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Dynamic Performance of Timber and Timber-Concrete Composite Flooring Systems

By

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for any 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. And 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.

Rajendra Rijal

February 2013

To My Wife & “Doshi” Raju Dai

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LIST OF PUBLICATIONS

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LIST OF NOTATIONS

α	damage severity estimator
γ	shear bond coefficient
δ	mid span deflection
δ_k	damping factor for mode k
λ_1	calibration factor for $LCAI_1$
λ_2	calibration factor for $LCAI_2$
λ_k	pole value for mode k
v	unit impulse velocity response
ξ, D	damping ratio
ρ	density
σ_x	standard deviation
υ	poisson's ratio
φn	normalised modal amplitude
Ψ	matrix of eigenvectors
Ψn	original modal amplitudes obtained before mass normalisation
ω_{dk}	damped natural frequency of mode k
ω_n	circular natural frequency
βij	damage indicator for the DI method
ϕ_i''	second derivative or curvature of i^{th} mode shape with respect to x
ω	frequency variable (Chapter 3)
*	complex conjugate (Chapter 3); denotes the damaged state (Chapter 6)
$\chi_m(f)$	magnification function
D_{max}	dynamic magnification factor
ρ_{max}	maximum harmonic response amplitude
$\overline{\omega}$	forcing frequency
$[m]$	mass matrix
$[\Lambda]$	diagonal matrix of poles
$\{\emptyset_n\}$	normalised modal vector
$\emptyset_i$	i^{th} mode shape

Δ	elastic deflection of the system
Δ_B	mid span deflection of the floor beam due to flexure and shear
Δ_G	deflection of the girder at the beam support due to flexure and shear
Δ_S	deflection of the supports such as column or wall due to axial strain
1-D	one-dimensional
2-D	two-dimensional
3-D	three-dimensional
a	flexibility coefficient; distance of load point from nearest support (Chapter 3)
A	area under $\chi_m^2(f)$
A_0	initial amplitude of the flooring system from heel drop test; mass modified stiffness matrix (Chapter 3)
A_1	mass modified damping matrix (Chapter 3)
a_o/g	acceleration limit
a_p/g	predicted acceleration ratio due to walking excitation
A_r	area associated with the resonance bandwidth ($f_n/\sqrt{2} < f < \sqrt{2}f_n$)
b	floor width
B	number of bits used to represent a sample in the ADC
B_c	width of concrete topping
B_0, B_1	force distribution matrices
c	damping coefficient
$LCAI_1$	first loss of composite action index
$LCAI_2$	second loss of composite action index
C_B	frequency coefficient
Cc	critical damping coefficient
CO_2	carbon dioxide
d	diameter of the shear connector
D_C	theoretical full composite deflection
D_I	measured partial composite deflection
D_N	theoretical fully non-composite deflection
D_w	depth of LVL web
$D_{xx}(\tau)$	auto RanDec function
$D_{xy}(\tau)$	cross RanDec function

E	modulus of elasticity; efficiency of composite systems (Chapter 2 - Section 2.11); dynamic-based degree of composite action (Chapter 6)
E_{cj}	mean MOE of concrete at the appropriate age
EI	flexural stiffness
$(EI)_b$	bending stiffness of the floor about an axis parallel to the beams
$(EI)_{ef}$	effective bending stiffness
$(EI)_l$	bending stiffness of the floor about an axis perpendicular to the beams
E_x	mean modulus of elasticity of LVL in x-direction
$f(\omega)$	input signal
F, P	point load
f'_b	characteristic bending strength
f'_c	characteristic compression strength parallel to grain
f'_p	characteristic compression strength perpendicular to grain
f'_s	characteristic shear strength
f'_{sj}	characteristic shear strength at joint details
f'_t	characteristic tensile strength
f_1	fundamental frequency
f_a & f_b	natural frequency corresponding to the first, *a*, and second point, *b*, of the *HBM*
f_b	mean bending strength
f_c	mean compression strength
f_{cm}	mean value of the compressive strength of concrete at the relevant age
f_{damped}	damped natural frequency
F_{ij}	fractional modal strain energy for undamaged beam
F_{max}	theoretical maximum Nyquist frequency limit
f_n	natural frequency
$f_{n(Exp)}$	experimental natural frequency
$f_{n(FE)}$	natural frequency from FE model
F_{Nyq}	nyquist frequency
F_{samp}	sampling frequency
f_t	mean tensile strength
$f_{undamped}$	undamped natural frequency
f_v	mean shear strength

g	acceleration due to gravity (9.81 m/s^2)
G	shear modulus
$g(\omega)$	output signal
$G_{ff(\omega)}$	input auto spectrum
$G_{fg(\omega)}$	cross input-output spectrum
$G_{gg(\omega)}$	output auto spectrum
$H(\omega)$	matrix of FRFs
$H_1(\omega)$	frequency response function
$H_{ij(j\omega)}$	FRF between the respond DOF *i* and reference DOF *j*
I	moment of inertia
i, n, M	mode number
k	stiffness
$k17$	factor for multiple nailed joints
K_{serv}	serviceability limit state stiffness
K_u	ultimate limit state stiffness
L, l	span
L_b	shear-free span between load points
m	mass of the floor ; mass per unit length (Chapter 7); mass per unit area (Section 7.1.4)
M_i	initial mass of moisture content test piece
M_o	dry weight of moisture content test piece
N	number of averaged time segments (Chapter 2); number of modes of vibration (Chapter 3); number of accelerometers (Chapter 6)
n_{40}	number of first-order modes with natural frequencies up to 40 Hz
$NFerror$	natural frequency difference between FE and experimental models
P_o	excitation force
Q_k	strength of shear connectors
R_d	deformation response factor
r_{ijk}	residue value for mode *k*
s_e	spacing of the shear connectors at the ends of the beam
S_{eff}	effective constant spacing of the shear connectors
s_m	spacing of the shear connectors in the middle of the beam
T_c	thickness of concrete topping

T_f	thickness of LVL flange
T_w	thickness of LVL web
$Tx(t_i)$	triggering condition applied to time history x(t)
W	effective weight of the floor
w	maximum short-term deflection; uniformly distributed load per unit length (Chapter 7)
$x(k)$	discrete series
x(t)	response time history
y(t)	response time history
y_0	maximum deflection
y_1 & y_2	amplitudes of the response peaks of the 1st and 2nd cycle
y_n	amplitude of n^{th} cycle response
y_{n+m}	amplitude of the $(n + m)^{th}$ cycle response
y_w	weighted average value of the static deflection
Z_{ij}	normalised damage indicator

LIST OF ACRONYMS

ADC	analogue-to-digital converter
BM	bird-mouth
CA	composite action
CMSE	cross-modal strain energy
COMAC	coordinate of modal assurance criterion
CoV	coefficient of variation
DD	damage detection
DI	damage index
DOF	degree of freedom
MOE	modulus of elasticity
EBM	equivalent beam method
EMA	experimental modal analysis
FDPI	frequency domain direct parameter identification
FE	finite element
FEA	finite element analysis
FEM	finite element model
FFT	fast Fourier transform
FRF	frequency response function
FRST	foundation for research science and technology
FWPA	forest and wood products Australia
Glulam	glue laminated timber
HBM	half-power bandwidth method
IRF	impulse response function
LCA	loss of composite action
LCAI	loss of composite action index
LDA	logarithmic decrement analysis
LVDT	linear variable differential transformer
LVL	laminated veneer lumber
MAC	modal assurance criterion
MC	moisture content

MDI	modified damage index
MDOF	multi degree of freedom
MT	modal testing
NDI	non-destructive inspection
NS	normal screw
NZ	New Zealand
Pty Ltd	proprietary limited
R & D	research and development
RanDec	random decrement
RMS	root mean square
SCC	steel-concrete composite
SDOF	single degree of freedom
SLS	serviceability limit state
STIC	structural timber innovation company
TCC	timber-concrete composite
ULS	ultimate limit state
UTS	University of Technology Sydney

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ABSTRACT

In recent years, there has been an increasing trend in Australia and New Zealand towards the use of long-span timber and timber-concrete composite (TCC) flooring systems for the construction of multi-storey timber buildings. The popularity of these flooring systems is because of their low cost, easy construction and the use of environmentally sustainable materials. Due to their light-weight, such long-span floors are however highly susceptible to vibrations induced by service loads. Although long-span timber and TCC flooring systems can easily be designed to resist the static loads using currently available design guidelines, it is crucial to also investigate the dynamic behaviour of these floors as the occupant discomfort due to excessive vibration may govern the design. Moreover, many structural failures are caused by dynamic interactions due to resonances, which highlight the importance of investigating the dynamic behaviour of flooring systems. To date, there are very limited design guidelines to address the vibration in long-span floors, especially composite floors, due to a lack of sufficient investigation.

In 2009, a research consortium named Structural Timber Innovation Company (STIC) was founded, with the aim to address various issues encountered with structural timber buildings including timber and TCC flooring systems. STIC is conducting Research and Development (R & D) work in a number of key areas to provide a new competitive edge for commercial and industrial structural timber buildings. The R & D work is undertaken with three parallel objectives at three universities, namely, the University of Technology Sydney (UTS), the University of Canterbury (UC) and the University of Auckland (UA). The focus of UTS is the assessment of various performance issues of long-span timber only and TCC flooring systems for multi-storey timber buildings. The work presented in this thesis deals with the investigation of the dynamic performance of timber only and TCC flooring systems, which is one of the sub-objectives of the research focus at UTS.

In particular, the presented research assesses the dynamic performance of long-span timber and TCC flooring systems using different experimental und numerical test structures. For the experimental investigations, experimental modal testing and analysis

is executed to determine the modal parameters (natural frequencies, damping ratios and mode shapes) of various flooring systems. For the numerical investigations, finite element models are calibrated against experimental results, and are utilised for parametric studies for flooring systems of different sizes. Span tables are generated for both timber and TCC flooring systems that can be used in the design of long-span flooring systems to satisfy the serviceability fundamental frequency requirement of 8 Hz or above. For floors where vibration is deemed to be critical, the dynamic assessment using the 8 Hz frequency requirement alone may not be sufficient and additional dynamic criteria such as response factor, peak acceleration and unit load deflection need to be satisfied. To predict the fundamental frequency of various TCC beams and timber floor modules (beams), five different analytical models are utilised and investigated.

To predict the cross-sectional characteristics of TCC systems and to identify the effective flexural stiffness of partially composite beams, the “Gamma method” is utilised. Essential input parameters for the “Gamma method” are the shear connection properties (strength, serviceability stiffness and ultimate stiffness) that must be identified. Therefore, a number of experimental tests are carried out using small scale specimens to identify strength and serviceability characteristics of four different types of shear connection systems and three of them were adopted in the TCC beams. The connections included two types of mechanical fasteners (normal wood screw and SFS screw) and two types of notched connectors (bird-mouth and trapezoidal shape) with coach screw.

Traditionally, the composite action of a system is determined from static load testing using deflection measurements. However, static load testing is expensive, time consuming and difficult to perform on existing flooring systems. Therefore, two novel methods are developed in this thesis that determines the degree of composite action of timber composite flooring systems using only measurements from non-destructive dynamic testing. The core of both methods is the use of an existing mode-shape-based damage detection technique, namely, the Damage Index (DI) method to derive the loss of composite action indices (*LCAIs*) named as $LCAI_1$ and $LCAI_2$. The DI method utilises modal strain energies derived from mode shape measurements of a flooring system before and after failure of shear connectors. The proposed methods are tested and

validated on a numerical and experimental timber composite beam structure consisting of two LVL components (flange and web). To create different degrees of composite action, the beam is tested with different numbers of shear connectors to simulate the failure of connection screws. The results acquired from the proposed dynamic-based method are calibrated to make them comparable to traditional static-based composite action results. It is shown that the two proposed methods can successfully be used for timber composite structures to determine the composite action using only mode shapes measurements from dynamic testing.