DEVELOPMENT OF DESIGN PROCEDURES FOR TIMBER CONCRETE COMPOSITE FLOORS IN AUSTRALIA AND NEW ZEALAND PART 1 – DESIGN METHODS

Prof Keith Crews & Dr Christophe Gerber

Centre for Built Infrastructure Research, University of Technology Sydney, Australia

1 Introduction

Timber concrete composite (TCC) floor systems are relatively new to Australia and New Zealand and satisfactory performance requires a rigorous design procedure addressing both ultimate and serviceability limit states. TCC structures have a degree of complexity since they combine two materials that have very different mechanical properties and respond in different ways to their environment. Furthermore, most TCC structures exhibit partial (not full) composite action and this adds to the complexity of the system.

Several design procedures are discussed in the literature. Amongst these, the Eurocode 5 (EC5) procedure is relatively straightforward and has been successfully implemented in Europe. It utilises a simplification for modelling the complex timber - concrete interaction known as the "Gamma coefficients" method, which manipulates properties of the concrete member in order to predict the cross-section characteristics of the structure.

The details of this research are presented in two papers. Part 1 deals with design procedures, whilst Part 2 discusses and extensive R&D program of connection testing and the derivation of characteristic properties.

2 Scope

The EC5 approach has been adopted as the underlying basis for the design procedures presented in this document; modified to comply with current design codes and practices in Australia[1]. It comprises normative parameters for the strength and safety (ultimate limit state) and informative guidelines for appearance, deflection limits and comfort of users (serviceability limit states). Whilst the latter must be defined by designers to meet the specific functional requirements of the floor under consideration, it is recommended that the Guidelines in this document should be adopted as a <u>minimum</u> standard for TCC floors.

At the time of publication, there is still considerable uncertainty about some aspects of long term deflection of TCC floors and as such the design procedures contained in this document are limited to floors not exceeding 8m in span and utilising the notched connections prescribed in Table 1.

3 Design requirements

Load type and intensity, load combinations and modification factors for both the ultimate and the serviceability limit states have been defined in accordance with the AS/NZS 1170 series (AS/NZS 2002a; 2002b).

[1] With minor modifications the same approach is relevant for New Zealand.

The limit states that require checking can be summarised as follows:

1. the **short-term ultimate limit state**; where the structure response to the maximum load is analysed. It generally corresponds to short-term exertion of the structure.
2. the **long-term ultimate limit state**. This analysis focuses on the structure response to a quasi permanent loading and aims at avoiding failure due to creep of the timber member in particular*.
3. the **short-term serviceability limit state**. This corresponds to the instantaneous response of the structure to an imposed load.
4. the **long-term serviceability limit state**. This analysis aims to identify the service life behaviour of structure considering the time-dependent variations of the material properties; in particular creep.
5. the **1.0-kN serviceability limit state**. This corresponds to the instantaneous response of the structure to an imposed point load of 1.0 kN at mid-span.

*Checking the end-of-life ultimate limit states corresponds to an attempt to analyse and assess the durability and reliability of the structure.

3.1 Connection behaviour

The structural behaviour of the connection is a significant parameter in the design of a TCC floor. The elastic properties of the connection are used for both limit states and accounted for in the identification of the Gamma coefficients in the design procedure.

4 Design procedure

The design procedure has three fundamental stages:

1. The initial stage of the design procedure focuses on identifying of the characteristics of the TCC cross-section.
2. Assessment of the strength capacity of the structure is completed in the second stage of the procedure; whilst
3. The final stage deals with the serviceability limit state.

4.1 Cross-section characteristics

The effective (apparent) stiffness of the composite cross-section is:

$$(EI)_{ef} = E_c I_c + E_t I_t + \gamma_c E_c A_c a_c^2 + \gamma_t E_t A_t a_t^2 \qquad (1a)$$

Note: The subscripts c and t refer to concrete and timber respectively, unless otherwise specified. The contribution of the formwork (if present) is neglected in the design.

where the section properties in (1a) are given by:

$$I_c = \frac{b_c h_c^3}{12}; \qquad I_t = \frac{b_t h_t^3}{12} \qquad (2a); (2b)$$

$$\gamma_c = \frac{1}{1 + \frac{\pi^2 E_c A_c s_{ef}}{K_i L^2}}; \qquad \gamma_t = 1 \qquad (3a); (3b)$$

$$A_c = b_c h_c; \qquad A_t = b_t h_t \qquad (4a); (4b)$$

$$a_c = \frac{\gamma_t E_t A_t H}{\gamma_c E_c A_c + \gamma_t E_t A_t}; \qquad a_t = \frac{\gamma_c E_c A_c H}{\gamma_c E_c A_c + \gamma_t E_t A_t} \qquad (5a); (5b)$$

The height factor "H" is defined by:

$$H = \frac{h_c}{2} + a_f + \frac{h_t}{2} \qquad (6)$$

where:

- the tributary width of the concrete member is assessed with (AS 2001, p. 93):

$$b_c = b_t + 0.2a; \qquad b_c = b_t + 0.1a \qquad (7a); (7b)$$

- the effective spacing (refer to Figure 1) of the connections is given by:

$$s_{ef} = 0.75 s_{min} + 0.25 s_{max} \qquad (8)$$

- where all connectors are evenly spaced within the end quarter spans

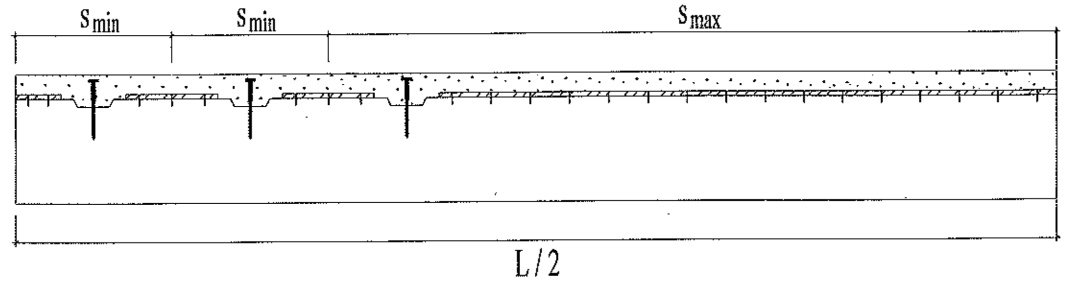


Figure 1: Connection-related distances.

- and the stiffness of the connection corresponds to (refer to TABLE 1):

$$K_{ser} = \frac{0.4 R_m}{v_{0.4}}; \qquad K_{eff} = \frac{K_{ser}}{j_{2,long}}; \qquad K_u = \frac{0.6 R_m}{v_{0.6}} \qquad (9a); (9b); (9c)$$

Note: Whilst it is understood that the creep behaviour of TCC floors is quite complex, the "creep component" for long term defections is modelled using the j_2 factor. This is consistent with AS 1720.1 (2010), which uses a simplified multiplier to the initial short term deflection. A value of $j_{2,long}$ between 3.0 and 4.0 is currently recommended for indoor applications.

4.2 Strength of the composite cross-section – concrete & timber members

The load combinations and factors for the ultimate limit state (ULS) must comply with the relevant provisions of AS / NZS1170 series (AS/NZS 2002a; 2002b). The checks imposed on a structure under flexural action or flexural and axial actions are described in Sections 3.2 and 3.6 of AS 1720.1 (AS 1997) respectively. These requirements apply to TCC floor structures as follows:

- bending strength – the concrete and timber members resist a combination of bending moment and/or axial force.
- flexural shear strength – the timber member resists the flexural shear force.
- bearing strength – the timber member resists the support action/reactions.

4.2.1 Strength requirements for Bending strength

At the extreme fibres – upper and lower – the concrete and timber members experience compression and tension stresses which result in combined bending and axial stresses as defined in Equation (10). The check is completed for the upper and lower fibres of the concrete member and for the lower fibre of the timber member[2].

$$\frac{N^*}{(\phi N)}+\frac{M^*}{(\phi M)}\leq 1.0 \text{ (expressed as stress ratios)} \qquad (10)$$

The general expression for bending stress is defined in Equation (11):

$$\sigma_{b,i}=\pm\frac{1}{2}\frac{E_i h_i M^*}{(EI)_{ef}} \qquad (11)$$

Specifically, the stresses in the concrete and timber member respectively are:

$$\sigma_{b,c}=\pm\frac{1}{2}\frac{E_c h_c M^*}{(EI)_{ef}}; \qquad \sigma_{b,t}=\pm\frac{1}{2}\frac{E_t h_t M^*}{(EI)_{ef}} \qquad (11a); (11b)$$

Equations (11a) and (11b) respectively identify the bending moment capacity:

$$\phi M_u=\phi f_c'\frac{2(EI)_{ef}}{\gamma_c E_c h_c}; \qquad (\phi M)=\phi k_1 k_4 k_6 k_9 k_{11} k_{12} f_b'\frac{2(EI)_{ef}}{\gamma_t E_t h_t} \qquad (12a); (12b)$$

These capacities must be greater than the design moment M^*, which is derived from loading requirements and boundary conditions of the TCC structure. The axial (in-plane) stress is predicted using Equation (13):

$$\sigma_{c/t,i}=\pm\frac{\gamma_i E_i a_i M^*}{(EI)_{ef}} \qquad (13)$$

Specifically, the stresses in the concrete and timber member respectively are:

$$\sigma_{c,c}=-\frac{\gamma_c E_c a_c M^*}{(EI)_{ef}}; \qquad \sigma_{t,t}=\frac{\gamma_t E_t a_t M^*}{(EI)_{ef}} \qquad (13a); (13b)$$

Assessment of the axial stress is derived from the flexural action. However, (13a) and (13b) can be manipulated to identify the (corresponding) design axial force:

$$N_c^*=\sigma_{c,c}A_c; \qquad N_t^*=\sigma_{t,t}A_t \qquad (14a); (14b)$$

where the allowable axial forces are defined as:

$$\phi N_u=\phi f_c' A_c; \qquad (\phi N)=\phi k_1 k_4 k_6 k_{11} f_t' A_t \qquad (15a); (15b)$$

[2] An efficient design of a TCC cross-section occurs when the concrete member is fully under compressive stress and the timber member is mainly subjected to tensile stress. It is possible for the timber beam to experience compression, but this is not critical because the timber material exhibits adequate compression capacity.

4.2.2 Strength requirements for Flexural shear strength

In the absence of structural reinforcement in the concrete member, the flexural shear strength is provided by the timber member, therefore,

$$(\phi V)\geq V^* \qquad (16)$$

Where for rectangular sections:

$$(\phi V)=\phi k_1 k_4 k_6 k_{11} f_s' \frac{2A_t}{3} \qquad (17)$$

Note: Some conditions, (for example use of a deep notch), may require reducing the shear plane area by using the net area of the (beam) cross-section.

4.2.3 Strength requirements for Bearing strength

The bearing strength is provided by the timber member, therefore,

$$(\phi N_p)\geq N_p^* \qquad (18)$$

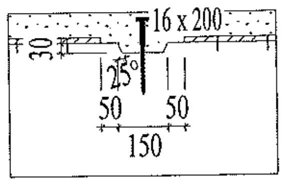
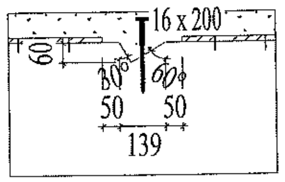
in which:

$$(\phi N_p)=\phi k_1 k_4 k_6 k_7 f_p' A_p \qquad (19)$$

4.3 Strength of the composite cross-section – connection capacity

The connection (or notch) transfers the shear force occurring between the members under flexure. The actual mechanics of this force transfer are relatively complex. However a prescriptive approach that defines connection capacities (based on empirical test data - refer TABLE 1) that ensures the design procedure remains user-friendly, has been adopted for this document.

TABLE 1: CHARACTERISTIC PROPERTIES OF THE CONNECTION

Connection type	Beam width[*^†] b_t *mm*	Strength Q_k *kN*	SLS stiffness K_{ser} *kN/mm*	ULS stiffness K_u *kN/mm*
	48	46	81	58
	63	78	105	76
	48	55	35	34
	63	66	96	69

[*] connection properties for beams 48 mm < b_t < 63 mm, are derived by linear interpolation.

[^] for beam, b_t > 63 mm, a reduction coefficient is applied: $k_{u,red}=\left(\frac{b_t}{63}\right)^{1.42}$ & $k_{s,red}=\left(\frac{b_t}{63}\right)^{0.42}$.

[†] for other connection types, empirical values must be established.

4.3.1 Shear strength of the connection

A global assessment of the connection strength is performed. It includes the assessment of the strength of the first connection, V^*_{max}, and the connection located at the quarter-span area, $V^*_{L/4}$.

$$(\phi N_j) \geq Q^* \tag{20}$$

NOTE: Refer to TABLE 1, for empirical strengths of the specified connections.

where:

$$(\phi N_j) = \phi k_1 k_4 k_6 Q_k \tag{21}$$

and the effective shear force in the connection located near the support equals:

$$Q^*_{(V^*_{max})} = -\frac{\gamma_c E_c A_c a_c s_{min}}{(EI)_{ef}} V^*_{max} \tag{22}$$

*(where x = 0 – refer to **Fehler! Verweisquelle konnte nicht gefunden werden.**, in Appendix Section **Fehler! Verweisquelle konnte nicht gefunden werden.**):*

and the effective shear force in the connection located at the 'quarter' span:

$$Q^*_{(V^*_{L/4})} = -\frac{\gamma_c E_c A_c a_c s_{max}}{(EI)_{ef}} V^*_{L/4} \tag{23}$$

*(where x = L/4 – refer to **Fehler! Verweisquelle konnte nicht gefunden werden.**, in Appendix Section **Fehler! Verweisquelle konnte nicht gefunden werden.**):*

4.3.2 Shear strength of the timber

The shear strength of the timber – tangential shear action in the area located between the support and the first connection is assessed and checked as follows:

$$(\phi N_V) \geq V^* \tag{24}$$

where:

$$(\phi N_V) = \phi k_1 k_4 k_6 f'_s (b_t l_s) \tag{25}$$

4.4 Serviceability verification / assessment of the composite cross-section

The load combinations and factors for the serviceability limit states (SLS) are defined in the AS/NZS 1170 series (AS/NZS 2002a; 2002b). Serviceability of the TCC structure is undertaken by checking the deflections against the limits defined to suit the functional requirements of the building being designed. In the absence of any specific limits the following are recommended:

- Short term Live load only, limited to span / 300
- Short term Point load deflection, limited to 2.0mm

The mid-span deflection under uniformly distributed load is assessed as follows:

$$\Delta = \frac{5(G^* + \varphi w^*_{imp})L^4}{384(EI)_{ef}} \tag{26}$$

For which the value of φ and $(EI)_{ef}$ are defined to suit the loading condition and duration.

4.4.1 Instantaneous short-term deflection:

The shrinkage and creep effect of the concrete member and the creep of the timber is neglected. Thus, $\varphi = 1.0$ and $(EI)_{ef}$ is approximated as defined in Equations (1a) to (9).

a) imposed load deflection check under uniformly distributed load, from Eqn (26),

b) deflection under 1.0 kN (vibration check):

$$\Delta = \frac{P^* L^3}{48(EI)_{ef}} \tag{27}$$

Where $P^* = 1.0$ kN (point load applied at mid-span).

4.4.2 Long-term end-of-life deflection

The shrinkage and creep of the concrete member and the creep of the timber are accounted for.

Thus, $\varphi = 4.0$ and $(EI)_{ef}$ is approximated as per Equations below.

a) permanent and imposed load (deflection check under uniformly distributed load),
b) permanent load only (deflection check under uniformly distributed load) Δ, is calculated using Equation: (26)

Where, the effective (apparent) stiffness of the composite cross-section is given by (1b) :

$$(EI)_{ef} = E_{c,lts} I_c + E_{t,lts} I_t + \gamma_{c,lts} E_{c,lts} A_c a_c^2 + \gamma_{t,lts} E_{t,lts} A_t a_t^2$$

I_c and I_t refer to Equations 2a and 2b and the gamma functions are given by Equations 3c and 3d

$$\gamma_{c,lts} = \frac{1}{1 + \frac{\pi^2 E_{c,lts} A_c s_{ef}}{K_{eff} L^2}}; \qquad \gamma_{t,lts} = 1$$

A_c and A_t are obtained from Equations (4a) and (4b) and the "distance" factors are given by Equations 5c and 5d.

$$a_c = \frac{\gamma_{t,lts} E_{t,lts} A_t H}{\gamma_{c,lts} E_{c,lts} A_c + \gamma_{t,lts} E_{t,lts} A_t}; \quad a_t = \frac{\gamma_{c,lts} E_{c,lts} A_c H}{\gamma_{c,lts} E_{c,lts} A_c + \gamma_{t,lts} E_{t,lts} A_t}$$

Where:

$$E_{c,lts} = \frac{E_c}{(1+\varepsilon_{cs})(1+\phi_{cc})} \qquad E_{t,lts} = \frac{E_t}{j_2} \qquad (28a); (28b)$$

Note: The recommended creep coefficient for TCC, j_2 = 3.0 to 4.0.

And:

$$\varepsilon_{cs} = k_1 \varepsilon_{cs.b} \qquad (29)$$

$$\phi_{cc} = k_2 k_3 \phi_{cc.b} \qquad (30)$$

for H refer to Equation (6)

for b_c refer to Equations (7a); (7b).

5 Concluding Comments

The design procedure presented in this paper is adapted from the design procedure of EC5 and modified to suit local practices and reflect research and development recently undertaken in Australia and New Zealand.

The design methodology adequately addresses the complexity of TCC structures, including the partial composite action provided by the connection and imposes a comprehensive series of strength checks on the cross-section components and serviceability checks with consideration to the long term performance of the structure.

Adapting the design procedure to suit Australian practices has been a challenging exercise and where assumptions have had to be made due to uncertainties, these have erred on being conservative. These assumptions are also areas for further research in order to address the uncertainties associated with them.

It is anticipated that further research will include:

- shear strength of the connection – size effect on the connection strength and stiffness,
- shear strength of the concrete notch – effect of the coach screw,
- shear strength wood portions between the notches,
- flexural shear strength of the beam – effect of deep notch and use of the net area of the shear plane,
- short-term serviceability – initial deflection and effect of concrete curing,
- long-term deflection
- influence of wood portions between the notches

Further work will also focus on making the design procedure more user-friendly wherever possible whilst preserving the safety and functionality of the design.

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APPENDIX

Notation

The symbols and letters used in the design procedure are listed below:

A_c	cross-sectional area of the concrete member
A_t	cross-sectional area of the timber member
A_l	bearing area for loading parallel to the grain (timber)
A_p	bearing area for loading perpendicular to the grain (timber)
A_{sl}	shear plane area for shear action parallel to the grain (timber)
A_{st}	cross-sectional area of the coach screw (TCC only)
a	distance between points of zero bending moment
a_c	distance for the concrete member
a_f	thickness of the formwork
a_t	distance for the timber member
b_c	tributary width of the concrete member
b_t	width (thickness) of the timber member
b_v	width of the notch (concrete)
d_o	length of the notch (concrete)
E_c	value of the modulus of elasticity of the concrete member
$E_{c,lts}$	value of the modulus of elasticity of the concrete member for long-term serviceability
E_t	value of the modulus of elasticity of the timber member
$E_{t,lts}$	value of the modulus of elasticity of the timber member for long-term serviceability
$(EI)_{ef}$	effective (apparent) stiffness of the TCC cross-section
f'_b	characteristic strength in bending
f'_c	characteristic strength in compression
f'_l	characteristic strength in bearing parallel to the grain

f'_p	characteristic strength in bearing perpendicular to the grain
f'_s	characteristic strength in shear
f'_t	characteristic strength in tension
G^*	design self-weight
H	factor for the height of the TCC cross-section
h_c	thickness of the concrete member
h_t	depth (height) of the timber member
I_c	second moment of area (moment of inertia) of the concrete member
I_t	second moment of area (moment of inertia) of the timber member
j_2	stiffness modification factor – load duration
K_{eff}	connection (shear key) stiffness for design of the Service Limit State – long-term deflection
K_i	connection (shear key) stiffness
K_{ser}	connection (shear key) stiffness for design of the Service Limit State – short-term deflection
K_u	connection (shear key) stiffness for design of the Ultimate Limit State
k_1	shrinkage strain coefficient (concrete)
k_1	duration of load (timber)
k_2	creep factor coefficient (concrete)
k_3	maturity coefficient (concrete)
k_4	moisture condition (timber)
k_6	temperature (timber)
k_7	length and position of bearing (timber)
k_9	strength sharing between parallel members (timber)
k_{11}	size factor (timber)
k_{12}	stability factor (timber)
L	span of the structure

l_s	length of the horizontal shear plane (timber)
M^*	design action effect in bending
ϕM_u	design capacity in bending (concrete)
(ϕM)	design capacity in bending (timber)
N^*	design action effect produced by axial force
N_p^*	design action effect in bearing produced by reaction at a support
ϕN_u	design capacity in axial stress (concrete)
(ϕN)	design capacity in axial stress (timber)
(ϕN_j)	design capacity of the connection in shear
(ϕN_l)	design capacity in bearing parallel to the grain (timber)
(ϕN_p)	design capacity in bearing perpendicular to the grain (timber)
(ϕN_v)	design capacity in shear parallel to the grain (timber)
(ϕN_θ)	design capacity in bearing at an angle to the grain (timber)
P^*	design action for point load action (Service Limit State)
Q^*	design action effect in shear in the connection
$Q^*_{V^*_{L/4}}$	design action effect in shear in the connection (at L / 4)
$Q^*_{V^*_{max}}$	design action effect in shear in the connection (at a support)
Q^*	design action for shear in the connection
Q_k	characteristic strength of the connection in shear
R_m	mean characteristic strength of the connection in shear (test data)
s_{ef}	factor for the connection spacing
s_{max}	distance of the first connector from mid-span
s_{min}	distance between the connectors (inside the external quarter-spans)
V^*	design action effect in flexural shear (also tangential shear)
$V^*_{L/4}$	design action effect in flexural shear (also tangential shear) at L / 4
V^*_{max}	design action effect in flexural shear (also tangential shear) at a support
(ϕV)	design capacity in flexural shear (timber)

ϕV_{uc}	design capacity in shear (concrete)
w^*_{imp}	imposed design load(s)

$\beta_{1,2,3}$	coefficients (concrete)
Δ	deflection at mid-span
γ_c	partial factor for material properties of the concrete member
$\gamma_{c,lts}$	partial factor for material properties of the concrete member – long-term serviceability
γ_t	partial factor for material properties of the timber member
$\gamma_{t,lts}$	partial factor for material properties of the timber member – long-term serviceability
ε_{cs}	design shrinkage strain (concrete)
$\varepsilon_{cs.b}$	basic shrinkage strain (concrete)
$v_{0.4}$	mean slip of the connection measured at 0.4 R_m (test data)
$v_{0.6}$	mean slip of the connection measured at 0.6 R_m (test data)
ϕ	capacity factor
ϕ_{cc}	design creep factor (concrete)
$\phi_{cc.b}$	basic creep factor (concrete)
φ	creep coefficient (timber)
θ	angle of the notch facet under compression,
σ_b	effective bending stress
σ_c	effective compression stress
σ_t	effective tension stress

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CONTENTS

16. Peer review of papers for the CIB-W18 Proceedings

Experts involved:

Members of the CIB-W18 "Timber Structures" group are a community of experts in the field of timber engineering.

Procedure of peer review

- Submission of manuscripts: all members of the CIB-W18 group attending the meeting receive the manuscripts of the papers at least four weeks before the meeting. Everyone is invited to read and review the manuscripts especially in their respective fields of competence and interest.

- Presentation of the paper during the meeting by the author

- Comments and recommendations of the experts, discussion of the paper

- Comments, discussion and recommendations of the experts are documented in the minutes of the meeting and are printed on the front page of each paper.

- Final acceptance of the paper for the proceedings with
  - no changes
  - minor changes
  - major changes
  - or reject

- Revised papers are to be sent to the editor of the proceedings and the chairman of the CIB-W18 group

- Editor and chairman check, whether the requested changes have been carried out.

List of CIB-W18 Papers, Nelson, New Zealand 2010