two (2) different screw formations: shear-tension and shear-compression. However, limited data available on the screw in shear-compression results in probable inaccuracy in data analysis.

1.5 Research Methodology of the Study

The shear force capacity and slip modulus data samples in this research study are obtained from the previously published work on the timber-concrete composite structure. The data samples are then established as a set of databases. Next, the data will be analyzed using the statistical analysis method utilized with Microsoft Excel. Several material properties that could affect the parameters of TCC must be considered for estimating shear force capacity and slip modulus (stiffness). From the analysis, the predictive model will be developed based on the databases by using the Multiple Linear Regression (MLR) method. In addition, the predictive model for screw formation in parallel shear-tension will be compared with the predictive model derived by Moshiri et al. (2014), Gelfi et al. (2002), and Symons et al. (2010).

1.6 Outline of Thesis

This thesis consists of five (5) chapters. Chapter 1 elaborates on timber-composite structures and different mechanical properties that will affect the crucial parameters of TCC. There is a discussion of the significant mechanical properties of TCC, including the stiffness, strength, and ductility of connection systems in timber-concrete composite structures. The limitations of existing design models for timber-concrete composite structures are further clarified in this chapter. The objectives of this study are enlisted to analyze the stiffness and shear force capacity in timber-concrete composite structures.

1.6.1 Chapter 2 – Literature Review

The literature review first discusses the history and development of the timber-concrete composite system. Then the utilization and mechanism of composite action in TCC structure are discussed. The general types of connection systems used in the timber-concrete composite system are reviewed. There is also a discussion on types of shear connections such as dowel-type connections, notches connections, and epoxy-bonded connections. Moreover, the comparison of the different connection systems is discussed based on Dias (2005). Practically, the experimental works through the push-out test are conducted to measure the slip modulus and shear force capacity. The analytical method for shear force capacity and stiffness of the inclined screw in crossed formation, shear-tension formation, and shear-compression formation are reviewed based on Du et al. (2019). Lastly, the conclusion is being drawn to summarize the entire content of Chapter 2.

1.6.2 Chapter 3 – Research Methodology

Generally, the push-out test was utilized in determining the mechanical properties and mode of failure of the screw connection. In this chapter, the general test guideline for the push-out test is included as well. The inclined screws at different formations and angles have been extensively tested in TCC connection systems. Usually, this type of connection is adapted in three (3) configuration types: X-formation (crossed) screws and parallel screws (shear-tension formation and shear-compression formation). The data relative to screw in shear-tension formation and shear-compression formation will be presented in tabulated form. A comprehensive parametric analysis was conducted to determine the influence of material properties on the shear force capacity and stiffness of TCC connections. Then, the data from the previous study, specifically for the inclined screws in shear-tension, will be analyzed using the statistical analysis method; mean, standard deviation, coefficient of variance, and regression (Multiple Linear Regression). The new predictive model of shear force capacity and stiffness will be proposed and compared to three (3) realization of models, which are derived from Gelfi et al. (2002), Moshiri et al. (2014), and Symons et al. (2010).

1.6.3 Chapter 4 – Result and Discussion

This chapter discusses the analysis of shear force capacity and stiffness of the screw connections by considering the database from previously published work. This chapter elaborates further on the study of shear force capacity and stiffness in TCC. The influence of material properties such as screw angle, diameter, and configurations, penetration length of the screw embedded in timber, and strength of concrete in the TCC system will be discussed. Then, the analysis of inclined screws in a different formation, particularly in shear-tension and shear-compression, will be presented and elaborated. The analysis of inclined screws in shear-tension will be extended by using statistical analysis. Multiple Linear Regression (MLR) analysis of the shear force capacity and stiffness of the screw connection will be conducted to develop the new empirical models. The new proposed models of strength and stiffness will be compared to the three (3) realizations mentioned earlier. The proposed model will be validated and verified.

1.6.4 Chapter 5 – Conclusion

The last chapter in this thesis contains the summary of the entire thesis and the recommendation for future work. It is intended to give additional data to the TCC study and thus improve the future timber-concrete composite structure's design method. In summary, the problem statement of this study is the shear force capacity and slip modulus have limitations, such as disregarding the significant effect of concrete on the screw connection. The EC5 standard as the official design guideline for predicting the slip modulus of connection in timber-timber assumed that the stiffness of the timber-concrete connection is twofold that of a timber-timber connection. Therefore, this research aims to evaluate the shear force capacity and stiffness of screw connections in timber-concrete composite (TCC) structures by considering the formation of screw connections embedded within the concrete from previously published work. The validation of predictive models on inclined screws, specifically in shear-tension, will also be included. Lastly, the recommendations for the research study will be outlined in this chapter.

CHAPTER 2

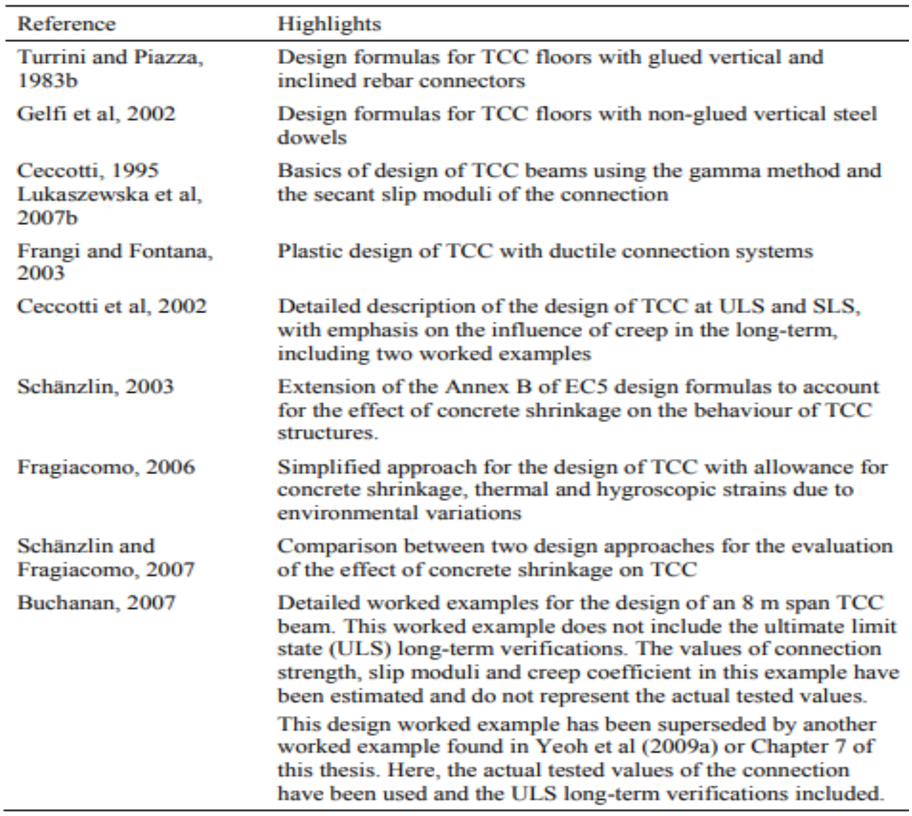
LITERATURE REVIEW

2.1 Introduction

This chapter provides an overview of the Timber-Concrete Composite (TCC) system. The history and application of TCCs will be reviewed in this paper. The composite structures made of timber and concrete have been studied for almost 80 years (Lukaszewska et al., 2009). However, according to Moshiri (2013), the TCC floors have gained interest over the last 30 years. Due to the limitation of the standard code of practice (EC5), the timber-concrete composite structure needs to be studied extensively to produce more reliable outcomes.

The literature review first discusses the history and evolution of the timber-concrete composite (TCC) system. Then the application and mechanism of composite action in TCC structure are discussed. The general types of connection systems used in the timber-concrete composite system are reviewed. There is also a discussion on types of shear connections such as dowel-type connections, notches connections, and epoxy-bonded connections. Moreover, the comparison of the different connection systems is discussed based on Dias (2005).

In addition, the mechanical properties such as slip modulus (stiffness) and shear force capacity of the timber-concrete composite are reviewed. The thesis aims to develop a statistical analysis of the stiffness and shear force capacity of an inclined screw as shear connectors. Lastly, the conclusion is being drawn to summarize the entire content of Chapter 2.



Reference	Highlights
Turrini and Piazza, 1983b	Design formulas for TCC floors with glued vertical and inclined rebar connectors
Gelfi et al, 2002	Design formulas for TCC floors with non-glued vertical steel dowels
Ceccotti, 1995 Lukaszewska et al, 2007b	Basics of design of TCC beams using the gamma method and the secant slip moduli of the connection
Frangi and Fontana, 2003	Plastic design of TCC with ductile connection systems
Ceccotti et al, 2002	Detailed description of the design of TCC at ULS and SLS, with emphasis on the influence of creep in the long-term, including two worked examples
Schänzlin, 2003	Extension of the Annex B of EC5 design formulas to account for the effect of concrete shrinkage on the behaviour of TCC structures.
Fragiacomo, 2006	Simplified approach for the design of TCC with allowance for concrete shrinkage, thermal and hygroscopic strains due to environmental variations
Schänzlin and Fragiacomo, 2007	Comparison between two design approaches for the evaluation of the effect of concrete shrinkage on TCC
Buchanan, 2007	Detailed worked examples for the design of an 8 m span TCC beam. This worked example does not include the ultimate limit state (ULS) long-term verifications. The values of connection strength, slip moduli and creep coefficient in this example have been estimated and do not represent the actual tested values. This design worked example has been superseded by another worked example found in Yeoh et al (2009a) or Chapter 7 of this thesis. Here, the actual tested values of the connection have been used and the ULS long-term verifications included.

Figure 2.1: The summary of published works for the design of the TCC system (Yeoh, 2010)

2.2 History and Evolution of Timber-Concrete Composite (TCC) Structures

The shortage of steel in Europe since World War I and World War II led to the development of Timber-Concrete Composite (TCC) constructions. TCC system development began with the use of nails and steel braces to combine two different materials. Steel Z-profiles or I-profiles were introduced in 1939 for connecting timber beam and concrete slab elements (Van der Linden, 1999). As a consequence, the development of the TCC system has shown a significant gap. Following the development of innovative joint technologies in the 1960s, substantial research began to take place in designing timber-concrete composite systems (Yeoh, 2010). The behaviours of the system are also quantified through calculations. TCC systems were also employed in building renovation and restoration. Consequently, almost 10,000 m^2 of timber floors were restored in 1997 utilizing a connector such as nails installed throughout the beam to connect the timber and concrete. In 1960, this technique was employed to rehabilitate a historic structure in Bratislava.

In the 1990s, there was a rise in interest in TCC systems for bridge construction, timber floor restoration, and new building construction. There has been a rising demand for mass timbers and timber-concrete composites since the early 2000s due to the necessity to address environmental problems in the building industry at that time. Timber is a sustainable alternative since it consumes less energy to produce the product and is able to absorb emitted carbon dioxide, CO_2. In general, the development of timber-concrete composite (TCC), mass timbers, and large solid wood panels for wall, floor, and floor construction receive less attention outside the European countries. However, European nations, particularly Germany, Austria, and Switzerland, began developing mass timbers in the mid-1990s, allowing additional time for research study and experimentation (Wentzel, 2019).

Figure 2.2 (a): TCC bridge "Birkbergbrücke" in Germany (Photo adopted by Jens Müller, n.d)

Figure 2.2 (b): TCC bridge after construction (courtesy of A.M.P.G Dias, 2013)

2.3 Application of Timber Concrete Composite Structure

TCC was increasingly used in renovating and post-strengthening existing timber floors in buildings and constructing new buildings and short-span bridges in most European countries (Ceccotti, 1995). TCC floors are significantly lightweight due to their lower density and are more economical than reinforced concrete or steel-concrete composite floors. The timber used for TCC floors is often glue-laminated timber (glulam), sawn lumber, composite lumber such as nail laminated timber (NLT), laminated veneer lumber (LVL), or cross-laminated timber (CLT). In beam floor style TCC, glulam timber and sawn lumber are often utilized, with plywood spanning between the beams. The beam floor system is primarily used for restoring and upgrading historic structures. On the other hand, nail laminated timber (NLT), laminated veneer lumber (LVL), and cross-laminated timber (CLT) were used for plate floor style TCC, enabling the rapid installation for large-sized building components in panel form.

Figure 2.3 (a): Ready CLT (Picture adapted from Mohd Snin, 2021)

Figure 2.3(b): Ready Glulam (Picture adapted from Mohd Snin, 2021)

Figure 2.3(c): Ready LVL (Picture adapted from Mohd Snin, 2021)

Traditional timber floors are prone to several problems, including vibrations, deflection, inadequate acoustics, and poor fire protection. These problems may be remedied using TCC floor systems. One of the benefits of timber application is an increment in thermal mass. Increased thermal mass helps reduce the energy required to insulate and ventilate the structure. It is conceivable to attain quick installation of timber from off-site prefabrication and utilize the timber as permanent formwork. Because TCC systems have a lower self-weight, they need a smaller foundation, resulting in low-cost foundations, fast construction, and low seismic forces. Consequently, this lightweight construction decreases the seismic force that the lateral system must withstand.

In a TCC floor system, the concrete functions as a protective layer for the timber, thus reducing the influence of temperature and delaying the timber's charring. Large timber members burned on the outside at a slow and constant rate while retaining strength and slowing down the rate of combustion, which extended some time for evacuation (Stone, 2013). The char protects the timber from significant deterioration, which helps maintain the structural performance and reduces its fuel effect in a fire event, which diminishes the heat and flame. (Stone, 2013). The char from the timber provides insulation to the concrete and the connector system from the impacts of increased temperature.

Finally, instead of steel or reinforced concrete, TCC structures may be utilized as an alternative to Industrial Building Systems (IBS) for building floor systems and short bridges across monsoon drains, particularly for pedestrians and light vehicles (Yeo et al., 2020).

2.4 Mechanism of Composite Action in TCC

Timber-concrete composite (TCC) system refers to the combination of two different materials that function as a composite system. The interaction between timber and concrete is achieved by shear connectors positioned at the interface of the two materials. The degree of composite action is a concept often used to assess the efficacy of the interaction, which relies mainly on the interlayer stiffness. The actual degree of composite action of TCC systems generally lies between the two extremes (Liu, 2016), which are (1) a lower limit, referred to as 'no composite action', in which there is no horizontal shear force transfer between the two layers, resulting in large interlayer slip and deflection; (2) an upper limit, referred to as 'fully composite action', in which there is complete shear force transfer between the two layers, resulting in zero interlayer slip and slight deflection (Yeoh, 2010).

Three general cases are being employed in the TCC system (Lukaszewka, 2009), which are i) full composite action (Fig. 2.4a), ii) partial composite action (Fig. 2.4b), and iii) no composite action (Fig. 2.4c). In the case of full composite action, the slip did not occur since the interlayer is completely stiff. In the case of no composite action, the interlayer stiffness is presumed to be 0, and free slip movement is permitted (Liu, 2016). It can be drawn that the case of partial composite action lies in the middle of the two extremes of full composite action (ideal performance) and no composite action (poor performance) (Yeoh, 2010).

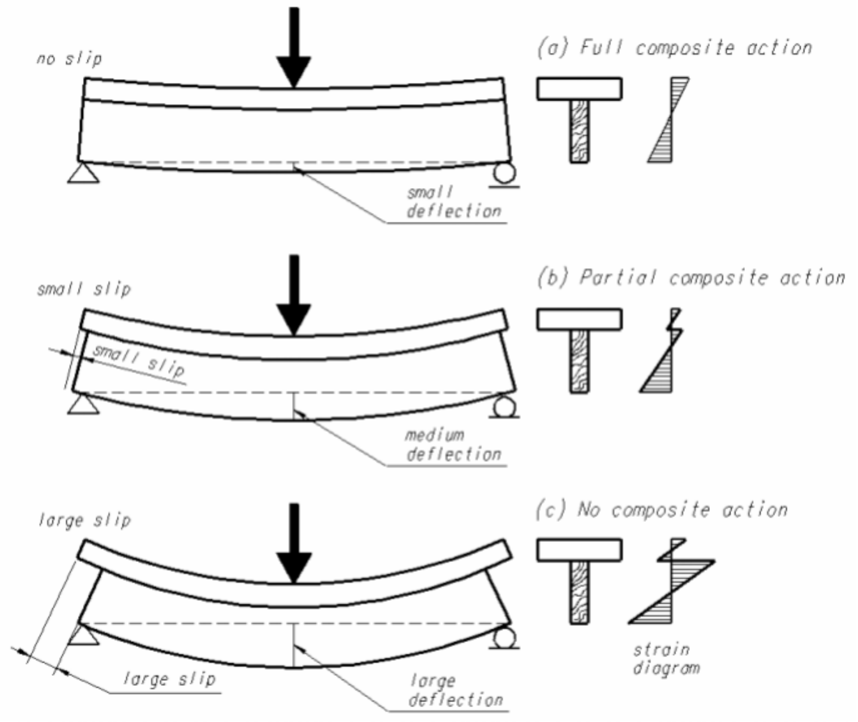
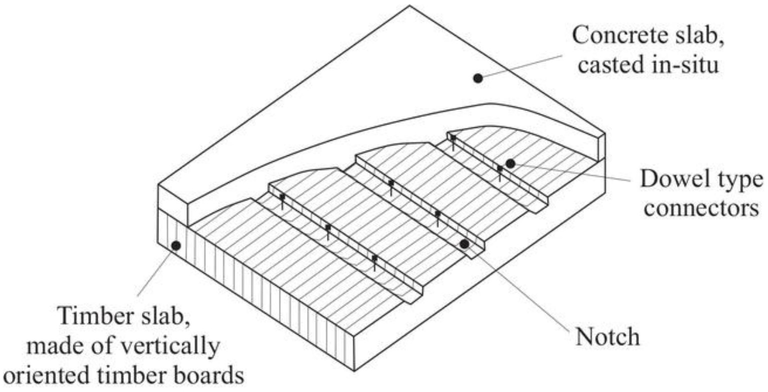


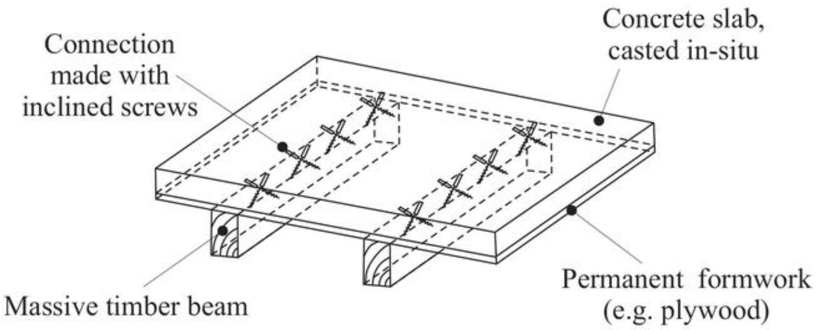
Figure 2.4: The Mechanism of Composite Action in TCC (Lukaszewka, 2009)

2.5 Connection System in TCC Structure

The connection system is one of the critical components in the design of TCC systems. According to Dias (2018), the connection system affects the stress distribution, deformations, and the whole system design due to the indeterminate nature of the systems. An ideal connection system’s properties should be strong enough to transmit shear forces generated at the interface, rigid enough to transfer the load with limited slip at the interface, and ductile enough to provide uniform load distribution and prevent fastener failure. According to Kavaliauskas et al. (2007), the use of inclined screws increases the resistance and stiffness of the connections, thus reducing the number of screws required in the composite floors under the same geometrical and loading configurations. Many studies have developed to focus on the development and characterization of specific connection systems. Dowel-type fasteners, notches, notches coupled with steel connectors, and other systems (e.g., direct gluing, nail plates, and glued steel mesh) are defined as the connection typologies based on the statistical analysis carried out by the Civil Engineering Department of the University of Coimbra.



(a)



(b)

Figure 2.5: Examples of slab and beam types of TCC floor systems. (a) An example of slab type of TCC floors. (b) An example of beam type of TCC floors.

2.6 Types of Shear Connection

In TCC, the timber joist mostly resists tension and bending, whereas the top of the concrete primarily resists compression. The shear forces were transmitted between the two components through the connection system. Therefore, the shear connection is essential to any timber-concrete composite system. It is noted that the connection needs to be stiffer, strong, and ductile enough to optimize the combined action. However, the number of components and installation time should be minimal to ensure an efficient system. The evaluation of the stiffness of the shear connector is essential because the slip modulus between the beam and the slab has a significant effect on the static and dynamic behavior of the timber-concrete composite structure (Gelfi et al., 2002). Hence, the design of timber-concrete composite structures generally needs to consider the slip occurring in the connection between the timber and concrete.

Figure 2.6(a) displays the joint or connection types grouped to stiffness. The stiffest connections are those in group (d), while the least rigid connections are those in the group (a). Connections in groups (a), (b), and (c) permit relative slip between concrete and timber, i.e., cross-sections do not remain planar under load. Only connections in the group (d) maintain planarity. Roughly speaking, systems with group (a) connections achieve 50% of the bending stiffness of systems with group (d) connections. The latter corresponds to a fully composite action. Design calculations for the group (d) connections are easily made. As there is no slip, the concrete layer is transformed into an equivalent timber section with the exact centre of gravity. As discussed below, the semi-rigid behaviour must be considered in the other cases.

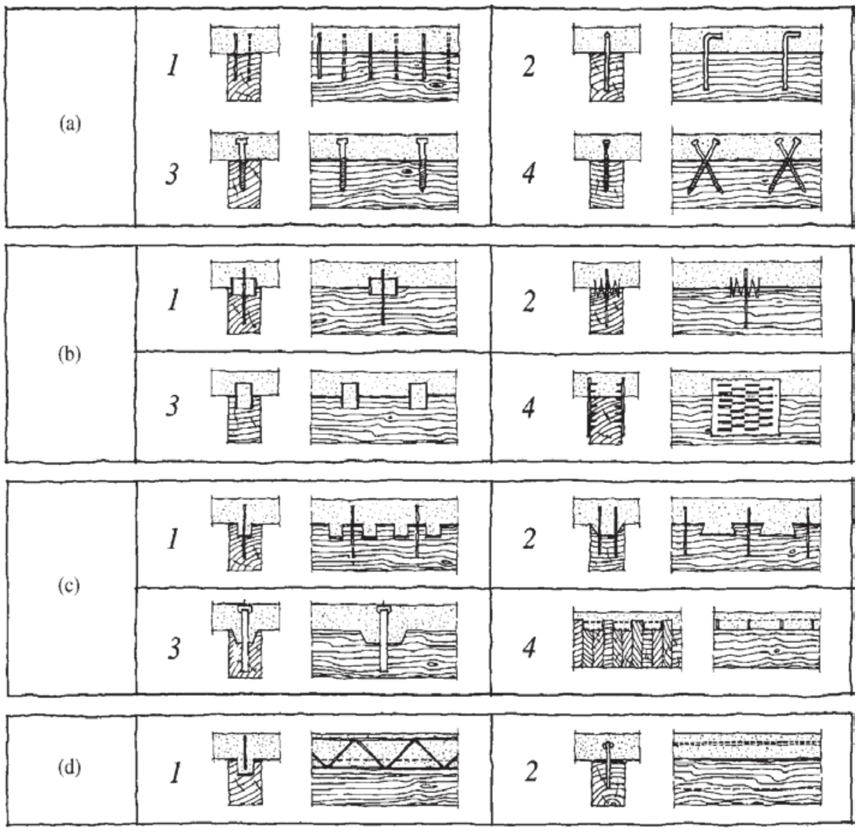


Figure 2.6 (a): 5 Examples of concrete–timber connections (Ceccotti, 1995) : (a1) nails; (a2) glued reinforced concrete steel bars; (a3/4) screws; (b1/2) connectors (split rings and toothed plates); (b3) steel tubes; (b4) steel punched metal plates; (c1) round indentations in timber, with fasteners preventing uplift; (c2) square indentations, ditto; (c3) cup indentation and prestressed steel bars; (c4) nailed timber planks deck and steel shear plates slotted through the deeper planks; (d1) steel lattice glued to timber; (d2) steel plate glued to timber

A questionnaire method was conducted by José et al. (2018) to get responses about the problems faced by the professionals in using the connections. 412 respondents filled the question from different fields consisting of engineering practitioners, manufacturers, and academia from 28 European countries and five non-European countries. The questionnaire consisted of four sections. The third section of the questionnaire asked the respondent's opinions on the common types of structures commonly used. Figure 2.6 (b) shows that most respondents are familiar with modern connection techniques such as screws, dowels, bolts, and nails. Most respondents answered that they often use screw connectors as a mean of fastener on designed timber structure.

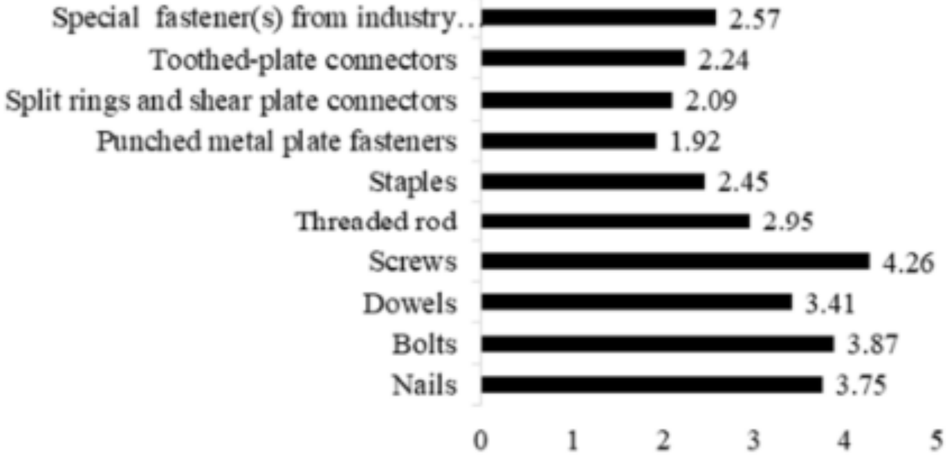


Figure 2.6 (b): The most common types of fasteners used (1- Never, 5 – Often) (José et al., 2018)

2.6.1 Dowel-Type Connections

One of the most prevalent connection technologies in timber constructions is dowel-type connectors. The force is transmitted primarily in bending and shear by dowel-type fasteners such screws, nails, bolts, staples, and dowels. Dias et al. (2018) present the distribution per fastener type in the dowel type fasteners organized within the following subgroup: dowels, screws, nails, inclined screws, and other metallic connectors (see Figure 2.6.1). From the figure, the screw connection is the most widely used product among dowel-type fasteners due to its high axial load-bearing capacity.

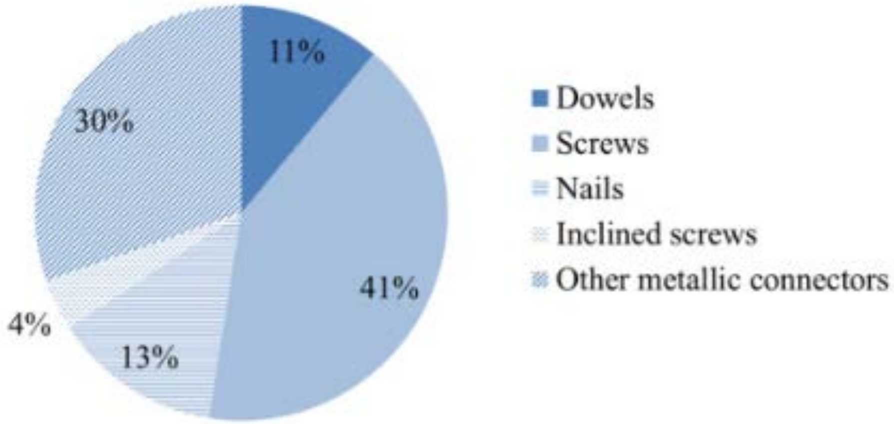
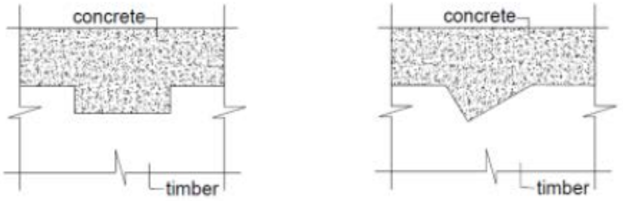


Figure 2.6.1: Distribution of the type of fasteners studied within the group of dowel-type fasteners (Dias et al., 2018)

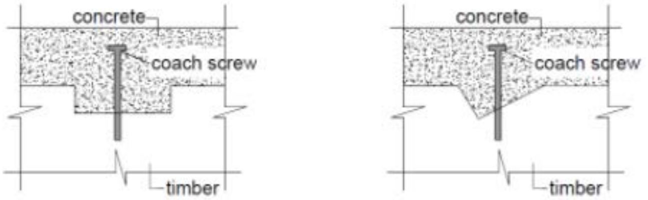
Screws have the advantage of being widely accessible and provide ease in installation. In reality, the present market's availability of self-tapping screws with continuous threads has made it possible to design an innovative geometric arrangement in which screws are inclined at various angles in a vertical plane. Numerous experimental and research studies have shown that using inclined screws enhances connection resistance and stiffness, thus reducing the number of screws required for composite floors with the same geometry and loading conditions.

2.6.2 Notches Connection

The structural timber element may be drilled, cut out holes, or have blocks bonded to it to form notch connections. Due to its simplicity, reduced cost, and superior mechanical performance, drillings, and cut-outs in timber members are often preferred. The notched connections have been successfully used for almost 100 years due to their simplicity and effectively connecting timber and concrete elements (Baldock and McCullough, 1941; Dias et al., 2018). However, the only drawback of this connection is that it has a low axial load carrying capacity, resulting in a brittle failure effect. Notched connections are often used in combination with steel fasteners to improve the axial load-bearing capacity and ductility of the whole connection system to solve these issues.



a) Rectangular notches b) Triangular notches



c) Rectangular notches with coach screw d) Triangular notches with coach screw

Figure 2.6.2: Notches connection (Mohd Snin, 2021)

2.6.3 Epoxy Bonded Connection

Complete interaction is a term to describe ideal composite action developed within two elements of concrete slab and timber stringers. It can be accomplished using a particular type of glue known as epoxy (Mat Lazim Zakaria, Chuah Chin Long & Yazid Jani). Due to stringent quality control and the difficulty of on-site application, glue and epoxy resin in the connection system are not entirely recommended (Yeoh et al., 2010). According to Dias et al. (2018), more research on the glued connection concerning the long-term behavior and the quality control during production is necessary for future use in TCC structures.

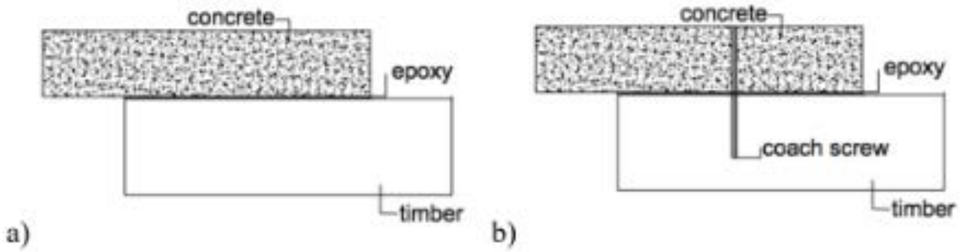


Figure 2.6.3: a) Epoxy connection, b) Epoxy with coach screw connections (Mohd Snin, 2021)

2.7 Comparison of Different Connection Systems

Over the last several decades, various connection systems have been invented, ranging from simple nails to concrete notches reinforced with steel bars. These connection systems have a unique load slip which is resulted from the push-out test. In general, the performance of connection systems is evaluated on three critical criteria: stiffness, strength, and ductility. It is noted that the connection systems should be: 1) strong enough to withstand the horizontal shear force along with the interface; 2) sufficiently stiff before yielding, resulting in a high degree of composite action; and 3) sufficiently ductile after yielding, offering overall ductility to the global TCC system. Figure 2.7.1 presents the comparison of different connection systems, while Table 2.7.1 shows the data on the influence of interlayers on TCC structure.

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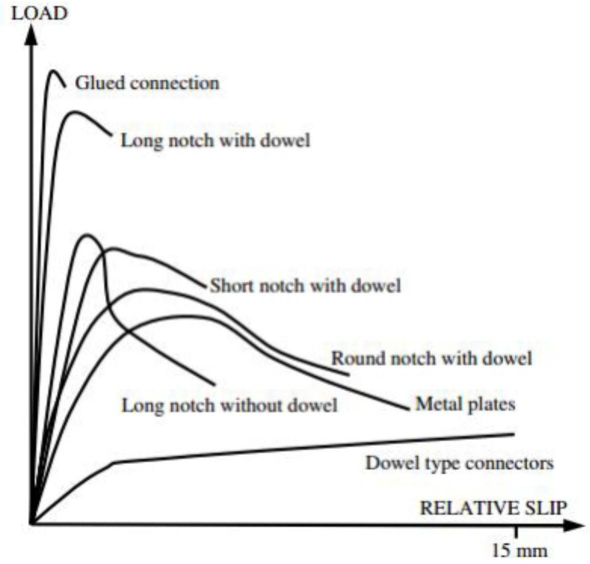

Figure 2.7.1: Comparison of different connection systems (Dias, 2005)

Table 2.7.1: Data on the Influence of Interlayer (Dias et al., 2015)

CONNECTION TYPE	LOAD CARRYING CAPACITY	CONNECTION STIFFNESS	REFERENCE
NAILS	13%	27%	Dias, 1999
INCLINED SCREWS	30%	50%	Van der Linden, 1999
NOTCHES COMBINED W/ DOWELS	30%	22%	Van der Linden, 1999
DOWELS	8%	35%	Dias, 2005
NOTCHES	16%	34%	Dias, 2005

2.8 Analytical Methods for Stiffness (Slip Modulus) and Shear Force Capacity of Inclined Screw as Shear Connection

Du et al. (2019) conducted thirty-six (36) push-out tests on glulam specimens to study the shear behaviour of the inclined screws consisting of different inclination angles and screw arrangements. The sample comprises one 150 mm x 300 mm x 400 mm central glulam member, two 80 mm x 400 mm x 400 mm concrete slabs, and two lag screws at both sides. The most crucial parameters in designing a timber-concrete structure system