Dynamic Behaviour of Long-Span Timber Ribbed-Deck Floors

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"And once the storm is over, you won't remember how you made it through, how you managed to survive. You won't even be sure, whether the storm is really over. But one thing is certain. When you come out of the storm, you won't be the same person who walked in. That's what this storm's all about."

- Haruki Murakami

To my mother, Papa, jiji-san and baba-san

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Bella Basaglia
August, 2019

List of Publications

Conference Papers

1. Basaglia, B., Lewis, K., Shrestha, R., Crews, K., (2015), 'A comparative life cycle assessment approach of two innovative long span timber floors with its reinforced concrete equivalent in an Australian context' , *International Conference on Performance-based and Life-cycle Structural Engineering,* 9 – 11 December 2015, Brisbane, Australia (presented)
2. Lewis, K., Basaglia, B., Shrestha, R., Crews, K., (2015), 'Innovation in the design of cross laminated timber for long span floors', *International Conference on Performance-based and Life-cycle Structural Engineering,* 9 – 11 December 2015, Brisbane, Australia
3. Hough, R., Basaglia, B., Passerini, S., (2016), 'Design and construction of a novel stacked glulam wall structure', *World Conference on Timber Engineering,* 22 – 25 August 2016, Vienna, Austria
4. Lewis, K., Basaglia, B., Shrestha, R., Crews, K.,(2016), 'The use of cross laminated timber for Long span flooring in commercial buildings', *World Conference on Timber Engineering,* 22 – 25 August 2016, Vienna, Austria
5. Basaglia, B., Shrestha, R., Crews, K., Yokoyama, Y., (2018), 'Vibration Response of a Long-Span LVL Floor: Comparison Between Japanese and Australian Assessment Measures', *World Conference on Timber Engineering,* 20 – 23 August 2018, Seoul, Republic of Korea (presented)

Journal Articles

1. Basaglia, B., Li, J., Shrestha, R., Crews, K., Forthcoming. 'Response prediction to walking-induced vibrations of a long-span timber floor', ASCE Journal of Structural Engineering. 10.1061/(ASCE)ST.1943-541X.0002888

List of Notations

[ ]	Matrix
{ } or **x**	Curly brackets or bold parameters indicate vectors
[M]	Mass matrix
[K]	Stiffness matrix
[C]	Damping matrix
α_i; α_i^s	DLF of the *i*-th harmonic and subharmonic, respectively.
$\bar{\alpha}_i(\bar{f}_j)$; $\bar{\alpha}_i^s(\bar{f}_j^s)$	Normalised dynamic load factor for *i*-th harmonic and subharmonic, respectively – in Živanović et al. (2007b) load model (Chapter 5)
δ	Joist mid-span deflection due to point load *P* applied at centre of joist
δ_c, δ_{mid}	Floor mid-span deflection due to point load *P* applied in the centre of the floor
$\theta(\bar{f}_j)$; $\theta(\bar{f}_j^s)$	Normalised phase angle for harmonic and subharmonic, respectively – in Živanović et al. (2007b) load model (Chapter 5)
$\mu_{e,n}$; $\mu_{r,n}$	Mass-normalised mode shape amplitudes of mode *n* at excitation and response nodes, respectively.
ξ	Damping ratio
ρ, ρ_m, DENS	Density (kg/m^3)
ρ_r	Resonant build-up factor
σ	Standard deviation
τ	Integration time constant for running root-mean-square average (s)
ϕ_i	Phase angle of the *i*-th harmonic
$\varphi_{FE,i}$; $\varphi_{FE,j}$	Numerically obtained mode shape vector for mode *i* and *j,* respectively.
$\varphi_{exp,i}$; $\varphi_{exp,j}$	Experimentally obtained mode shape vector for mode *i* and *j,* respectively.
$\{\psi_n\}$	Eigenvector of mode *n*
ω	Circular natural frequency (rad/s)

ω_i	Circular frequency of the *i*-th harmonic load component
ω_n	Eigenvalue or circular frequency of mode *n*
ω_D	Damped circular frequency (rad/s)
A_0	Mean value of weight normalised force (Chapter 5)
A_i	Dynamic load factor for the *i*-th harmonic – single footfall trace (Chapter 5)
a_{MTVV}	MTVV from weighted acceleration response (m/s^2)
$a_{w,p}$	Frequency-weighted peak acceleration (m/s^2)
$a_{w,rms}$	Frequency-weighted RMS acceleration (m/s^2)
$a_w(t)$	Frequency-weighted acceleration at time *t* (m/s^2)
$a_{w,rms}(t_0)$	Rolling frequency-weighted RMS acceleration (m/s^2) at instantaneous time of observation t_0
b	Floor width
c	Damping constant
c_{cr}	Critical damping
d	Diameter of screw
DLF_i	Dynamic load factor of the *i*-th harmonic
D_x; D_y	Flexural rigidity in the joist and cross-joist direction, respectively (Nm) – in Hu and Chui equation (2004)
D_{xy}	Shear rigidity of the multi-layered floor deck and torsion rigidity of the joist (Nm) – in Hu and Chui equation (2004)
$\bar{E}$	Mean modulus of elasticity
$\bar{E}_J$	Mean modulus of elasticity of the joist
$eVDV$; $eVDV_E$	Estimated VDV as per BS 6472-1 (1984); as per Ellis (2001)
$(EI)_l$; $(EI)_b$	Equivalent flexural rigidity of the floor structure about an axis perpendicular and parallel to the beam direction, respectively.
EX; EY; EZ	ANSYS notation for modulus of elasticity in element x-, y- and z-axes, respectively.
f	Cyclic frequency (Hz)
$f'b$	Bending strength (N/mm^2)
$f'c$	Compression parallel to grain (N/mm^2)

f_i^{FE}	Numerically obtained natural frequency for mode *i* (Hz)
f_i^{exp}	Experimentally obtained natural frequency for mode *i* (Hz)
$\bar{f}_j$	Frequency ratio between the current frequency line and pace frequency – in Živanović et al. (2007b) load model (Chapter 5)
f_{joist}; f_{girder}	Natural frequency of the joist and girder, respectively (Hz).
f_n; f_i	Cyclic frequency or natural frequency of mode *n* or *i* (Hz)
f_p	Pace frequency or walking frequency (Hz)
f_s	Sampling frequency (Hz)
f's	Shear in beams (N/mm^2)
f't	Tension parallel to grain (N/mm^2)
$F(\omega)$	Fourier transform of the excitation (input) signal
$F(t)$	Time varying force
F(x)	Objective function (Chapter 4)
G	Modulus of rigidity
g	Gravity (9.81 m/s^2)
g(x)	Constraint vector (Chapter 4)
GXY; GXZ; GYZ	ANSYS notation for shear modulus in x-y, x-z and y-z planes, respectively.
$H(\omega)$	Frequency response function for the input and output signals
$H_1(\omega)$; $H_2(\omega)$	FRF estimators
I	Moment of inertia
I_{eff}	Effective impulse (Ns)
I_j	Moment of inertia of the joist member
k	Stiffness (N/m)
K_{ser}	Slip modulus
KTx; KTy; KTz	Support stiffness for spring elements in the x-, y- and z-directions, respectively.
L, l	Length, floor span
m	Mass (kg)
m_a	Mass per unit area (kg/m^2)
m_l	Mass per unit length (kg/m)

M_n	Modal mass of mode n (kg)
m_s	Mass per unit area of floor sheathing (kg/m^2)
MAC_{ij}	Modal assurance criterion between mode i and j
$MAC_{ERROR,ij}$	$1 - MAC_{ij}$
$NF_{ERROR,i}$	Natural frequency error for mode i
n	Mode number
n_{40}	Number of eigenmodes with eigenfrequencies lower than 40 Hz for unit impulse calculation in Eurocode 5
n_j	Number of joists
P	1 kN point load (kN)
PRXY; PRXZ; PRYZ	ANYS notation for Poisson's ratio in x-y, x-z and y-z planes, respectively.
P_j	Parameter j for sensitivity study (Chapter 4)
Q	Walker weight (N)
R_i	Response i for sensitivity study (Chapter 4)
s	Spacing
S_{ij}	Sensitivity coefficient for each target response R_i to a certain change in parameter P_j
$S_{n,ij}$	Normalised sensitivity coefficient for each target response R_i to a certain change in parameter P_j
t	Time (s)
T	Duration of response measurement or exposure period (s)
T_f	Duration of a single footfall (s)
t_{RMS}	Period of $1/f_p$ from which RMS response is calculated (Chapter 5)
$u_{vel,max}$	Maximum unit impulse velocity response (m/Ns^2)
v_{MTVV}	MTVV from integrated velocity response (m/s)
v_{rms}	Root-mean-square velocity response (m/s)
w	Maximum instantaneous vertical deflection caused by a vertical concentrated static force F applied at any point on the floor
$w_{f,i}$	Weighting factor for the NF_{ERROR} of mode i (Chapter 4)

$w_{\varphi,i}$	Weighting factor for the MAC_{ERROR} for mode i (Chapter 4)
w_l	Load per unit length
W_m; W_b; W_k	Frequency-weighting curves provided in ISO 2631-2 (2003), BS 6471-1 (2008a), and ISO 2631-1(1997), respectively.
$X(\omega)$	Fourier transform of the response (output) signal
x_{min}; x_{max}	Lower and upper constraints for design variable x (Chapter 4)
x_u	Updated parameter from model updating (Chapter 4)
$y(t)$	Time varying displacement (m)
$\dot{y}(t)$	Time varying velocity (m/s)
$\ddot{y}(t)$	Time varying acceleration (m/s^2)

List of Acronyms

ASD	Auto-spectral density
CE	Complex exponential
CLT	Cross-laminated timber
CoV	Coefficient of variance
DAQ	Data acquisition
DFT	Discrete Fourier transform
DLF	Dynamic load factor
DMF	Dynamic magnification factor
DOF	Degree-of-freedom
EMA	Experimental modal analysis
ESPA	Equivalent sinusoidal peak acceleration
EWP	Engineered wood product
FE	Finite element
FFT	Fast Fourier transform
FRF	Frequency response function
FS	Footstep
FT	Fourier transform
IRF	Impulse response function
LSCE	Least-squares complex exponential
LSFD	Least-squares frequency domain
LVL	Laminated veneer lumber
MAC	Modal assurance criterion
MDOF	Multi-degree-of-freedom
MoE	Modulus of elasticity
MPC	Modal phase collinearity
MPD	Modal phase deviation
MTVV	Maximum transient vibration value
OSB	Oriented strand board
OS-RMS_{90}	One-step RMS for the 90^{th} percentile (HIVOSS guide)
PR	Pin-roller
RF	Response factor

RMS	Root-mean-square
SDOF	Single-degree-of-freedom
SFT	Single footfall trace
SIMO	Single-input, multiple-output
SISO	Single-input, single-output
SRSS	Square-root sum of squares
VDV	Vibration dose value

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Abstract

The development of engineered wood products and the environmental benefits of timber over conventional building materials has led to an increased interest in the use of timber for the construction of multi-storey buildings. Timber has a high strength-to-weight ratio making it structurally efficient for long-span floor applications (a common practice in commercial buildings). However, the low mass of such floors makes them more susceptible to walking-induced vibrations compared to heavier floors such as those made from concrete. In fact, when designing long-span timber floors, dynamic performance criteria tends to govern the design rather than strength. Unfortunately, there is a lack of specific vibration design guidance for long-span timber floors with much of the current criteria based on tests of short-span timber joist floors in residential applications. In addition, there is uncertainty as to how accurately other vibration design guides, mainly used for concrete and steel-concrete composite floors, predicts and assesses floor performance of long-span timber floors.

This thesis addresses this gap by investigating the dynamic behaviour of a long-span timber floor through both experimental and numerical methods. Impact hammer and walking tests with two subjects were performed on a 9 m span ribbed-deck floor which consists of a laminated veneer lumber (LVL) panel glued and screwed to three LVL web members, forming one cassette. The influence of various boundary conditions and cassette-to-cassette connections on the modal properties and floor response were explored. A numerical model of a single cassette, calibrated to measured results through model updating, was used to investigate three human walking load models including the deterministic modelling approach adopted in current vibration design guides. In addition, a numerical model representing the cassette-to-cassette connection was developed and updated using measured results of double cassette tests. These details were adopted in a multi-cassette floor model, based on the dimensions of a typical commercial building floor grid, to investigate the influence of common design parameters on modal properties and floor response.

One of the main findings from walking tests was that the floor exhibited neither a completely transient nor a completely resonant response, despite being classified as a 'high-frequency' floor. This assumption of floor behaviour resulted in inaccuracies in response prediction using current vibration design guides and it is proposed that a step-by-step load model which considers the stochastic nature of walking is more appropriate. This load model also provides the response time-history which allows an assessment of the duration of certain vibration amplitudes (through a cumulative distribution function) during the walking event to be considered in design.

Modal clustering was consistently observed, particularly for the first two or three modes, in the single and double cassette experiments as well as the multi-cassette numerical model. Furthermore, the multi-cassette model revealed that higher modes with low modal masses largely contributed to the floor response. This finding highlights that criterion which only considers the fundamental mode may not be adequate. In regards to design considerations which may benefit the floor response, damping was found to play a key role. This may be in the form of incorporating an elastomer (such as Sylomer®) at the support locations where experimental tests revealed that the damping ratio could increase from 1% to approximately 5% and 7% for the first and second modes, respectively. The findings from all investigations were used to provide guidance and commentary for a vibration design procedure, based on a finite element approach, suitable for long-span timber ribbed-deck floors which was presented in the form of a flow chart.