Structural Behaviour of Timber Concrete Composite Connections and Floors utilising Screw Connectors

A thesis submitted in fulfilment
of the requirement for the degree of
Doctor of Philosophy

By

Farzad Moshiri

Faculty of Engineering and Information Technology
University of Technology Sydney (UTS)

December 2014

To My Beloved Wife:

Azi

CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate

(Farzad Moshiri)

Sydney, December 2014

ACKNOWLEDGEMENT

I would like to express my gratitude to those who have supported me throughout my study and helped make this PhD research possible.

First of all, I am extremely grateful to my principal supervisor, Prof Keith Crews, for supporting me during the past five years. Keith has been supportive and has given me the freedom to pursue various projects without objection. He has also provided insightful discussions about the research.

I will forever be thankful to Dr Rijun Shretsha. Rijun has been helpful in providing advice many times during my journey. His encouragement, guidance and unfailing assistance throughout this study are deeply appreciated. I also thank my former co-supervisor, Dr Hamid Valipour, for his help and teaching while he worked at UTS. I am also very grateful to Dr Christophe Gerber for his scientific advice and knowledge and many insightful discussions and suggestions.

I also have to thank Prof Bijan Samali, the former head of school of Civil and Environmental Engineering at the University of Technology, Sydney for his helpful career advice, outstanding guidance, motivation, wisdom and caring support provided throughout my PhD.

I gratefully acknowledge the financial assistance provided by Structural Timber Innovation Company (STIC). Also, the financial assistance provided by University of Technology Sydney (UTS) as International Research Scholarship, and all administrative and technical support provided by the Faculty of Engineering and Information Technology at UTS is appreciated.

I wish to acknowledge my colleagues, especially those involved in this project such as Nima Khorsandnia, Zhinus Zabihi, Rajendra Rijal, Matthew Holmes and Mulugheta Hailu for providing generous help during this study.

Special thanks to the UTS laboratory staff (Rami Haddad, Peter Brown, David Dicker, David Hopper and other lab assistants) for their great efforts in providing technical support and assistance for all of my experimental tests. I would also like to thank final year students who completed their final year theses as part of the STIC project (Chris Garvan, Jarod Wakefield, Adam Iverach, Benjamin Chen, Tim Kurniadi, Zhuoran Chen and Angus Lumsden) for their support in completing the tests.

A special thanks to my family. Words cannot express how grateful I am to my brothers, my sister, my mother, and father for all of the sacrifices that they have made on my behalf. Their steadfastness and hardworking sprit was always a source of inspiration for me to aim high and to pursue my dreams. Their prayer for me was what sustained me thus far. I would also like to thank all of my friends who supported me in writing, and incented me to strive towards my goal.

This last word of acknowledgment I have saved for my beloved wife Azi, who has been with me all these years and has made them the best years of my life. Thanks a lot and I always love you.

"In your light I learn how to love. In your beauty, how to make poems. You dance inside my chest where no-one sees you, but sometimes I do, and that sight becomes this art."
― Rumi

Farzad Moshiri
December 2014

ABSTRACT

The traditional materials such as reinforced concrete and structural steel have been widely used in the construction market. These construction materials produce a large quantity of greenhouse gases as a by-product. An environmentally sustainable solution to decrease the production of greenhouse gases is creation of composites with other materials such as timber to reduce the amount of steel and concrete used in construction.

Timber-concrete composites (TCC) structures, extends upon this by combining timber and concrete in order to form a composite structural member that utilises the properties of both materials. Since the 1990s, Timber Concrete Composite (TCC) floors have been gaining wider recognition as being a viable and effective alternative to both reinforced concrete and traditional timber floors. TCCs are a structural form whereby a concrete slab is fixed to a timber joist at the interface using a suitable shear connector which transfers shear forces and impedes slip between concrete and timber. Hence, the strength, stiffness, location and number of shear connectors used at the composite interface are the key factors in determining the composite action, the strength and stiffness of a TCC system. TCC exploits the mechanical properties of each material favourably with the concrete in compression and the timber in tension. TCCs have several advantages over full timber construction, including improved strength (double), stiffness (triple), vibration control, fire performance and thermal and sound insulation. TCCs also have advantages compared to full concrete construction, including a much higher load capacity per unit of self-weight and a lower embodied energy.

Mechanical fasteners for example screw and dowel TCC connectors are relatively simple and easy to install, cost effective and structurally efficient connectors with lower labour requirement. With these considerations, mechanical fasteners can be preassembled in prefabrication or cast in situ TCC solutions. Hence, application of mechanical fasteners in TCCs overcomes the drawbacks of alternative connection such as notch type connection and reduces the time required to construct a TCC system.

This research investigates the experimental parametric study on the effect of different types of high-performance concrete on mechanical properties of TCC connections and

floors using locally available materials in Australia to evaluate their potential for use in the construction market. A parametric study of mechanical fasteners such as crossed SFS VB, crossed SPAX and coach screws connections in different lengths (short and long SFS VB), angles (±30°, ±45° and ±60°) to the connection face and a number of crossed SFS VB and SPAX at 45° series utilising 17mm plywood formwork interlayer and different types of concrete was carried out. Hence, the effects of connector type, inclination angle and length of screw and existence of plywood interlayer on mechanical properties of the TCC connections were investigated. Moreover, two innovative TCC shear connection systems were put forward and assessed for their suitability as a substitute or replacement for existing connection systems using push-out test.

The application of high-performance concrete such as light-weight concrete and self-consolidating concrete provides a great deal of benefits in TCC technology to minimize the dead-load on the timber component or increase the concrete workability and accelerate the process of pouring. Such weight reduction and increased workability may be favourable in the renovation of old timber floors. The use of TCC technology is also advantageous in new multi-storey buildings for aspects such as prefabrication and mitigation of excess dead load – leading to saving on foundation and walls and/or column sizes.

This research investigates the effect of different types of high-performance concrete on the mechanical properties of TCC connections and floors using locally available materials in Australia to evaluate their potential for use in construction market.

Push-out test was used to determine the mechanical properties and failure modes of shear connections and once the mechanical properties of connection type were identified, full-scale TCC modules utilising different types of shear connector and concrete properties were subjected to four-point bending tests. Hence, the predictions of full beam behaviour using the connection properties were validated and the effect of shear connection and concrete type on structural behaviour of an entire floor was investigated.

Literature reports a significant lack of information on analytical closed-form equations to predict the strength and stiffness of TCC connections utilising vertical and inclined fasteners to be used in the design of timber composite beams.

This study reviewed the methodology of available analytical models for prediction of the strength and serviceability stiffness of vertically inserted single timber to timber and TCC shear connections and validated their accuracy using the experimental push-out test results. Moreover, an analytical strength model based on some adjustment to EYM to predict the strength of TCC connections utilising single and crossed screws inclined to the timber grain was proposed. This research also presented a model for the stiffness of TCC connections using crossed inclined screws. The Winkler theory of beam on elastic foundation proposed was extended to derive the serviceability slip modulus of TCC connections with inclined screws which were loaded in tension and compression.

In addition, a 3-D FE model has been put forward to simulate different TCC connections such as single and multiple wood screws and inclined coach screw utilising the commercial FE analysis software ANSYS. The findings of this part demonstrate that by using a simple numerical model, the behaviour of TCC connections can be accurately modelled and can therefore be used for parametric study of changes in end distance, edge distance, member thickness, screw diameter, screw length and number of screws.

LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

a	Unknown parameter used in mathematical model
a	Distance between support and load in four-point bending test (l/3)
a_1	Fastener spacing
a_2	Fastener spacing between rows
$a_{3,t}$	End distance in a row (loaded end)
$a_{3,c}$	End distance in a row (loaded edge)
$a_{4,t}$	Edge distance in a row (loaded edge)
$a_{4,c}$	Edge distance in a row (unloaded edge)
a_1	Distance between centroids of concrete floor and effective TCCs
a_2	Distance between centroids of timber webs and effective TCCs
a_3	Distance between centroids of timber flange and effective TCCs
A	Section area
A	Section area of steel fastener
A_t	Section area of timber member
Anal.	Analytical
AS	Australian Standards
A_α	Cross-sectional area of the fastener at the timber-concrete interface
b	Unknown parameter used in mathematical model
b_2	Width of the LVL web
B_i	Constant coefficients based on the compatibility conditions
b_w	Web width

b_{ef}	Effective width in TCC section
c	Unknown parameter used in mathematical model
CC	Conventional concrete
CoV	Coefficient of variation
$cos\alpha$	Cosine function of angle α
$cosh\alpha$	Hyperbolic cosine function of angle α
d	Diameter of screw including thread
dx	Part of a screw of length
d_1	Major diameter of screw
d_2	Core diameter of screw
d_{ef}	Effective diameter equal to 0.75 times the fastener diameter
d_k	Head diameter of screw
d_s	Shank diameter of screw
D_N	Theoretical fully non-composite deflection
D_I	Measured deflection for partially composite action
D_C	Theoretical full-composite deflection
D_f	Ductility as the ratio of ultimate to yield deformations
D_u	Ductility as the ratio of slip at maximum load to yield slip
DCA	Degree of composite action in composite system
DLWC	Dry light-weight concrete
e/d	End distance to diameter ratio of fasteners
E	Napier's constant
E	Modulus of Elasticity
EC5	Eurocode 5
E_c	Modulus of elasticity of concrete
$E_{c,m}$	Mean Modulus of Elasticity of concrete
E_s	Modulus of elasticity of steel shear connector
E_t	Modulus of elasticity of timber
E_x	Elastic modulus in the tangential direction
E_y	Elastic modulus in the longitudinal direction
E_z	Elastic modulus in the radial direction
$E_{\tau x}$	Tangent moduli (tensile and compressive) in the *x* direction
$E_{\tau y}$	Tangent moduli (tensile and compressive) in the *y* direction

$E_{\tau z}$	Tangent moduli (tensile and compressive) in the *z* direction
$E_{t,\alpha}$	Modulus of elasticity of timber in parallel and perpendicular directions
E_T	Tangent modulus
EI	Apparent stiffness of timber composite module
EI_{eff}	Effective bending stiffness of timber composite module
EPS	Expanded polystyrene
EPS LWC	Expanded polystyrene light-weight concrete
Exp.	Experiment/experimental
EYM	European yield model
f	Vector of surface load
F	Shear force in the connector
FE	Finite element
F_p	Shear force in the connector parallel to the grain
F_t	Shear force in the connector transverse to the grain
$f_{a,0}$	Withdrawal strength of screw inserted parallel to the grain
$f_{a,\alpha}$	Withdrawal strength of screw inserted at an angle of α to the grain
$f_{ax,k}$	Characteristic withdrawal strength perpendicular to the grain
f_b	Bending stress
$f(i)$	Load capacity of failure mode i
f_m	Bending strength of the timber flange in TCC section
f_t	Tension strength of the timber flange in TCC section
f_c	Uniaxial crushing stress of concrete
f_t	Uniaxial tensile cracking stress of concrete
$f_{t\text{-}t}$	Failure load at interface of timber-timber connection
f_c	Compression strength of the timber flange in TCC section
f_{cb}	Biaxial crushing stress of concrete
f_1	Biaxial crushing stress under the ambient hydrostatic stress state
f_2	Uniaxial crushing stress under the ambient hydrostatic stress state
$f_{c,m}$	Mean compressive strength of concrete
$f_{c,i}$	Mean compressive strength of concrete at age of i day (i=3,7 and 28)
$f_{ct.sp,i}$	Mean indirect tensile strength of concrete at age of i day (i=3,7 and 28)
f_p	Stress in compression perpendicular to grain
$f_{h,\alpha}$	Embedment strength of timber at an angle of α to the grain

$f_{h,d}$	Designed embedment strength of timber
$f_{h,0}$	Embedment strength of timber parallel to the grain
$f_{h,0,k}$	Characteristic embedment strength of timber parallel to the grain
$f_{h,i,k}$	Characteristic embedment strength in timber member i
$f_{h,k}$	Embedment strength of the timber and mechanical fastener
f_u	Ultimate tensile stress of fastener
$f_{c,w}$	Design compressive strength of the timber web in TCC section
f_m	Flexibility matrix of the beam on the elastic foundation
f_s	Stress in longitudinal shear LVL hySPAN project
$f_{t,w}$	Design tensile bending strengths of the timber web in TCC section
f_v	Design planar shear strength of the web in TCC section
f_y	Tangent modulus
f'_b	Bending strength of plywood
f'_c	Stress in compression in the plane of the sheet in plywood
f'_p	Stress in compression normal to the plane of the sheet in plywood
f'_s	Shear stress of plywood
f'_t	Tension strength of plywood
$F_{ax,\alpha}$	Axial withdrawal load capacity of inclined fastener
$F_{ax,Rk}$	Characteristic axial withdrawal capacity of the fastener
F_{ave}	Average load applied to the module at third-spans
$F_{LoadCell}$	Applied load in each loadcell
F_{lat}	Elastic forces acting perpendicular to the axis of fastener
F_{ax}	Elastic forces acting parallel to the axis of fastener
F_{est}	Estimated maximum load
F_{max}	Load carrying capacity
$F_{multiple}$	Load carrying capacity of the multiple fasteners
F_{single}	Characteristic load carrying capacity of single fastener
F_{ser}	Lateral load at SLS
F_u	Ultimate tensile capacity of screw
$F_{V,Rk}$	Characteristic load-carrying capacity per shear plane per fastener
FRC	Fibre reinforced concrete
Full C.	Full composite
FKN	Normal contact stiffness factor in ANSYS

FKT	Contact stiffness factor in ANSYS
FTOLN	Allowable penetration in ANSYS
h_1	Depth of the concrete slab
h_2	Depth of the timber web
h_3	Depth of the timber bottom flange
h_{ef}	Effective depth in box shape TCC section
$h_{f,c}$	Depth of compression flange in box shape TCC section
$h_{f,t}$	Depth of tension flange in box shape TCC section
HPC	High-performance concrete
HSC	High-strength concrete
I	Second moment of area of TCC section
I_s	Second moment of area of steel connector
I	With interlayer
I_c	Second moment of area for concrete slab
I_t	Second moment of area for timber joist
G	Modulus of Rigidity
G	Permanent action (self-weight or 'dead load')
G_{xy}	Shear modulus in the xy plane
G_{yz}	Shear modulus in the yz plane
G_{xz}	Shear modulus in the xz plane
Gτxy	Tangent modulus (shear) corresponding to the *xy* plane
Gτyz	Tangent modulus (shear) corresponding to the *yz* plane
Gτxz	Tangent modulus (shear) corresponding to the *xz* plane
J_i	Parameter of member i in stiffness model proposed by Kuenzi (1955)
kN	Kilo newton
k	Foundation modulus of material
k_1	Smeared slip modulus of shear connection
k_d	Minimum of $d/8$ and 1
K	Slip modulus of shear connection
K	Global stiffness of the timber composite module
K	Stiffness matrix
K_i	Parameter of member i in stiffness model proposed by Kuenzi (1955)
K_s	Serviceability slip modulus of shear connection

$K_{s,0.4}$	Serviceability slip modulus of shear connection
$K_{u,0.6}$	Ultimate slip modulus of shear connection
$K_{u,0.8}$	Slip modulus of shear connection corresponding to $0.8F_{max}$
$K_{\perp}$	Stiffness of connector for lateral loading
$K_{\parallel}$	Stiffness of connector for withdrawal loading
$\hat{K}$	Non-dimensional stiffness by Symons, Persaud and Stanislaus (2010a)
k_c	Lateral instability factor in design of timber composite in compression
k_c	Foundation modulus of concrete
k_t	Foundation modulus of timber
k_p	Foundation moduli of timber parallel to the grain
k_t	Foundation moduli of timber transverse to the grain
LVDT	Linear variable differential transformer
l	Span length of the beam
L	Screw length
L_i	Parameter of member i in stiffness model proposed by Kuenzi (1955)
l_{ef}	Penetration length of the threaded part for mechanical fastener, t-d
L- L_s	Threaded length of screw
LVL	Laminated veneer lumber
LWC	Light-weight concrete
mm	Millimetres
MPa	Mega Pascal
M	Bending moment transferred between timber and concrete in TCCs
M_1	Internal moment on the free end of the beam on the elastic foundation
M_{exp}	Experimental bending moment obtained from four-point bending test
M_u	Bending moment due to factored loads in TCCs
M_y	Yield moment of fastener
$M_{y,Rk}$	Characteristic fastener yield moment
MOE	Modulus of elasticity
MOR	Module of rupture
n	Number of fastener
n_{ef}	Effective number of fastener
N	Shear force transferred between timber and concrete
N	Shape function matrix

$N_{d,,j}$	Design capacity of connection
Non C.	Non-composite
NSW	New South Wales
NZS	New Zealand Standards
p	Thread pitch of screw
PVA	Polyvinyl alcohol-fibres
q	Shear flow of the TCC section
q_m	Matrix of actual displacements corresponding to the redundant
q_{om}	Matrix of actual displacements of the redundant action, due to the loads
Q_k	The 5th percentile strength
Q	First moment of area for concrete slab in TCC section
Q	Imposed action for each occupancy class
Q_k	Characteristic capacity of screw
Q_m	Matrix of redundant
R	Sample correlation coefficient
R	Collapse load in TCC connection
RH	Relative humidity
s	Connectors spacing
S	Surface
S_F	Part of the surface
s_e	Connectors spacing at the beam-ends
s_m	Connectors spacing at
$sin\alpha$	Sine function of angle α
$sinh\alpha$	Hyperbolic sine function of angle α
SCC	Self-consolidating concrete
SFRC	Steel fibres reinforce concrete
SG	Strain gauge
SLS	Serviceability limit state
STIC	Structural Timber Innovation Company
t(x)	Shear flow along the beam length
t	Timber thickness or the embedded length of fastener in timber
t	Traction vector
t_1	Head side thickness of fastener in a single shear connection

t_2	Point side penetration in a single shear connection
$t_{0.1}$	Value in standard for (n − 1) degrees of freedom and a probability of 0.1
T	Temperature
$tan\alpha$	Tangent function of angle α
t/d	Slenderness ratio (fastener depth/fastener diameter)
$\hat{t}$	Non-dimensional embedment (embedment depth/fastener diameter)
TCC	Timber-concrete composite
u	Displacement vector
u_d	Small slip design in design of TCC shear connector
UEA	Unequal angle
UTS	University of Technology, Sydney
ULS	Ultimate limit state
V	Shear force transferred between timber and concrete in TCC connector
V	Volume
V_1	Internal load acting on the free end of the beam on the elastic foundation
V_b	Maximum shear force at beam-end in design of TCC connectors
$V(x)$	Shear force in the cross-section of TCC along the beam
V_{sd}	Design shear force at connection in TCC modules
W_{eq}	Equivalent uniformly distributed load
W_E	External work done by the external force in a TCC connection
W_I	Internal energy in a TCC connection
WI	Without interlayer
x	Length parameter of fastener
y	Elastic transverse deformations of a connection on elastic foundation
$y_{5percent}$	5^{th} percentiles of the lower probability limit
y_{ij}	Deformation array in flexibility matrix of the beam
$y(x)$	Elastic deformations of a timber connection at point x along the fastener
y_{10}	Slip at interface of materials
Z	Foundation depth
π	pi
π	Total potential energy
β	Ratio between embedment strength of timber members
β	Factor as a function of the fastener's diameter to spacing ratio

β	Ratio of of k_t/k_p
β	coefficient in Canadian standard
θ	Inclination angle of fastener to the vertical direction (90- α)
α	Inclination angle of fastener to the horizontal direction (90- θ)
θ_{ij}	Rotation array in flexibility matrix of the beam
θ_{20}	Rotation at interface of materials
δ	Mid-span deflection of a simply supported composite beam
$\delta_{\perp}$	Perpendicular component of slip in shear connector
$\delta_{\parallel}$	Parallel components of slip in shear connector
Δ_p	Slip component parallel to the grain
Δ_t	Slip component transverse to the grain
Δ	Slip at interface of timber composite connection
Δ_{ax}	Axial displacement of fastener
Δ_{lat}	Slip at the interface of the concrete and timber in a TCC connection
σ	Standard deviation
σ	Stress
σ^a_h	Ambient hydrostatic stress state of concrete
σ_x	Yield stresses (tensile and compressive) in the *x* direction
σ_y	Yield stresses (tensile and compressive) in the *y* direction
σ_z	Yield stresses (tensile and compressive) in the *z* direction
σ_i	Axial stress in TCC section
$\sigma_{b,i}$	Bending stress in TCC section
$\sigma_{i,b}$	Total normal stresses in TCC section
$\sigma_{f,c,max}$	Extreme fibre flange design compressive stress in TCC section
$\sigma_{f,t,max}$	Extreme fibre flange design tensile stress in TCC section
$\sigma_{w,c,d}$	Design compressive stress of the timber web in TCC section
$\sigma_{w,t,d}$	Design tensile stress of the timber web in TCC section
$\sigma_{f,c}$	Mean flange design compressive stress in TCC section
$\sigma_{f,t}$	Mean flange design tensile stress in TCC section
$\sigma_{2,N}$	Tensile and bending stresses of timber in TCC section
$\sigma_{2,M}$	Bending stresses of timber in TCC section
σ_y	Shear yield stress of the fastener

σ_p	Yield stress
ε	Strain
Υ	Shear bond coefficient
Υ_v	Material safety factor
λi	Parameter of member i in stiffness model proposed by Kuenzi (1955)
υ	slip at interface of composite materials
υ	Axial deformations of a connection on elastic foundation
υ_0	Axial deformations of a connection on elastic foundation at (x=0)
υ_i	Slip measurement at specified points
υ_y	Elastic deformation of connector
υ_u	Slip corresponding to maximum load at connection
υ_f	Deformation associated to load-drop (80% of the maximum load)
υ	Poisson's ratio
υ_{xy}	Poisson's ratio in the xy plane
υ_{yz}	Poisson's ratio in the yz plane
υ_{xz}	Poisson's ratio in the xz plane
τ_{mean}	Design shear stress in TCC section
$\tau_{2,max}$	Maximum shear stress in the web of a box shape TCC section
τ_{xy}	Shear yield stress in the *xy* plane
τ_{yz}	Shear yield stress in the *yz* plane
τ_{xz}	Shear yield stress in the *xz* plane
ρ	Mass per unit volume
ρ_k	Characteristic mass per unit volume of timber
ρ_m	Mean mass per unit volume of timber
Φ	Capacity factor
2-D	Two dimensional
3-D	Three dimensional