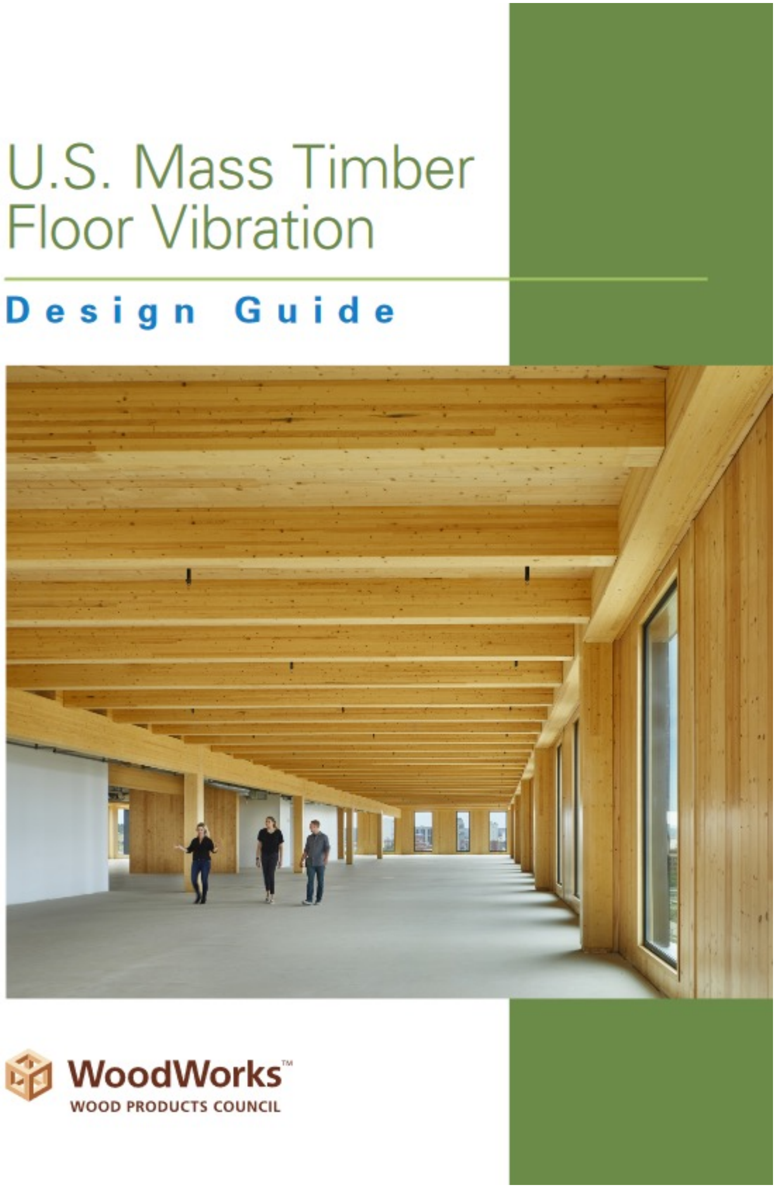

Mass Timber Floor Design for Walking-Induced Vibrations

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Technical Director | KPFF Portland

WoodWorks Symposium
May 27, 2021

Session: 4A Mass Timber Floor Vibration

Disclaimer: This presentation was developed by a third party and is not funded by WoodWorks or the Softwood Lumber Board.

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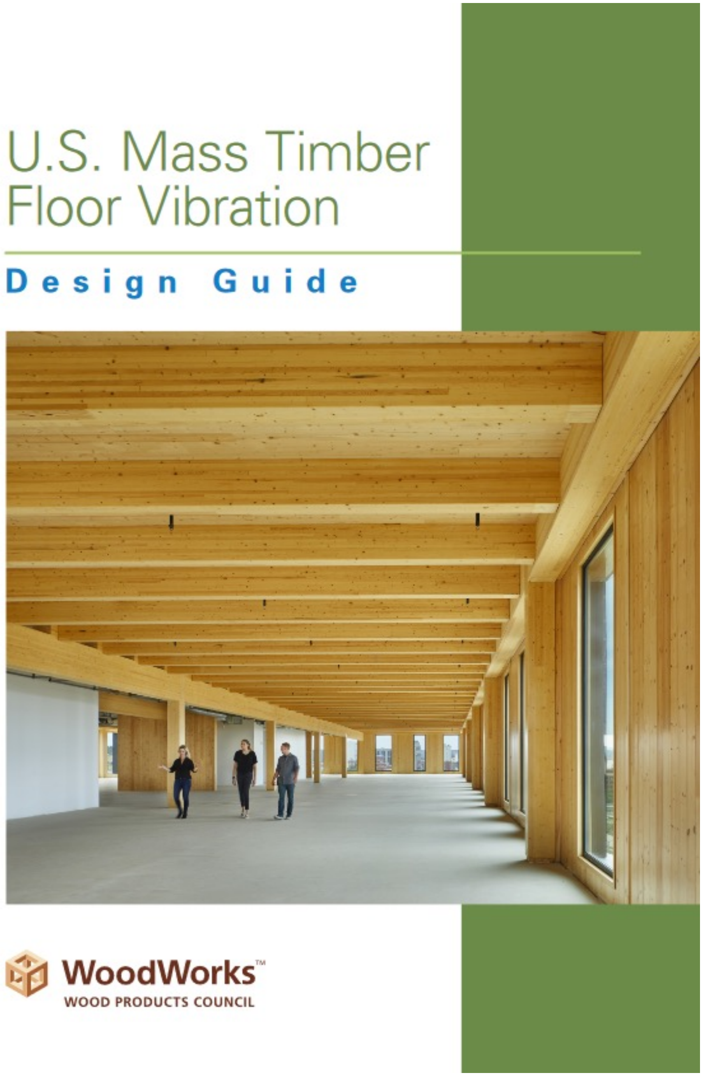
Acknowledgements



U.S. Mass Timber Floor Vibration Design Guide

FIRST EDITION, MARCH 2021

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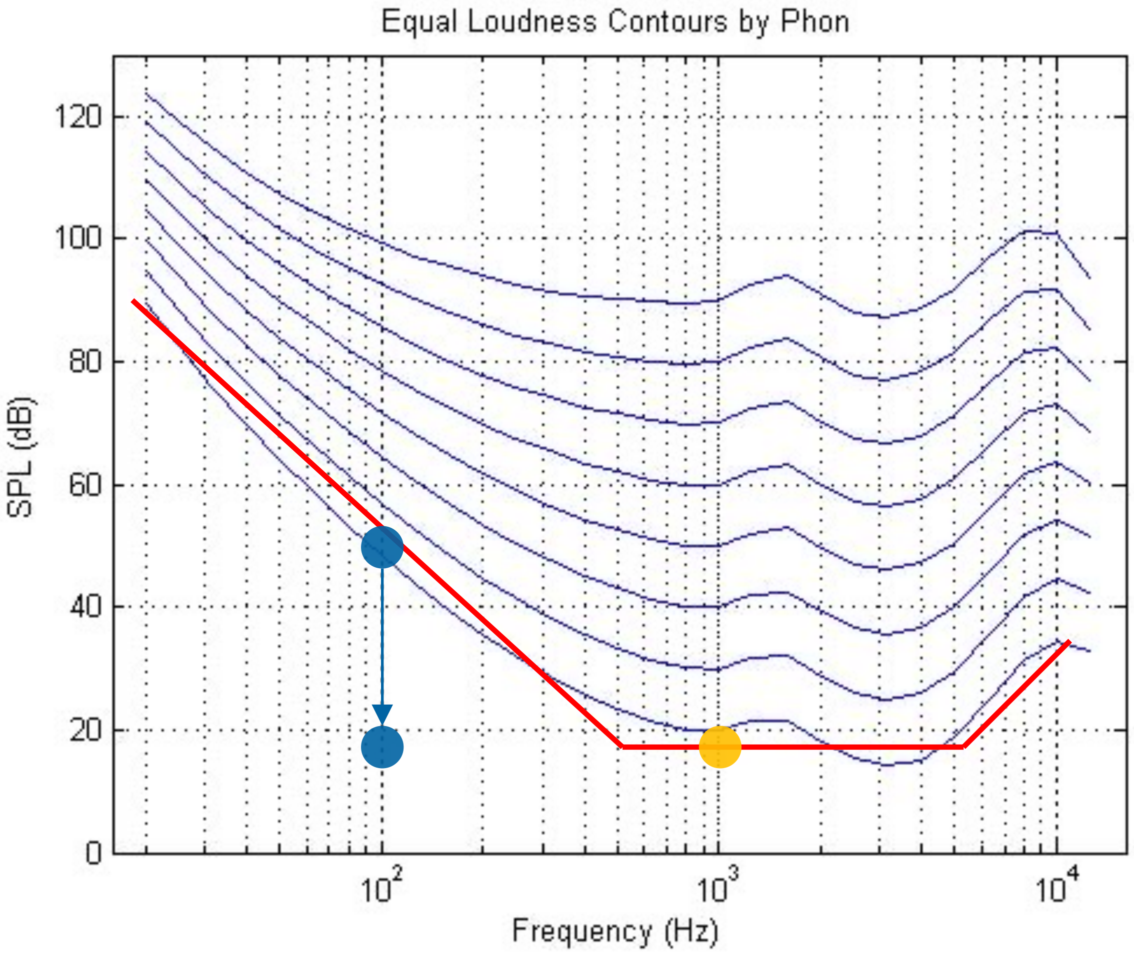
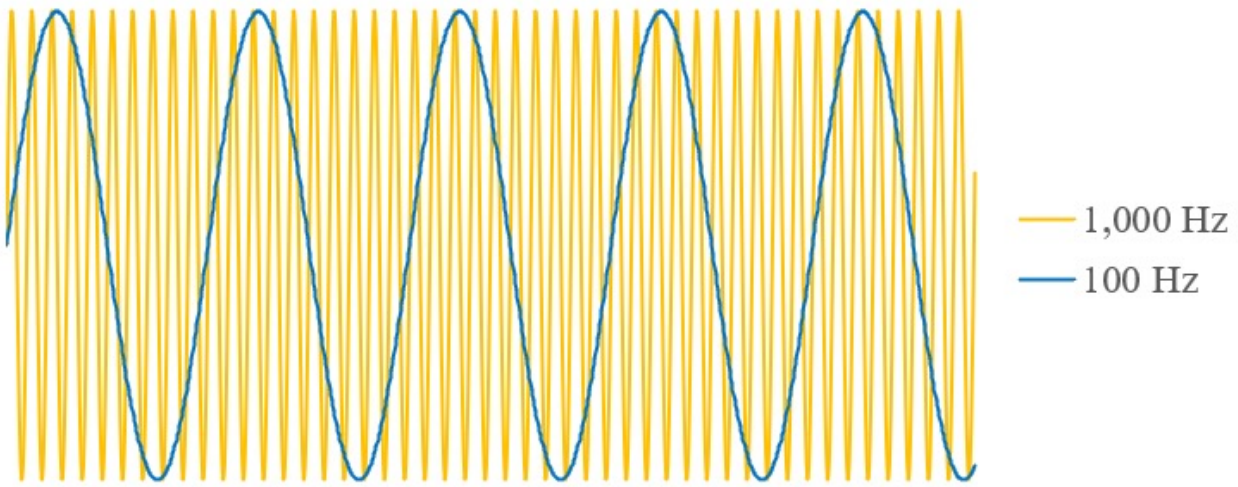
Outline

- Vibration Sensitivity and Subjectivity
- Understanding Floor Vibration
- Floor Vibration Criteria
- Mass Timber Floor Vibration Design Decisions
- Mass Timber Floor Vibration Design Methods and Modeling
- Mass Timber Floor Vibration Design Examples

Vibration Sensitivity and Subjectivity

Vibration Sensitivity and Subjectivity





Vibration Sensitivity and Subjectivity

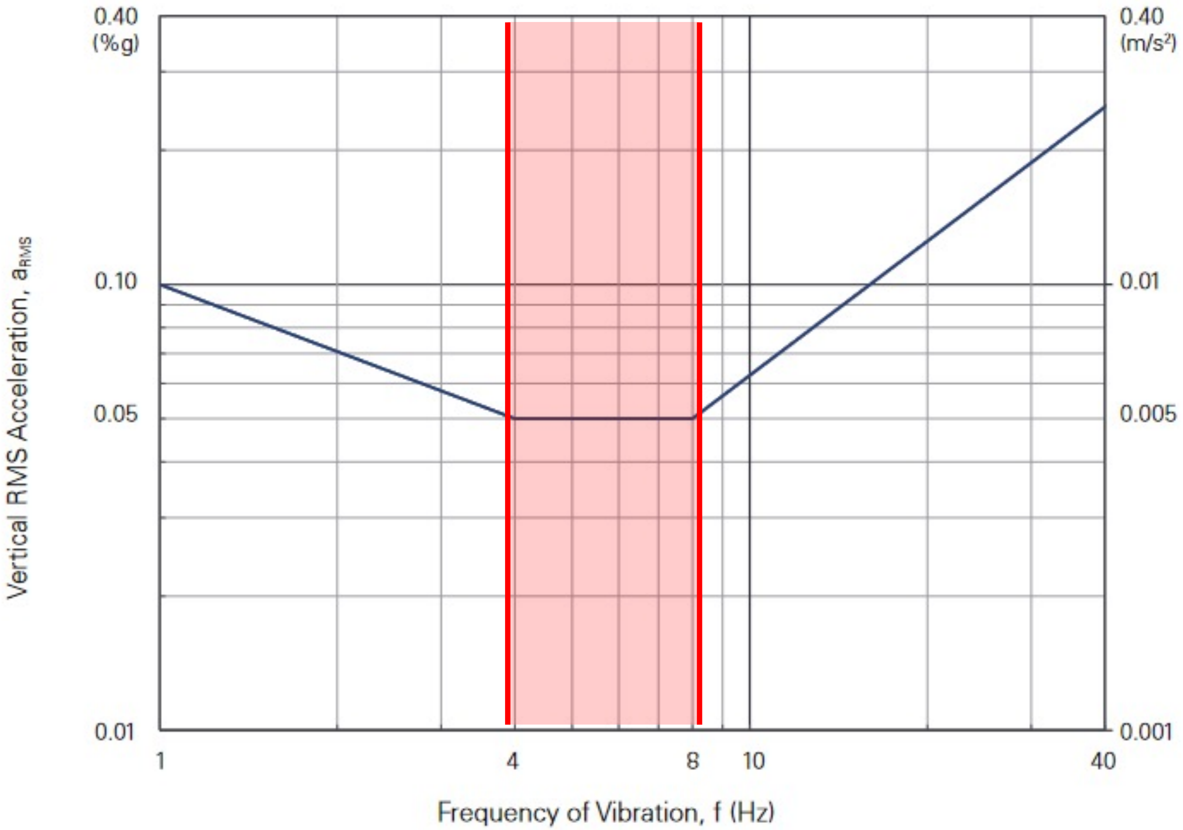
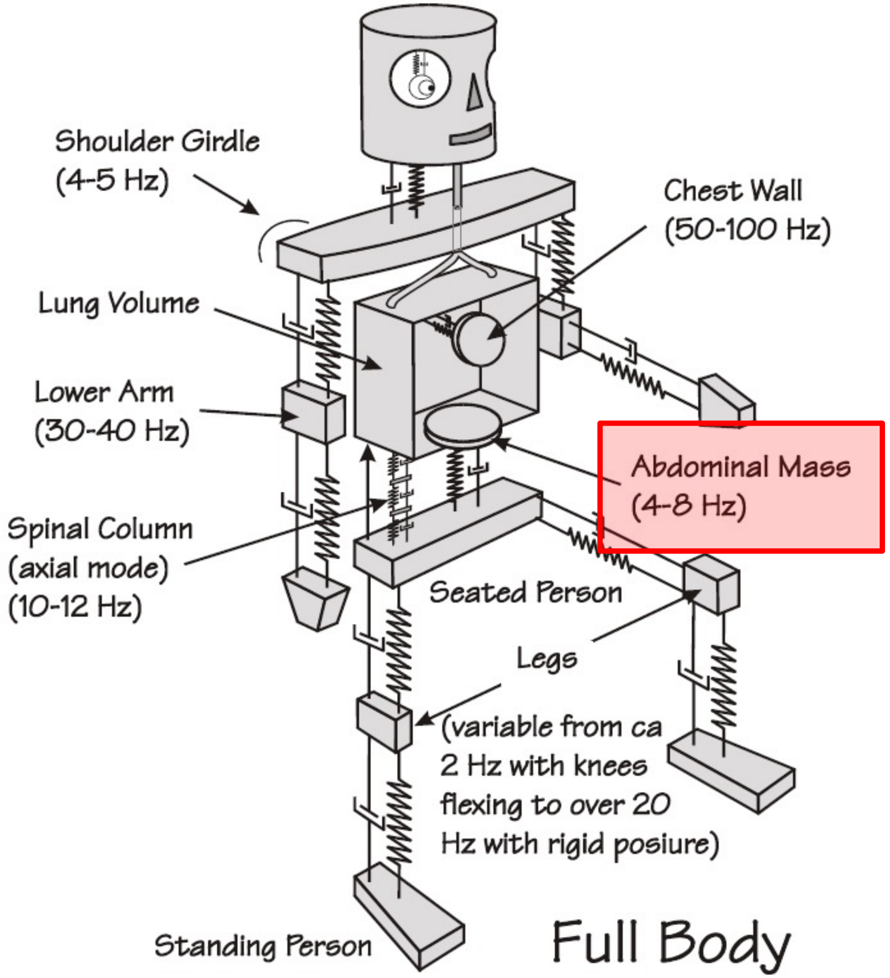


FIGURE 2-4: Human limits of perception of z axis RMS acceleration (ISO 10137)



Understanding Floor Vibration

Understanding Floor Vibration

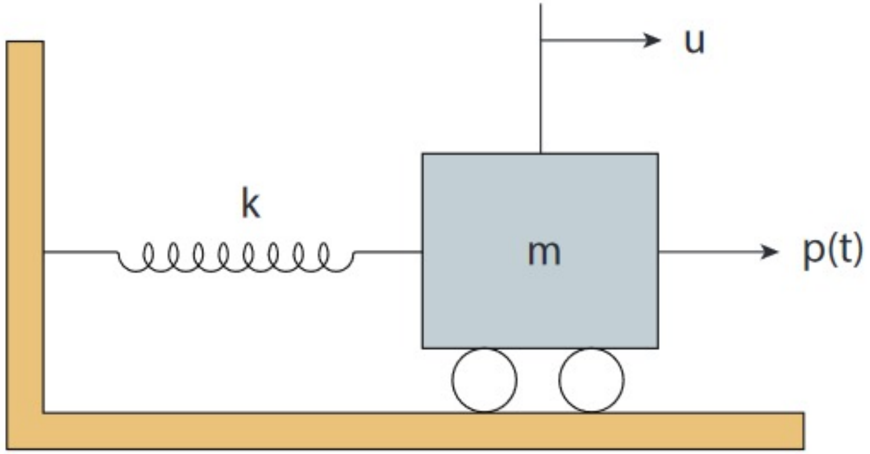
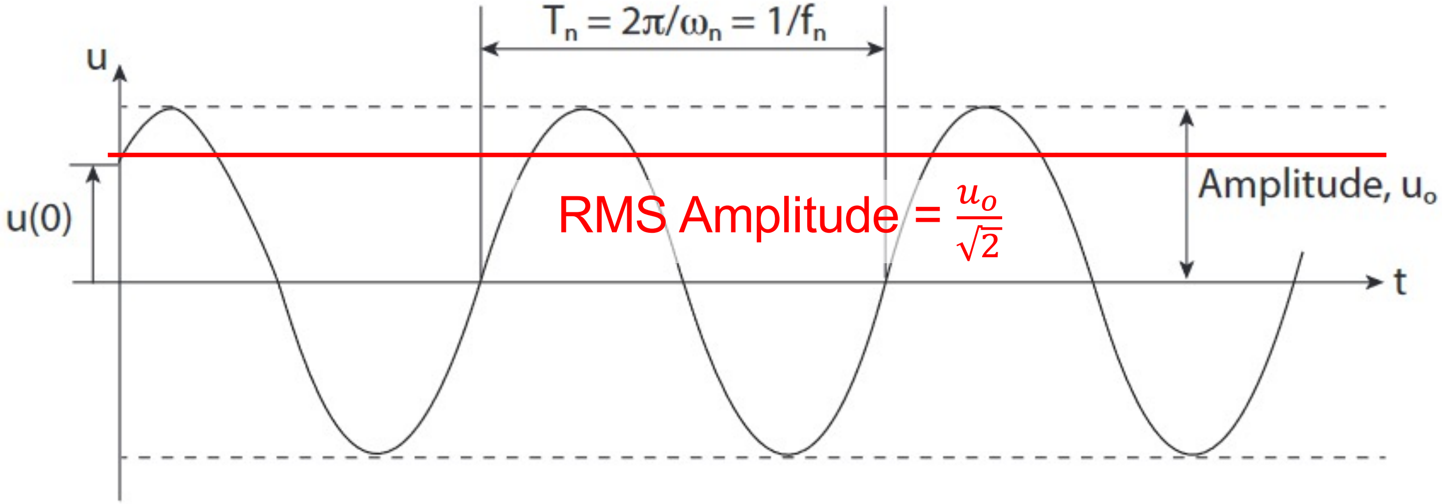


FIGURE 2-1: SDOF vibration



$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

Understanding Floor Vibration

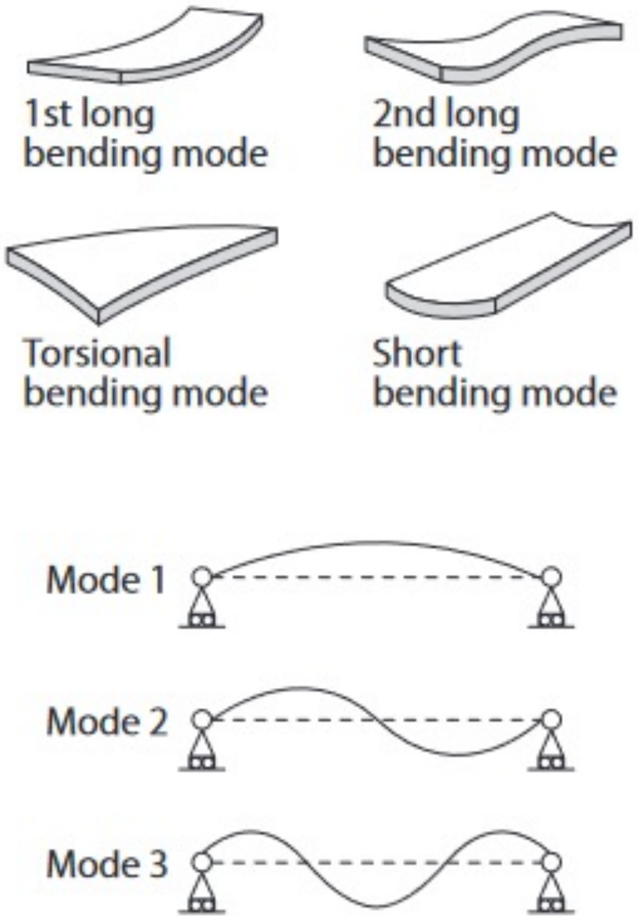


FIGURE 2-3: Vibration mode shapes

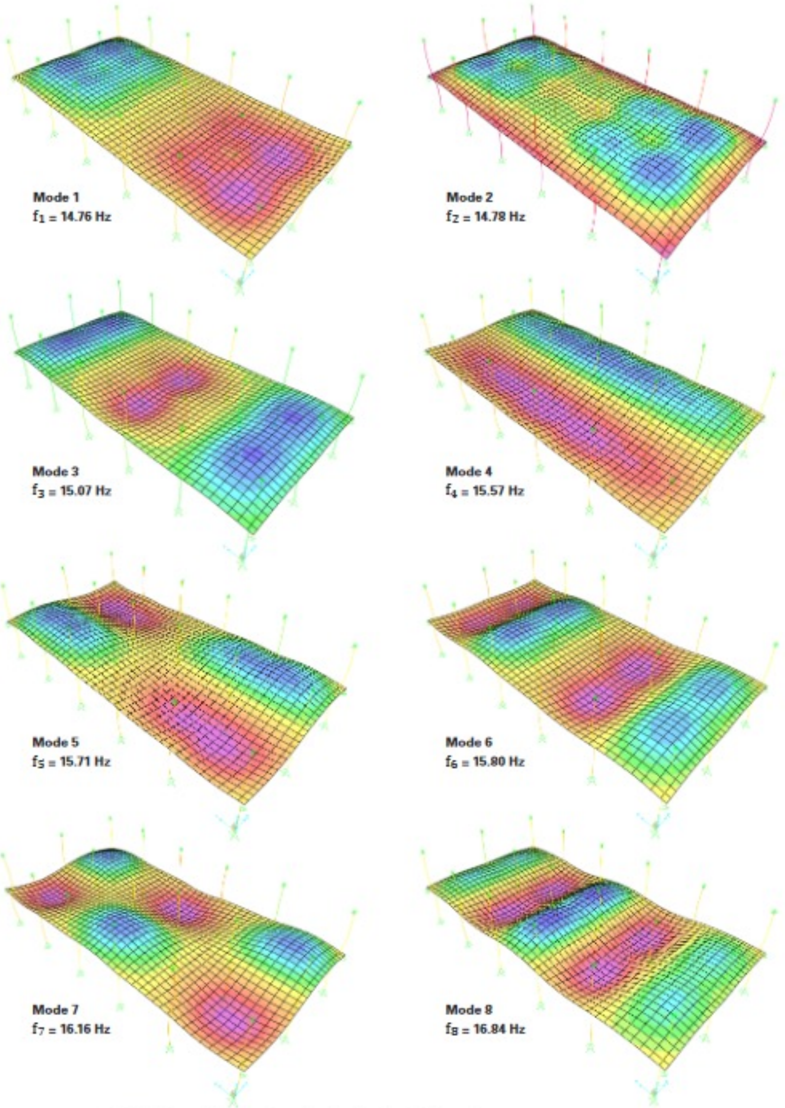


FIGURE 9-11: SAP2000 modal analysis results for the first eight modes

Understanding Floor Vibration

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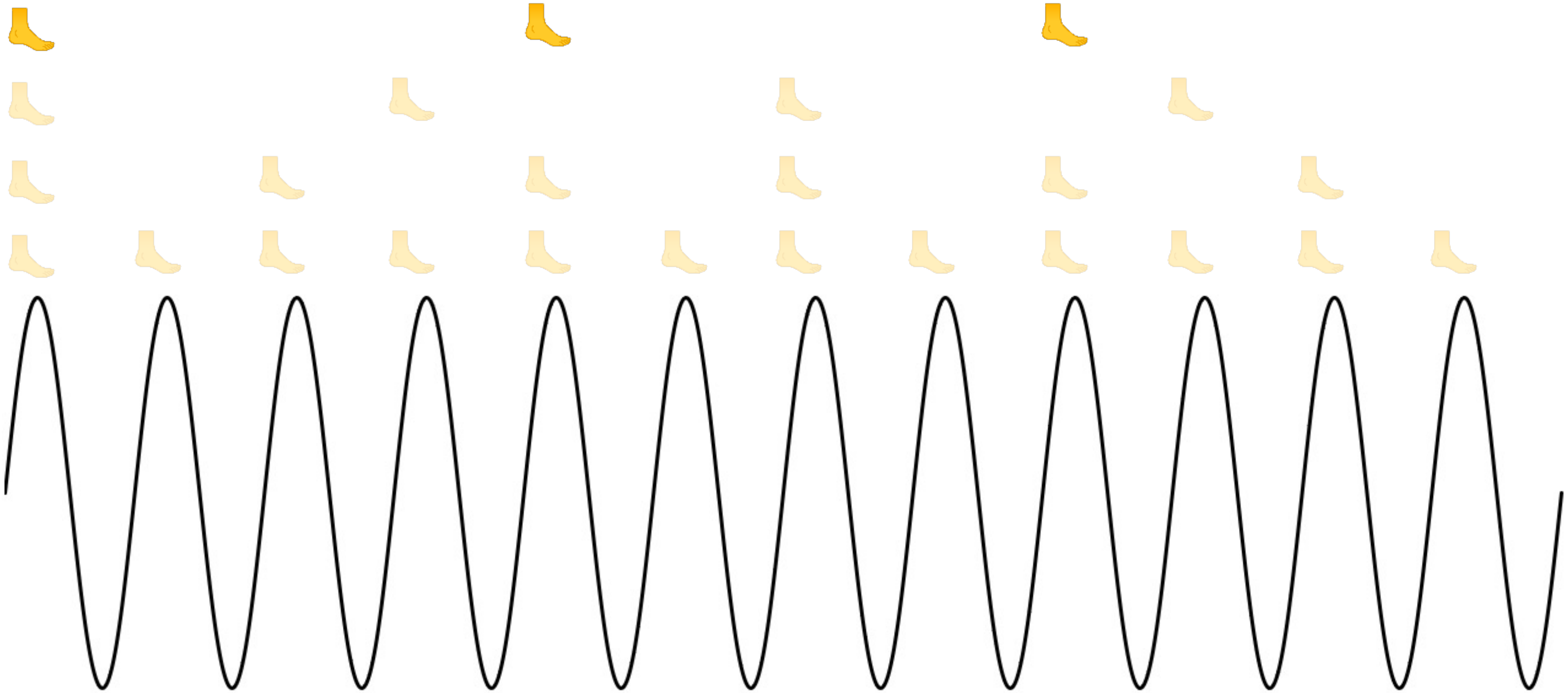
TABLE 3-7: Example walking frequencies (AISC Design Guide 11)

Walking Speed	Walking Frequency (Hz)	Steps Per Minute (SPM)	Potential Occupancies
Very slow (uncommon)	1.25	75	Laboratories, surgical theaters
Slow	1.6	95	Bedrooms, hotel rooms
Moderate	1.85	110	Residential living areas, office work areas
Fast	2.1	126	Corridors, shopping malls, airports

Understanding Floor Vibration



1.5 Hz Walking

2 Hz Walking

3 Hz Running

6 Hz “Running”

6 Hz Floor

4th Harmonic

(= 1.5 Hz x 4)

Understanding Floor Vibration

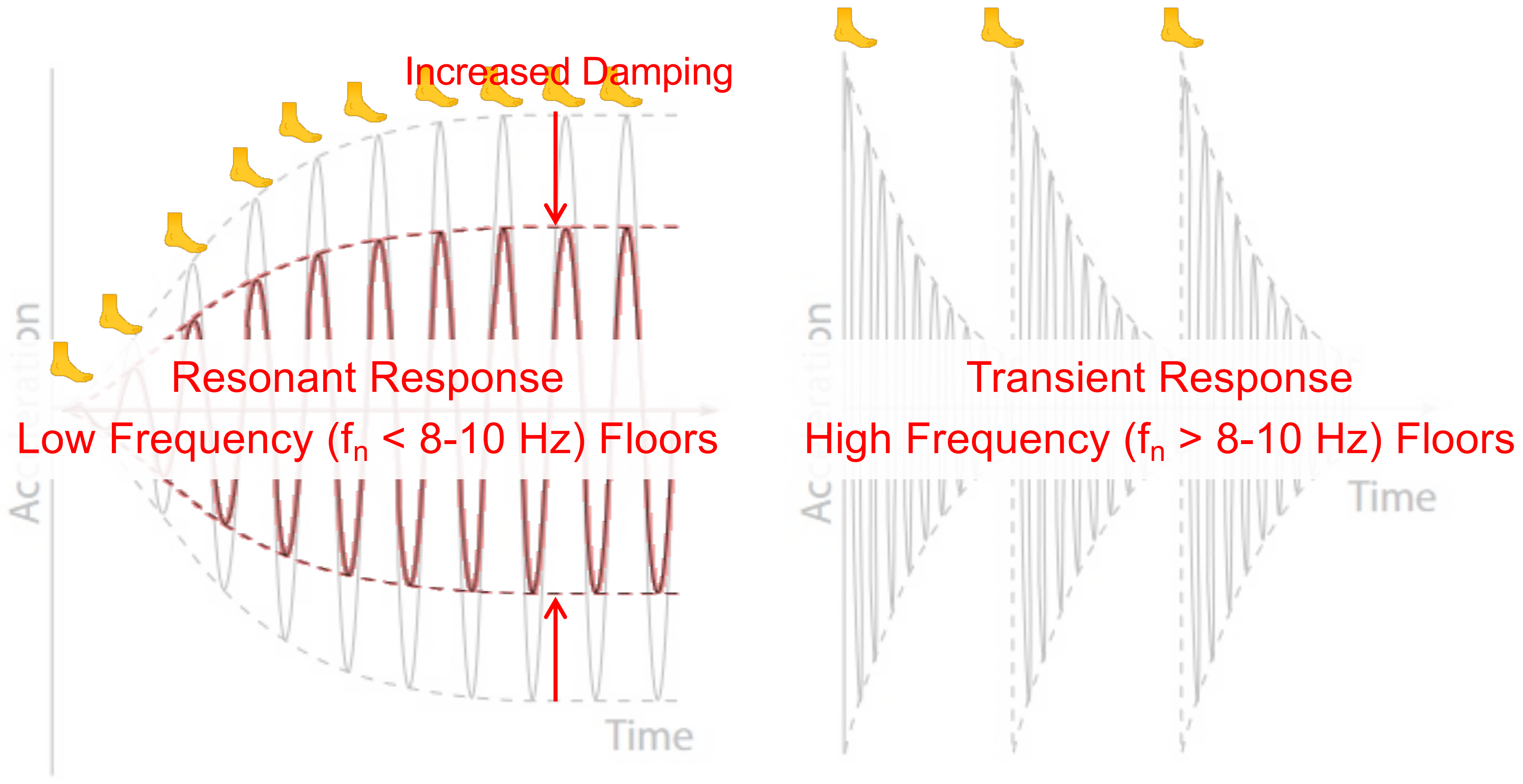


FIGURE 2-2: Build-up to resonant response (left) and transient response (right) of damped systems

Floor Vibration Criteria

Floor Vibration Criteria

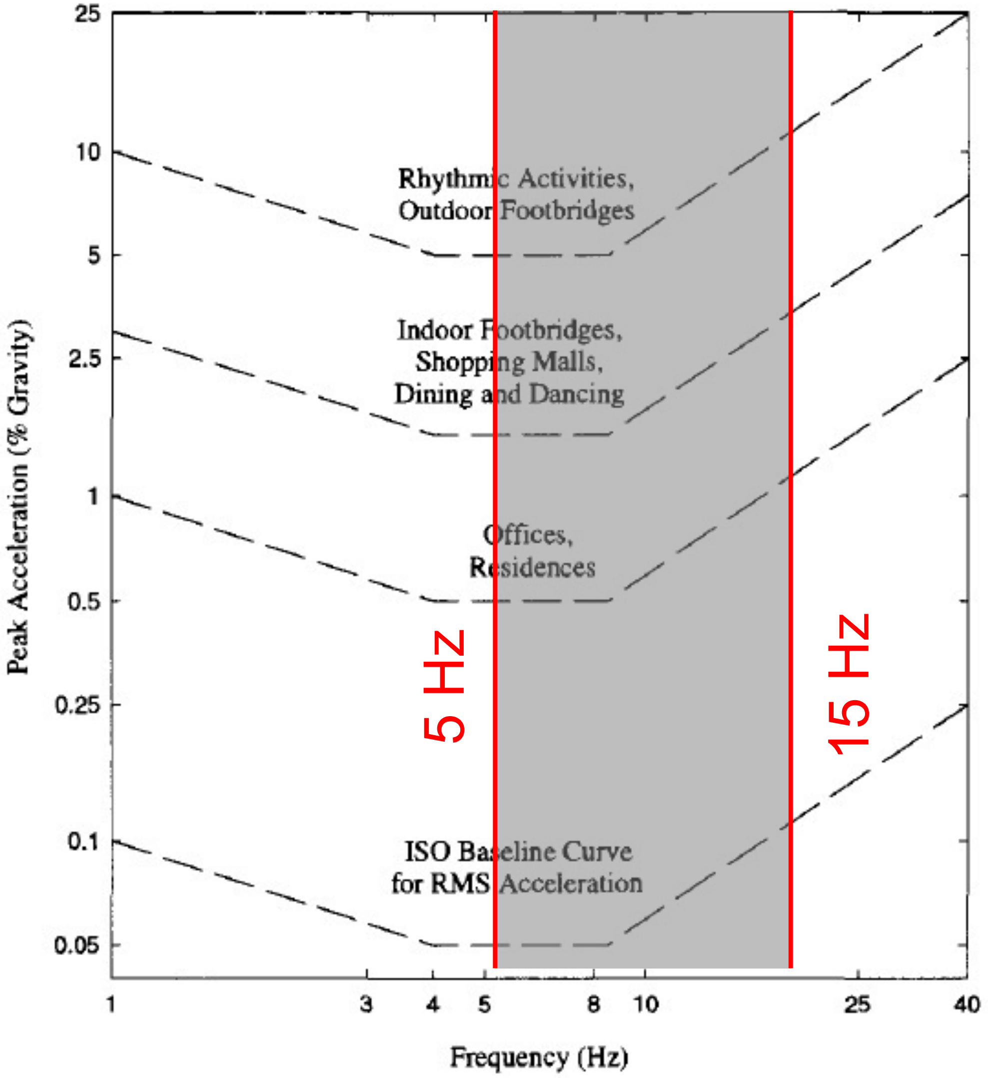


TABLE 3-13: Suggested performance targets

Place	Peak Acceleration Target	RMS Velocity Target
Offices or residences	0.5% g	16,000-32,000 mips
Premium offices or luxury residences	0.3% g	8,000-16,000 mips

Floor Vibration Criteria

TABLE 3-14: Generic velocity criteria for sensitive equipment

Designation	RMS Velocity Limit	Application
N/A	6,000 mips	Hospital patient rooms
N/A	4,000 mips	Surgery facilities, laboratory robots, bench microscopes up to 100x, operating rooms
VC-A	2,000 mips	Microbalances, optical comparators, mass spectrometers, industrial metrology laboratories, spectrophotometers, bench microscopes up to 400x
VC-B	1,000 mips	Microsurgery, microtomes and cyrotomes for 5-10 μm slices, tissue and cell cultures, optical equipment on isolation tables, bench microscopes greater than 400x, atomic force microscopes
VC-C	500 mips	High-precision balances, spectrophotometers, magnetic resonance imagers, microtomes and cyrotomes for < 5 μm slides, chemotaxs, electron microscopes at up to 30,000x
VC-D	250 mips	Cell implant equipment, micromanipulation confocal microscopes, high-resolutions mass spectrometers, electron microscopes at greater than 30,000x
VC-E	125 mips	Unisolated optical research systems, extraordinarily sensitive systems

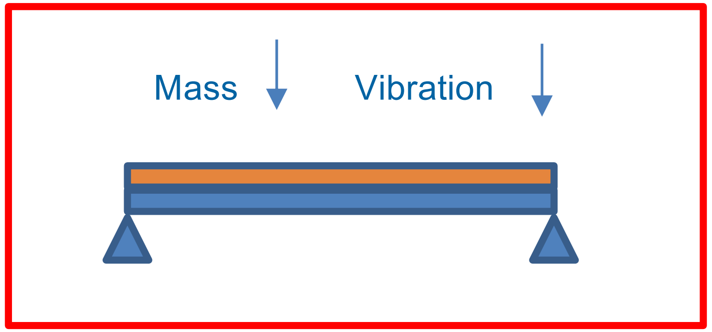
Mass Timber Floor Vibration Design Decisions

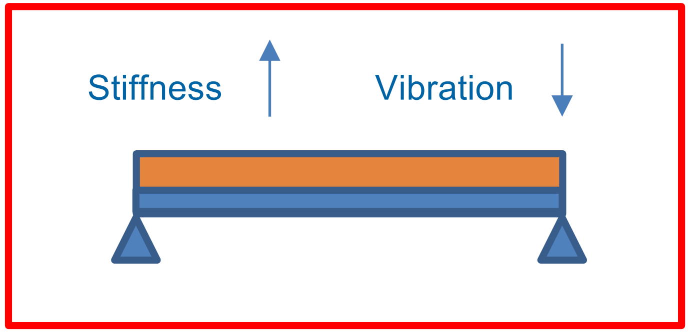
Mass Timber Floor Vibration Design Decisions

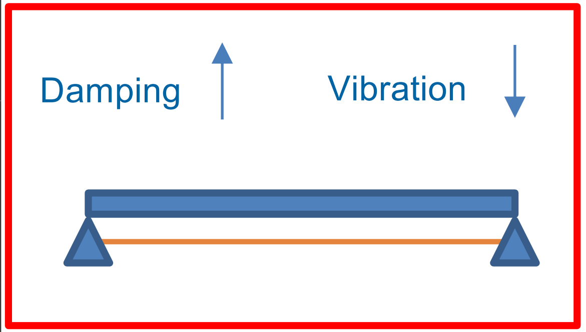
Parameters within design control

- Mass
- Stiffness
- Damping
- Vibration Path

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$







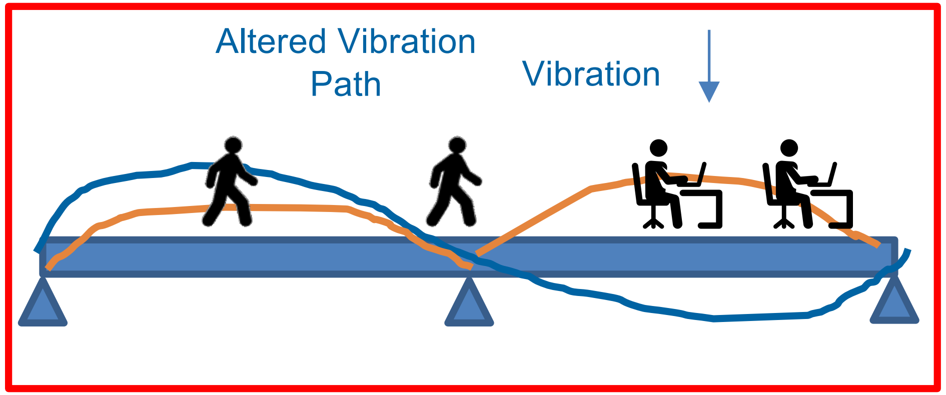


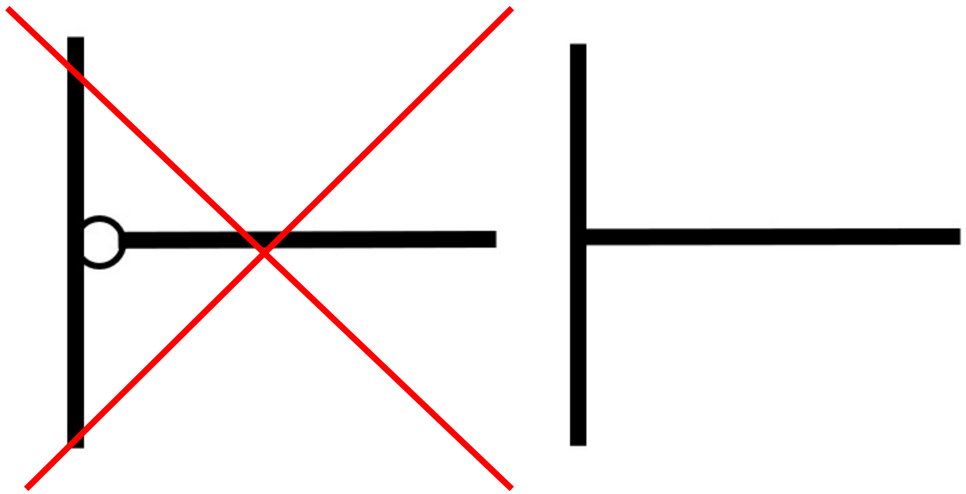
TABLE 3-2 Proposed mass timber floor damping ratios

Category	Range of Damping ζ (% critical)	Discussion
Lightly damped	1-2%	The lower end includes bare floors without topping and with minimal furnishing. The higher end includes floors with concrete topping and furnishings.
Moderately damped	2-4%	Lower values include bare timber-concrete composite floors, or timber floors with a floating concrete layer and full furnishings. The higher values include floors with floating floor layers, raised floors, full furnishings and mechanical systems. Floors with both furnishings and permanent partitions, not otherwise accounted for, could also be represented at the higher end of this damping range.
Heavily damped	4-5%	Floors in this range represent the upper limit of inherent damping. These floors likely include floating toppings, raised floors, suspended ceilings, furnishings, fixtures and/or permanent partitions not otherwise taken into account.
Explicit damping control	5%+	Generally, mass timber floors do not have more than 5% damping unless explicit damping control (e.g., a tuned mass damper) is added. These systems are beyond the scope of this guide.

Mass Timber Floor Vibration Design Decisions

"Free" Stiffness

- Dynamic modulus of concrete, $E_{c,dyn} = 1.35*E_c$
- Appropriate modeling of connections for vibration evaluation
- Nonstructural walls
- Incidental timber-timber or timber-concrete composite action



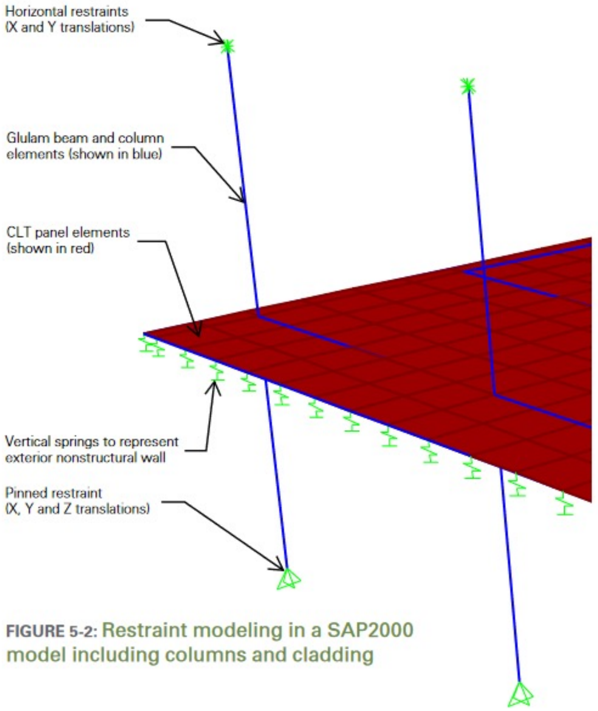


FIGURE 5-2: Restraint modeling in a SAP2000 model including columns and cladding

Mass Timber Floor Vibration Design Decisions

$$EI_{eff} = EI_1 + EI_2 + \gamma_1 * EA_1 * a_1^2 + \gamma_2 * EA_2 * a_2^2$$

$$a_1 = \frac{\gamma_2 * (EA)_2 * r}{\gamma_1 * (EA)_1 + \gamma_2 * (EA)_2}$$

$$a_2 = \frac{\gamma_1 * (EA)_1 * r}{\gamma_1 * (EA)_1 + \gamma_2 * (EA)_2}$$

$$\bar{z} = \frac{\gamma_1 * (EA)_1 * \bar{z}_1 + \gamma_2 * (EA)_2 * \bar{z}_2}{\gamma_1 * (EA)_1 + \gamma_2 * (EA)_2}$$

$$r = (h_1 + h_2)/2$$

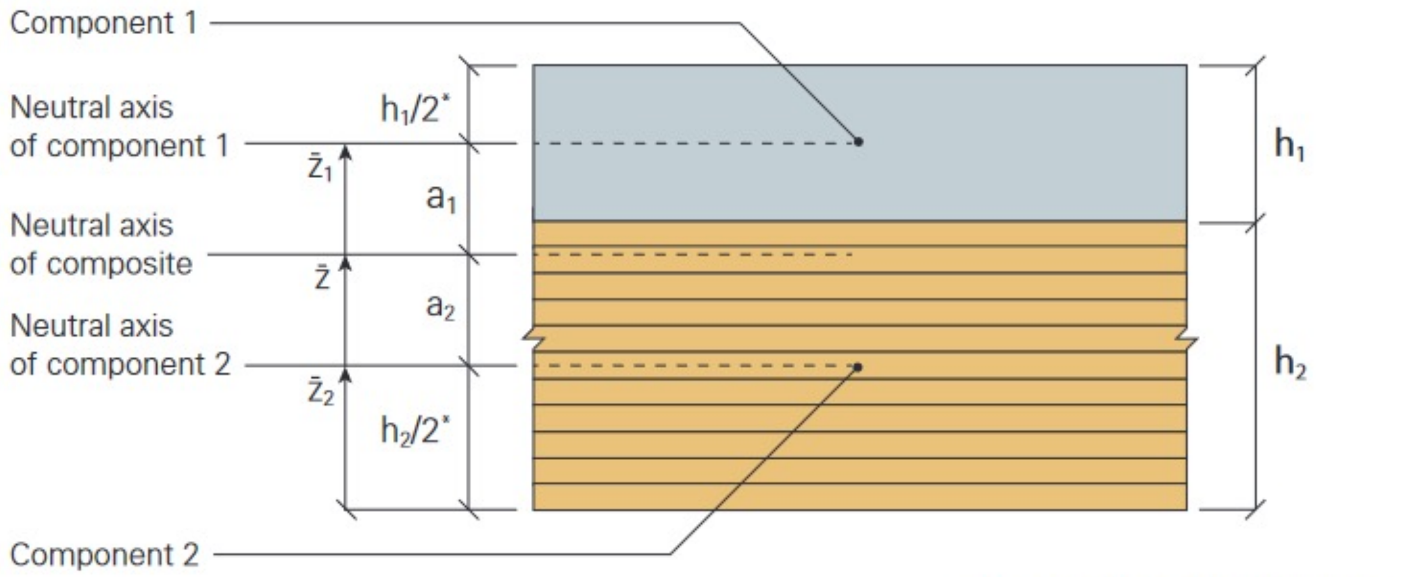


FIGURE 3-1: Two-component composite system

Mass Timber Floor Vibration Design Decisions

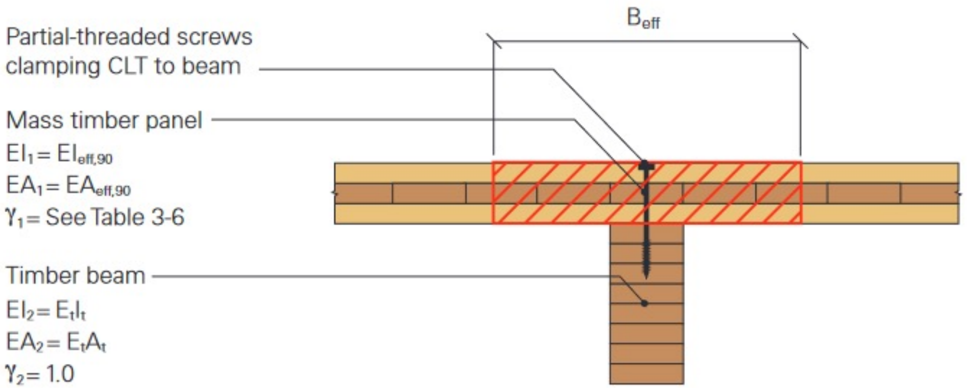


FIGURE 3-3: Mass timber panel on timber beam

TABLE 3-6 Suggested composite action between floor assembly components

Case		Partial Composite Action Factor (γ)	
		Strength & Deflection	**Vibration Design**
Concrete topping on mass timber panel detailed as a TCC system with explicit composite action		From testing or detailed analysis	Potentially higher than for strength & deflection
Incidental Composite Action	Concrete topping cast directly on mass timber floor with nominal connection	N/A[1]	0.15-0.50[2]
	Concrete topping cast directly on mass timber floor with no connection	N/A[1]	0.05-0.15[2]
	Concrete topping on acoustic mat or slip-sheet on mass timber panel	N/A[1]	0-0.05[2]
	Mass timber panel in direct contact with timber beam with clamping connection	N/A[3]	0.5-1.0[2]

[1] Only the mass timber panel is considered; the cementitious topping layer is ignored.
[2] Values are based on limited testing and field observations.
[3] Only the beam is considered; potential contribution from the mass timber panel and topping is ignored.

Mass Timber Floor Vibration Design Methods and Modeling

Mass Timber Floor Vibration Design Methods and Modeling

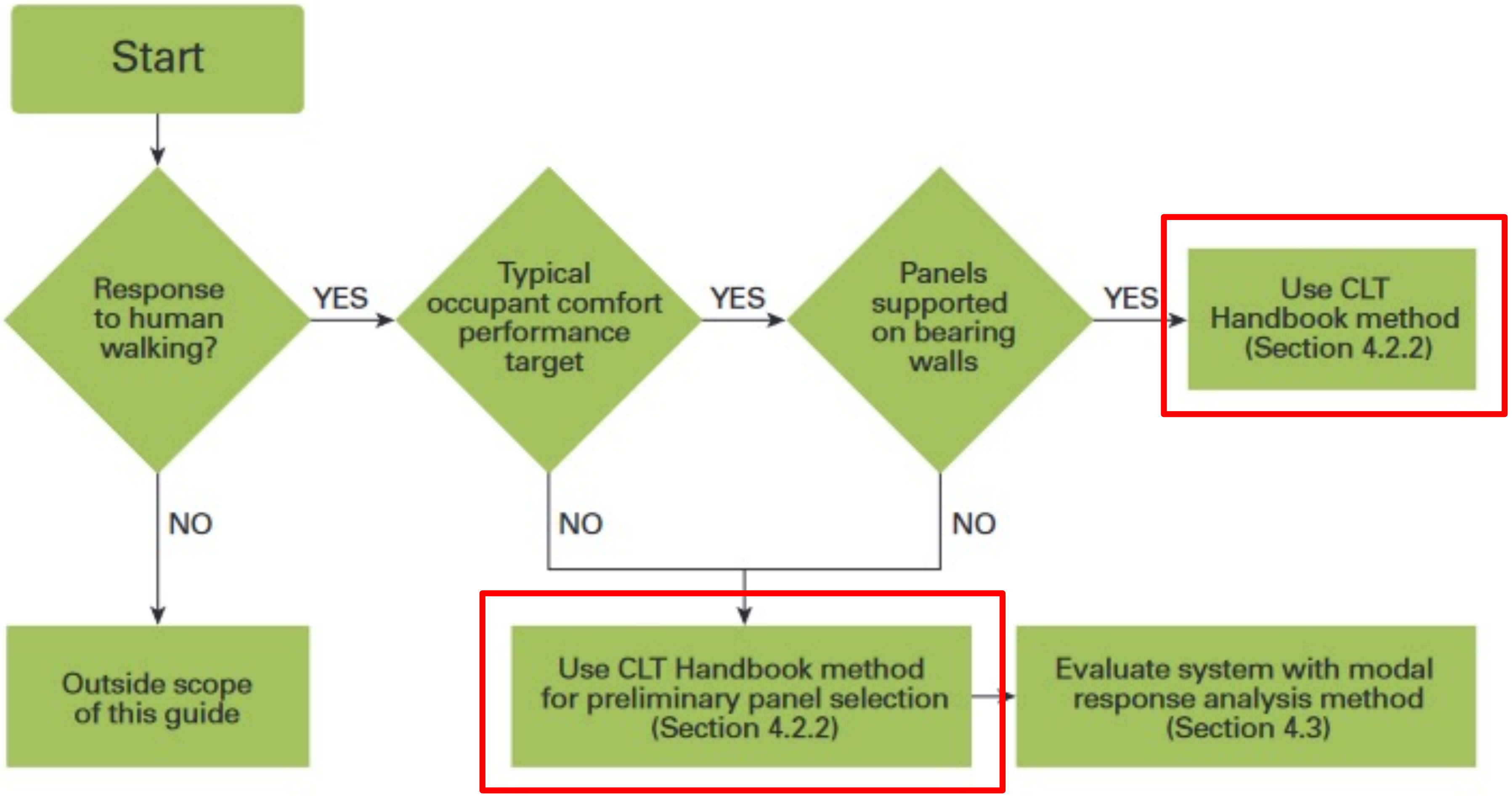


FIGURE 4-1: Vibration design flow chart

Mass Timber Floor Vibration Design Methods and Modeling

CLT Handbook Method

- Empirically derived span limit for bare CLT on “rigid” supports (e.g., bearing walls)
- Does not directly apply for CLT panel on beam systems
- Increased span available for multi-span panels with nonstructural elements or cementitious toppings
- Reduced span required for heavy cementitious toppings

$$L_{lim} \leq \frac{1}{12.05}\frac{(EI_{eff})^{0.293}}{(\bar{\rho}A)^{0.122}} \text{ (ft)}$$

$$L_{lim} \leq \frac{1}{13.34}\frac{(EI_{eff})^{0.293}}{(w)^{0.122}} \text{ (ft)}$$

TABLE 4-4: CLT Handbook method recommended span limit

Grade	t_p (in)	$EI_{eff,f,0}$ (10^6 lbf-in²/ft)	G	Density, ρ, at MC=12% (pcf)	$\bar{\rho}$	A (in²/ft)	L_{lim} (ft)
E1	4.125	115	0.42	28.1	0.45	49.5	13.1
E1	6.875	440	0.42	28.1	0.45	82.5	18.2
E1	9.625	1080	0.42	28.1	0.45	115.5	22.7
E2	4.125	102	0.49	32.5	0.52	49.5	12.4
E2	6.875	389	0.49	32.5	0.52	82.5	17.2
E2	9.625	963	0.49	32.5	0.52	115.5	21.6
E3	4.125	81	0.36	24.2	0.39	49.5	12.0
E3	6.875	311	0.36	24.2	0.39	82.5	16.7
E3	9.625	769	0.36	24.2	0.39	115.5	20.9
E4	4.125	115	0.55	36.3	0.58	49.5	12.7
E4	6.875	440	0.55	36.3	0.58	82.5	17.6
E4	9.625	1089	0.55	36.3	0.58	115.5	22.1
E5	4.125	101	0.43	[illegible]	0.46	49.5	12.6
E5	6.875	[illegible]	[illegible]	[illegible]	[illegible]	82.5	17.5
E5	9.625	962	0.43	28.7	0.46	115.5	21.9
V1	4.125	108	0.49	32.5	0.52	49.5	12.6
V1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17.6
V1	9.625	1027	0.49	32.5	0.52	115.5	22.0
V1(N)	4.125	108	0.49	32.5	0.52	49.5	12.6
V1(N)	[illegible]	415	[illegible]	32.5	[illegible]	[illegible]	17.6
V1(N)	9.625	1027	0.49	32.5	0.52	115.5	22.0
V2	4.125	95	0.42	28.1	0.45	49.5	12.4
V2	[illegible]	363	[illegible]	28.1	[illegible]	[illegible]	17.2
V2	9.625	898	0.42	28.1	0.45	115.5	21.5
V3	4.125	95	0.55	36.3	0.58	49.5	12.0
V3	[illegible]	363	[illegible]	36.3	[illegible]	[illegible]	16.7
V3	9.625	899	[illegible]	36.3	[illegible]	[illegible]	20.9
V4	4.125	74	0.36	24.2	0.39	49.5	11.7
V4	6.875	285	0.36	24.2	0.39	82.5	16.3
V4	9.625	706	0.36	24.2	0.39	115.5	20.4
V5	4.125	88	0.43	28.7	0.46	49.5	12.1
V5	6.875	337	0.43	28.7	0.46	82.5	16.8
V5	9.625	835	0.43	28.7	0.46	115.5	21.0
S1	4.125	132	0.64	41.8	0.67	49.5	13.0
S1	6.875	506	0.64	41.8	0.67	82.5	18.1
S1	9.625	1252	0.64	41.8	0.67	115.5	22.6
S2	4.125	114	0.64	41.8	0.67	49.5	12.4
S2	6.875	438	0.64	41.8	0.67	82.5	17.3
S2	9.625	1085	0.64	41.8	0.67	115.5	21.7
S3	4.125	114	0.64	41.8	0.67	49.5	12.4
S3	6.875	438	0.64	41.8	0.67	82.5	17.3
S3	9.625	1085	0.64	41.8	0.67	115.5	21.7

“Rule of Thumb”

Vibration Span Limits

4 1/8” 3-ply – 12 to 13ft

6 7/8” 5-ply – 16 to 18ft

9 5/8” 7-ply – 20 to 22ft

Mass Timber Floor Vibration Design Methods and Modeling

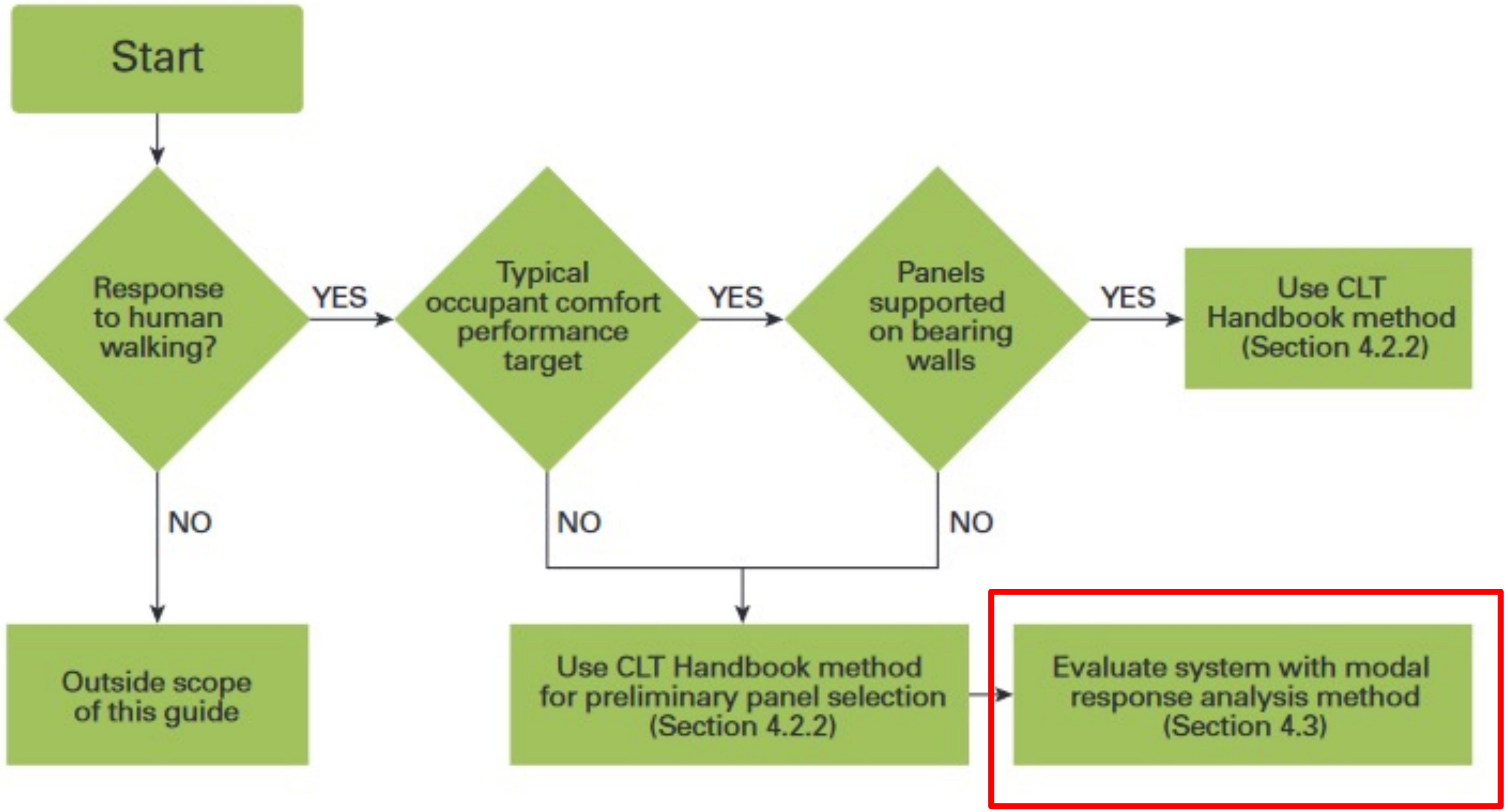


FIGURE 4-1: Vibration design flow chart

Mass Timber Floor Vibration Design Methods and Modeling

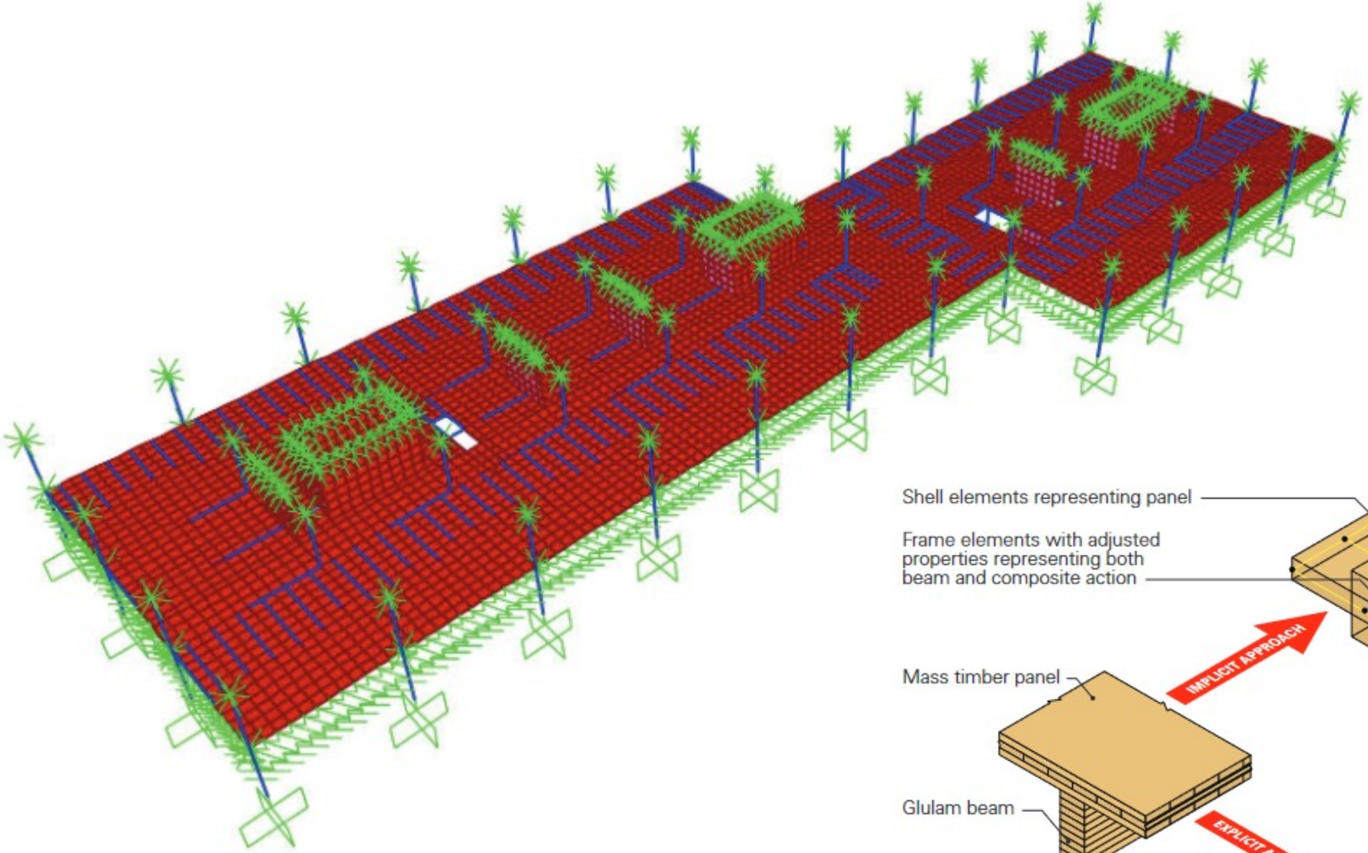


FIGURE 5-1: Example floor vibration model in SAP2000

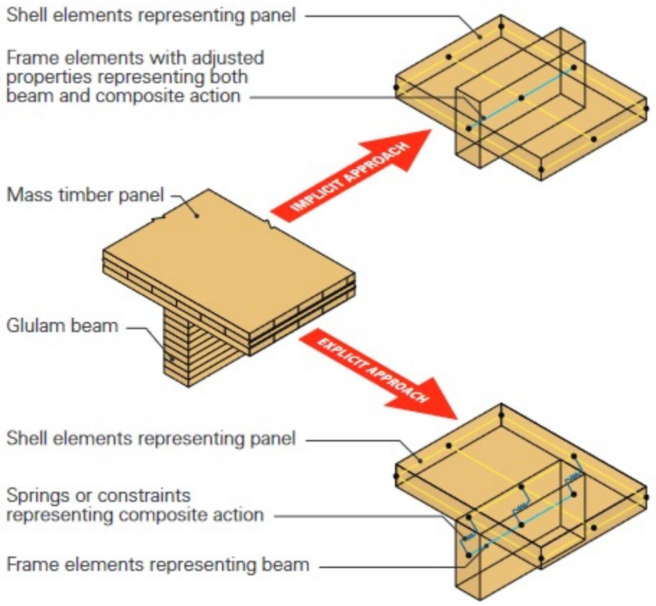


FIGURE 5-4: Implicit vs. explicit modeling of a glulam beam and a mass timber floor panel

TABLE 5-1: Property modification factors for isotropic material modeling

Orientation	Property Modification Factor
Strong axis axial	$f11 = \frac{EA_{eff,0}}{E_{ref} * A_{gross}}$
Weak axis axial	$f22 = \frac{EA_{eff,90}}{E_{ref} * A_{gross}}$
In-plane shear	$f12 = \frac{GA_{eff,e}}{G_{ref} * A_{gross}}$
Strong axis flexure	$m11 = \frac{EI_{eff,f,0}}{E_{ref} * I_{gross}}$
Weak axis flexure	$m22 = \frac{EI_{eff,f,90}}{E_{ref} * I_{gross}}$
Out-of-plane torsion*	$m12 = \min(v13, v23)$
Strong axis out-of-plane shear	$v13 = \frac{GA_{eff,f,0}}{G_{ref} * A_{gross}}$
Weak axis out-of-plane shear	$v23 = \frac{GA_{eff,f,90}}{G_{ref} * A_{gross}}$

** Consensus on the out-of-plane torsion stiffness of most mass timber products does not exist in the literature. Its property modification factor is therefore conservatively taken as the lower of that for strong or weak axis out-of-plane shear.*

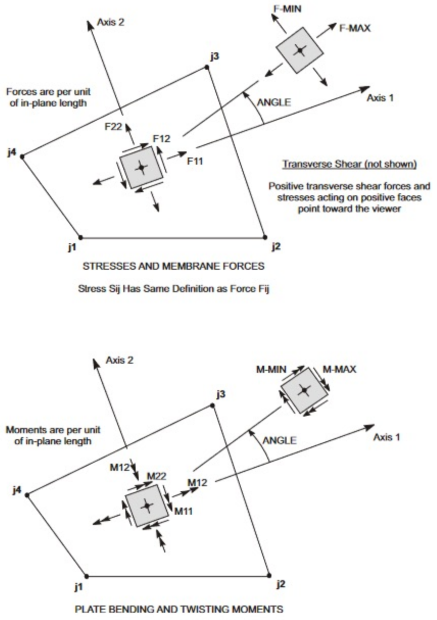


FIGURE 5-3: Local axes and corresponding stress orientation definitions for one commercially available software platform (SAP2000)

Mass Timber Floor Vibration Design Methods and Modeling

Resonant Response Calculation

$$a_{real,h,m} = \left(\frac{f_h}{f_m}\right)^2 \frac{F_h \mu_{r,m} \mu_{e,m} \rho_{h,m}}{\hat{m}_m} \frac{A_m}{(A_m{}^2 + B_m{}^2)}$$

$$a_{imag,h,m} = \left(\frac{f_h}{f_m}\right)^2 \frac{F_h \mu_{r,m} \mu_{e,m} \rho_{h,m}}{\hat{m}_m} \frac{B_m}{(A_m{}^2 + B_m{}^2)}$$

$$A_m = 1 - \left(\frac{f_h}{f_m}\right)^2$$

$$B_m = 2\zeta_m \frac{f_h}{f_m}$$

$$a_{real,h} = \sum_{m=1}^{N} a_{real,h,m}$$

$$a_{imag,h} = \sum_{m=1}^{N} a_{imag,h,m}$$

$$a_h = \sqrt{a_{real,h}^2 + a_{imag,h}^2}$$

$$a_p = \sqrt{\sum_{h=1}^{4} a_h{}^2} = \sqrt{a_1{}^2 + a_2{}^2 + a_3{}^2 + a_4{}^2}$$

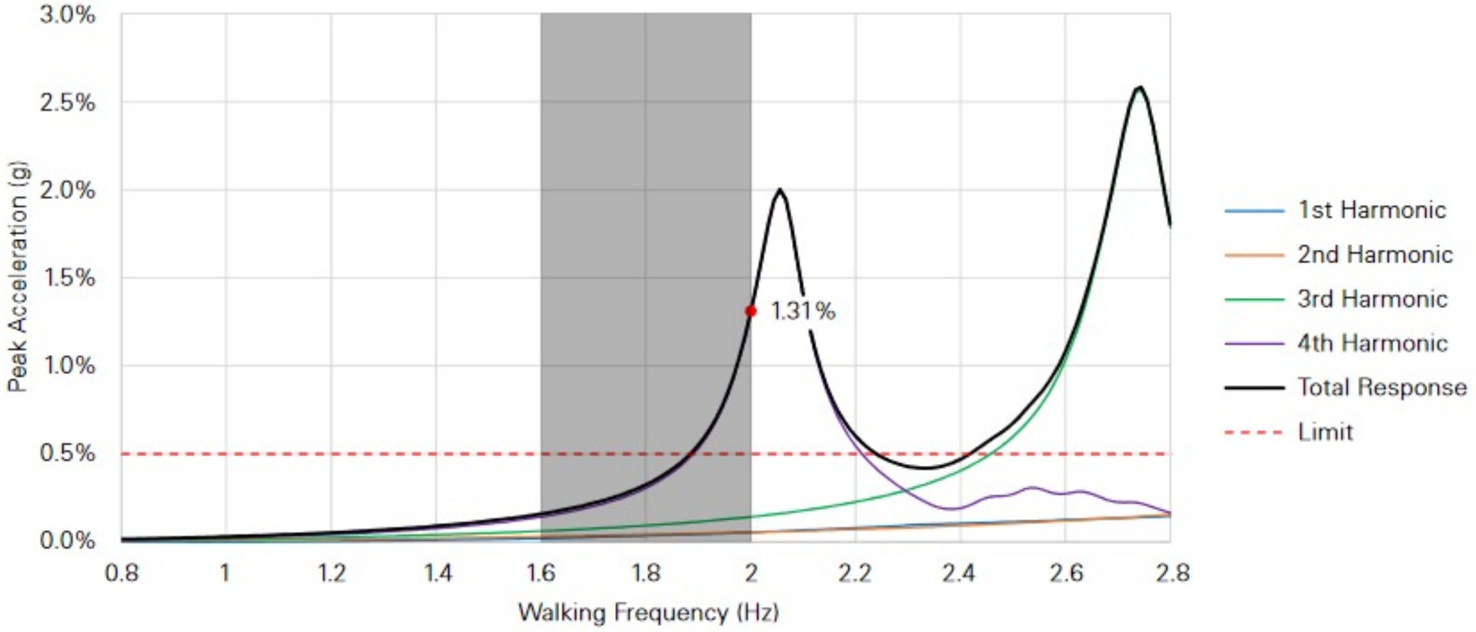


FIGURE 6-2: Example post-processor output for evaluating floor vibration performance based on resonant response for a given excitation and response node; area in grey indicates walking frequencies of interest

Mass Timber Floor Vibration Design Methods and Modeling

Transient Response Calculation

$$\hat{v}_m = \mu_{r,m}\mu_{e,m}\frac{I_{eff,m}}{\hat{m}_m}$$

$$v_m(t) = \hat{v}_m e^{-2\pi\zeta f_m t}\sin(2\pi f_m t)$$

$$v(t) = \sum_{m=1}^{N} v_m(t)$$

$$v_{RMS} = \sqrt{\frac{1}{T_w}\int_0^{T_w}(v(t))^2 dt}$$

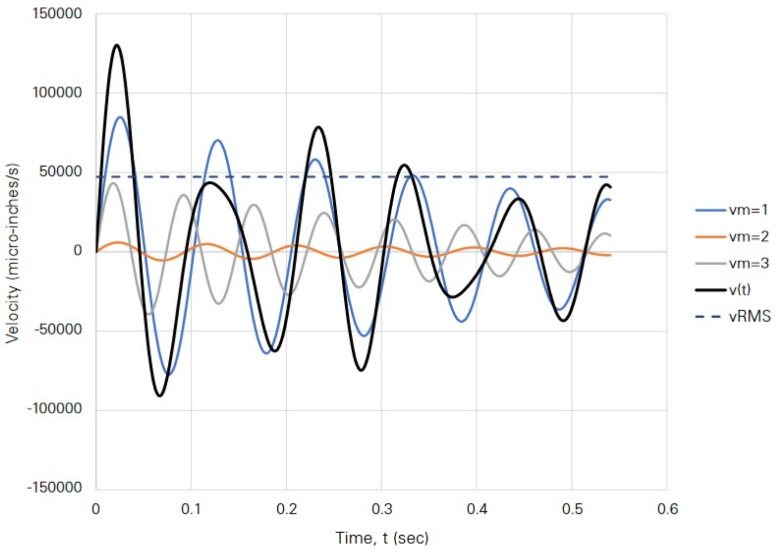


FIGURE 4-6: Sample velocity response history

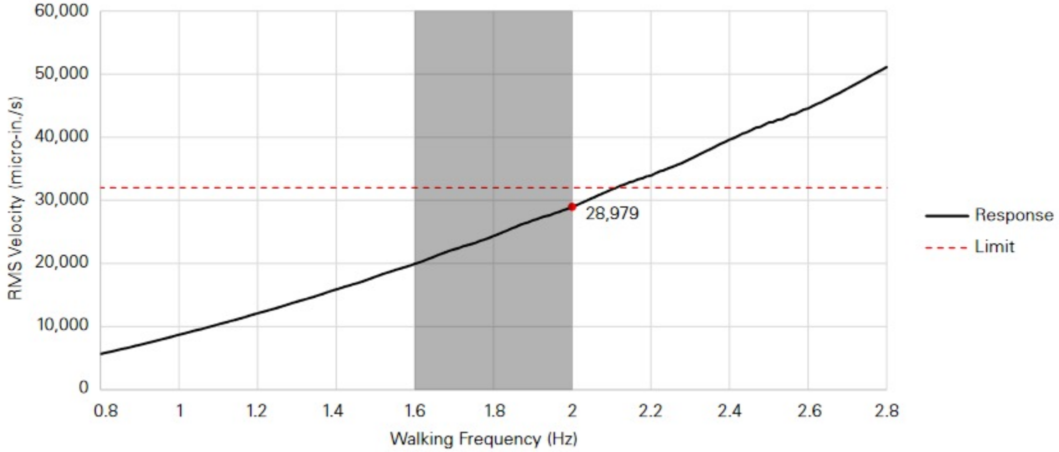


FIGURE 6-3: Example post-processor output for evaluating floor vibration performance based on impulsive response for a given excitation and response node; area in grey indicates walking frequencies of interest

Mass Timber Floor Vibration Design Methods and Modeling

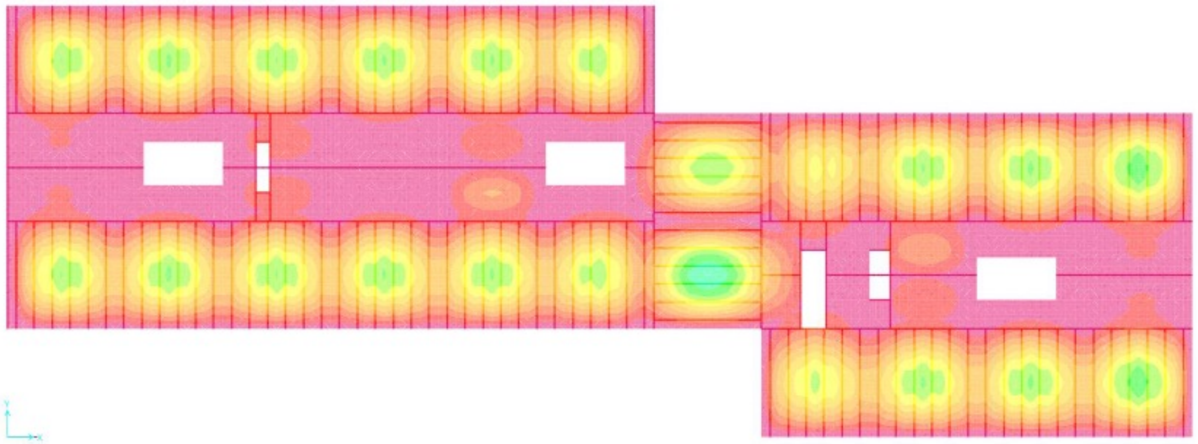


FIGURE 6-4: Example post-processor output for evaluating floor vibration performance based on an envelope of results for all combinations of response and excitation nodes; cooler colors indicate areas of higher (less desirable) floor vibration

$f_{w,min}$	0.8	Hz
$f_{w,max}$	2.8	Hz
g	32.2	ft/sec^2
a_{total}	0.01310	g

h	1		h	2		h	3		h	4	
f_h	2	Hz	f_h	4	Hz	f_h	6	Hz	f_h	8	Hz
DLF	0.431		DLF	0.091		DLF	0.071		DLF	0.065	
F_h	72.3	lb	F_h	15.4	lb	F_h	12.0	lb	F_h	10.9	lb
N	550		N	1100		N	1650		N	2200	
ρ_h	1		ρ_h	1		ρ_h	1		ρ_h	1	
a_h	0.000549	g	a_h	0.000549	g	a_h	0.0014	g	a_h	0.013	g

Mode	f_m	$\mu_{r,m}$	$\mu_{e,m}$	m_m^{hat}	A_m	B_m	$a_{real,h,m}$	$a_{imag,h,m}$	A_m	B_m	$a_{real,h,m}$	$a_{imag,h,m}$	A_m	B_m	$a_{real,h,m}$	$a_{imag,h,m}$	A_m	B_m	$a_{real,h,m}$	$a_{imag,h,m}$
-	Hz	ft	ft	lb-ft-sec^2	-	-	ft/sec^2	ft/sec^2	-	-	ft/sec^2	ft/sec^2	-	-	ft/sec^2	ft/sec^2	-	-	ft/sec^2	ft/sec^2
1	6.69	-0.00017	-0.00017	83.33	0.91068	0.01195	2.32E-09	3.04E-11	0.64272	0.02391	2.78E-09	1.04E-10	0.19612	0.03586	1.55E-08	2.84E-09	-0.42912	0.04782	-1.17E-08	1.31E-09
2	7.57	0.00074	0.00074	83.33	0.93016	0.01057	3.53E-08	4.01E-10	0.72066	0.02114	3.87E-08	1.13E-09	0.37148	0.03171	1.31E-07	1.12E-08	-0.11737	0.04228	-5.98E-07	2.15E-07
3	7.99	-0.00044	-0.00044	83.33	0.93740	0.01001	1.13E-08	1.21E-10	0.74962	0.02002	1.20E-08	3.21E-10	0.43664	0.03002	3.61E-08	2.48E-09	-0.00152	0.04003	-2.43E-08	6.40E-07
4	8.00	-0.00576	-0.00576	83.33	0.93750	0.01000	1.92E-06	2.05E-08	0.75000	0.02000	2.04E-06	5.43E-08	0.43749	0.03000	6.11E-06	4.19E-07	-0.00002	0.04000	-4.35E-08	1.09E-04
5	8.00	0.03616	0.03616	83.33	0.93756	0.00999	7.55E-05	8.05E-07	0.75026	0.01999	8.01E-05	2.13E-06	0.43808	0.02998	2.40E-04	1.64E-05	0.00102	0.03998	1.10E-04	4.28E-03
6	8.02	0.09111	0.09111	83.33	0.93779	0.00998	4.78E-04	5.08E-06	0.75117	0.01995	5.06E-04	1.34E-05	0.44012	0.02993	1.51E-03	1.03E-04	0.00467	0.03991	3.13E-03	2.68E-02
7	8.10	0.04037	0.04037	83.33	0.93898	0.00988	9.19E-05	9.67E-07	0.75590	0.01976	9.69E-05	2.53E-06	0.45079	0.02964	2.85E-04	1.87E-05	0.02362	0.03952	2.32E-03	3.89E-03
8	8.11	0.00025	0.00025	83.33	0.93922	0.00986	3.62E-09	3.80E-11	0.75686	0.01972	3.82E-09	9.95E-11	0.45294	0.02959	1.12E-08	7.29E-10	0.02746	0.03945	9.77E-08	1.40E-07
9	8.11	-0.13679	-0.13679	83.33	0.93925	0.00986	1.05E-03	1.10E-05	0.75700	0.01972	1.11E-03	2.88E-05	0.45325	0.02958	3.24E-03	2.11E-04	0.02799	0.03944	2.85E-02	4.02E-02
10	8.13	-0.00244	-0.00244	83.33	0.93951	0.00984	3.33E-07	3.48E-09	0.75805	0.01968	3.50E-07	9.08E-09	0.45562	0.02951	1.02E-06	6.60E-08	0.03222	0.03935	9.40E-06	1.15E-05

FIGURE 6-1: Example post-processor resonant response calculations

Mass Timber Floor Vibration Design Examples

Mass Timber Floor Vibration Design Example 1

This example demonstrates…

- CLT panels spanning to bearing walls
- Floor system where the CLT Handbook Method is applicable
- Expected performance differences between single span versus multi-span panels
- Modeling capabilities and inputs in RFEM
- Detailed resonant and transient response calculations
- Typical occupancy vibration criteria

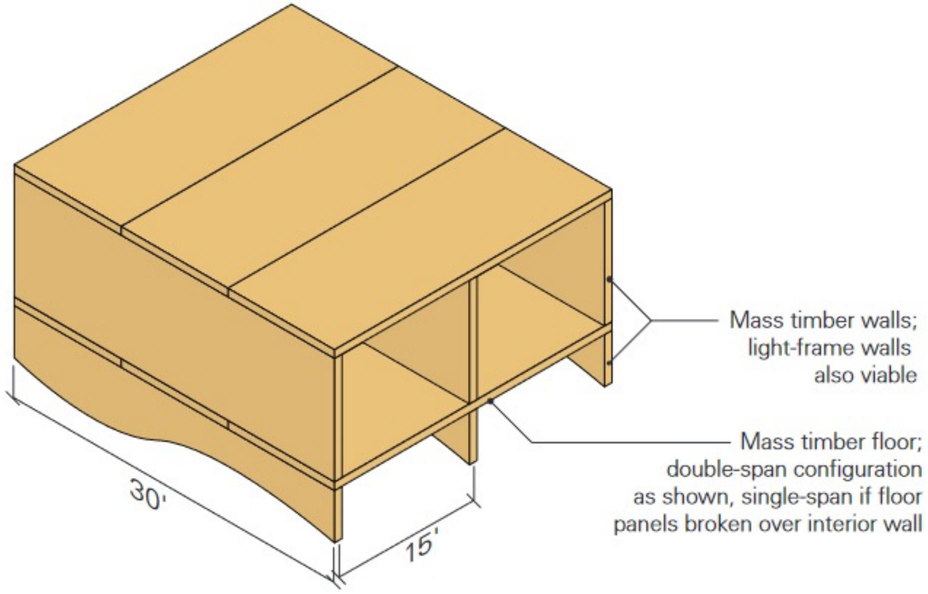


FIGURE 7-1: Floor system considered in this example

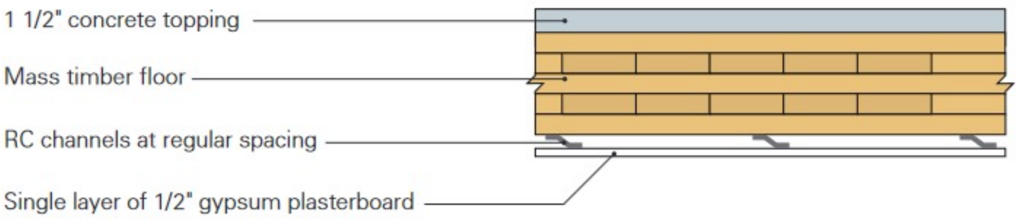


FIGURE 7-2: CLT floor assembly

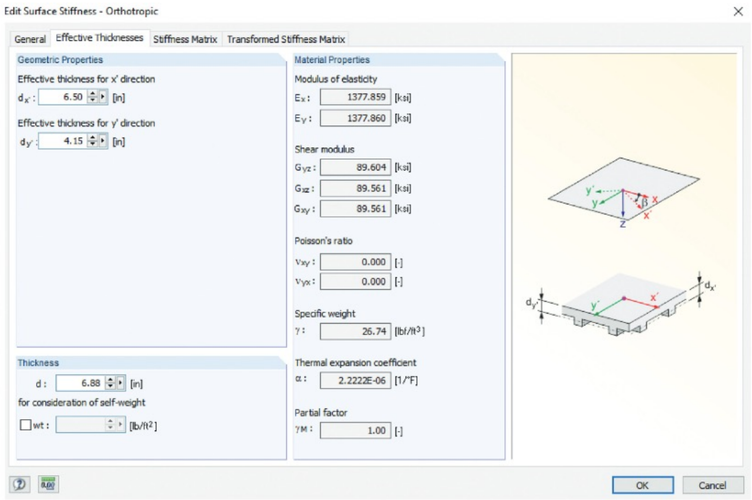


FIGURE 7-5: Orthotropic surface properties

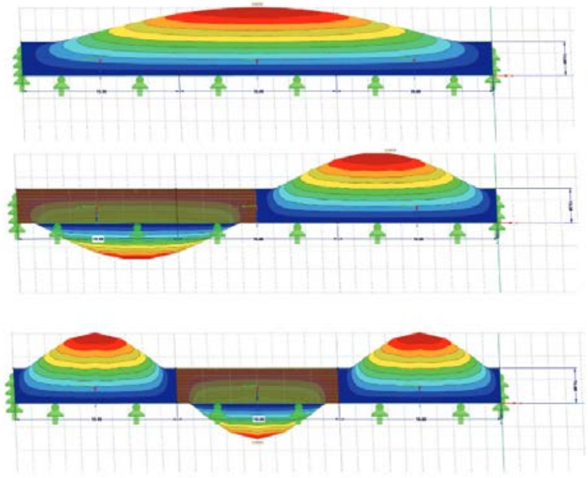


FIGURE 7-7: Single-span first three mode shapes

Mass Timber Floor Vibration Design Example 2

This example demonstrates…

- NLT panels spanning to glulam beams
- Floor system where the CLT Handbook Method is not applicable
- Expected performance differences between considering versus neglecting nonstructural exterior walls in model
- Modeling capabilities and inputs in RFEM
- Detailed resonant and transient response calculations
- Typical occupancy vibration criteria

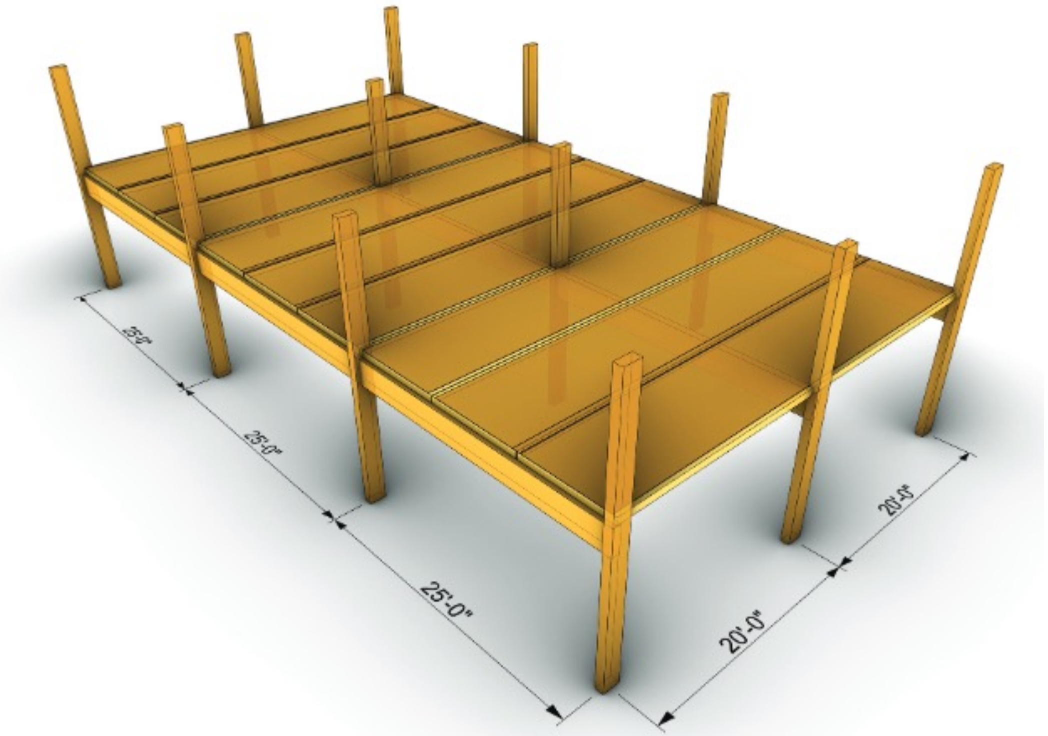


FIGURE 8-1: Structural system considered in this example

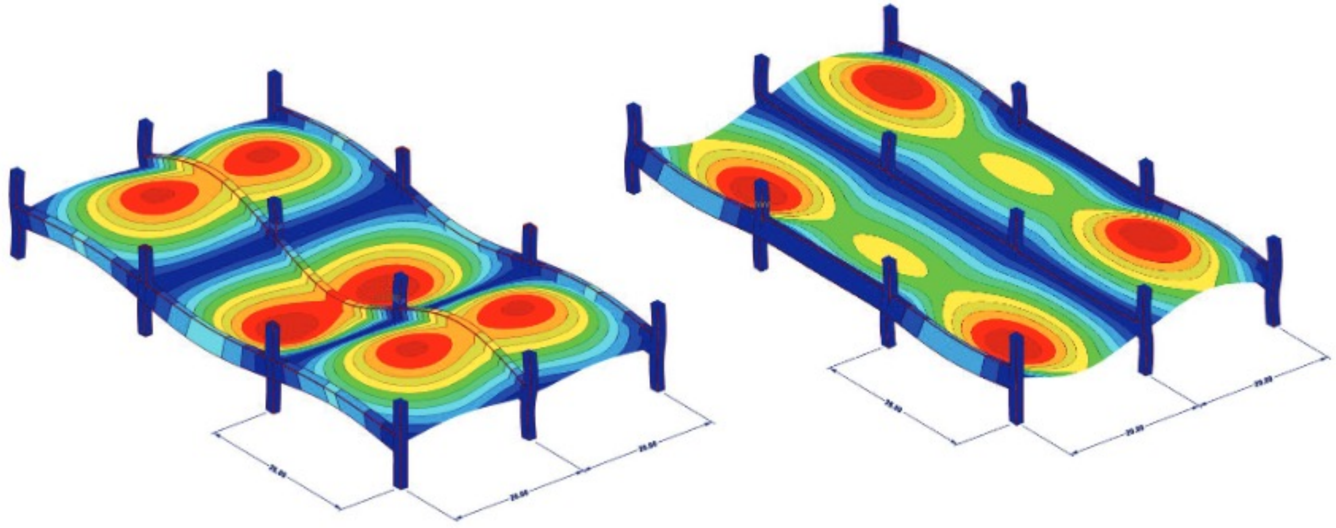


FIGURE 8-4: Mode shapes for mode 1 (left) and mode 2 (right)

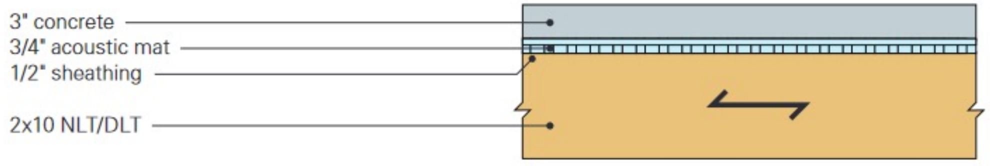


FIGURE 8-2: Floor build-up

Mass Timber Floor Vibration Design Example 3

This example demonstrates…

- CLT panels spanning to glulam beams
- Floor system where the CLT Handbook Method is not applicable
- Detailed timber-concrete composite action calculations and property modification factors
- Modeling capabilities and inputs in SAP2000
- Detailed transient response calculations
- Sensitive equipment vibration criteria

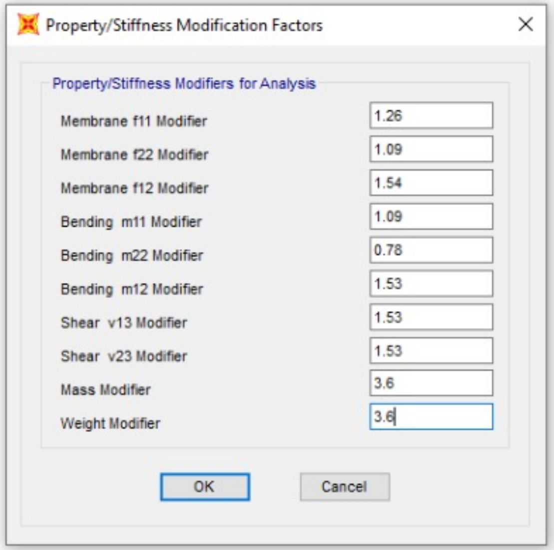
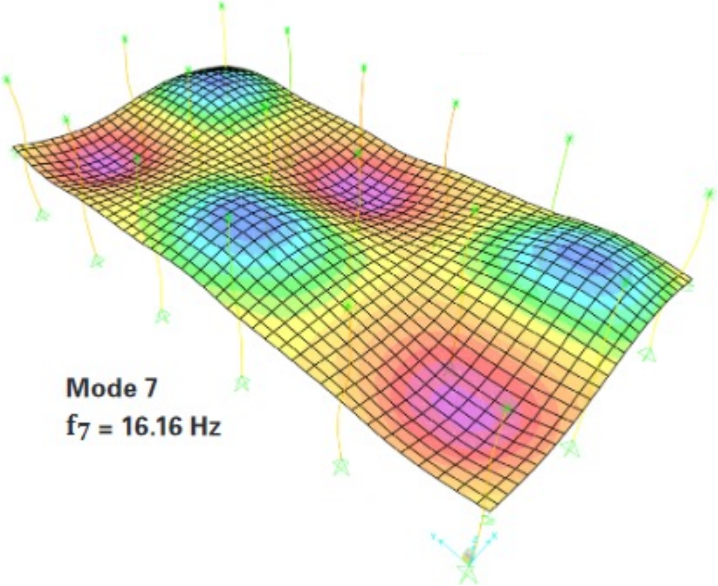


FIGURE 9-6: Shell property/stiffness modification factors



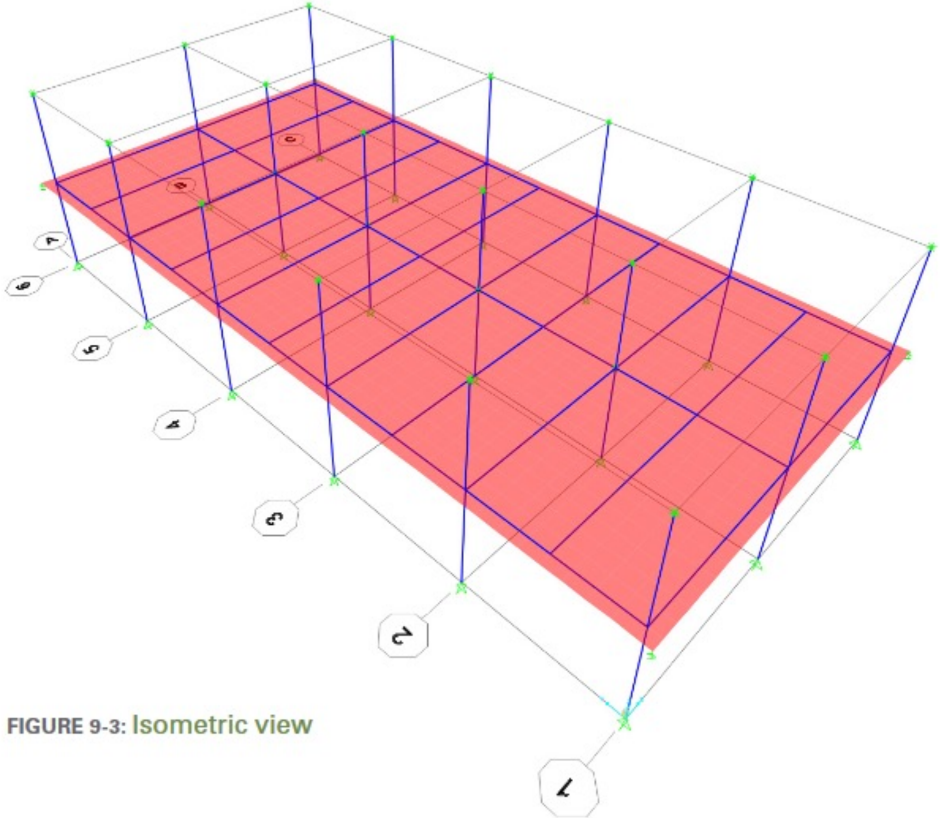


FIGURE 9-3: Isometric view

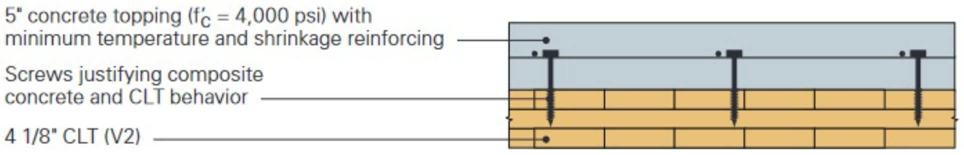
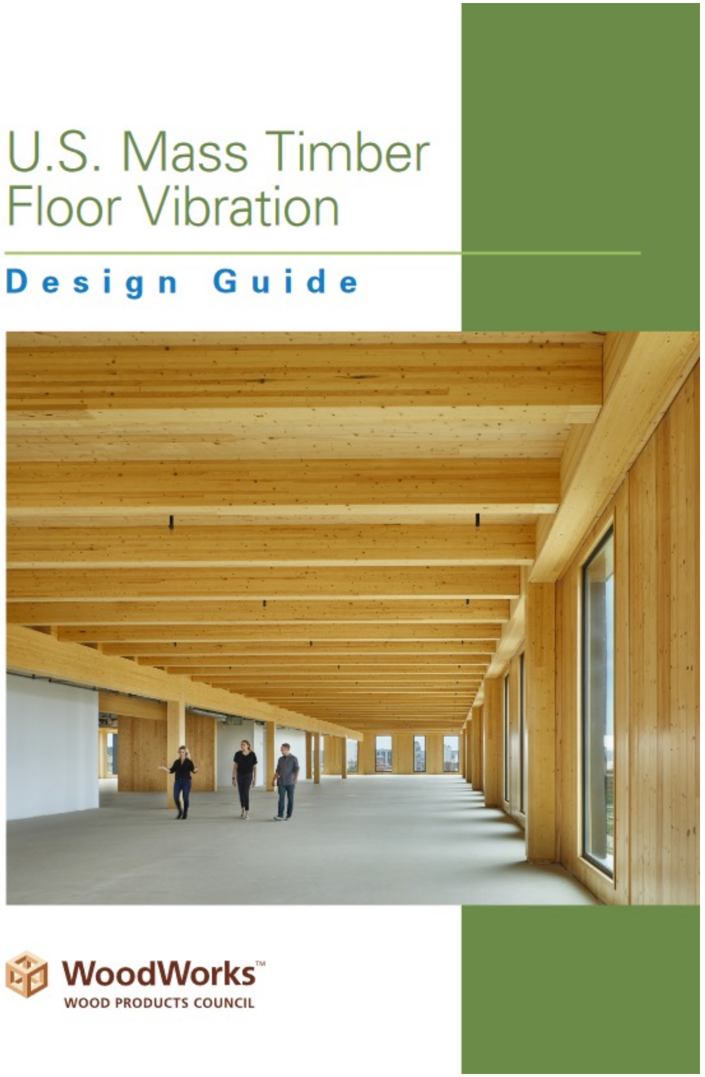


FIGURE 9-1: Floor assembly considered in this example



U.S. Mass Timber Floor Vibration Design Guide

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https://www.woodworks.org/wp-content/uploads/wood_solution_paper-Mass-Timber-Floor-Vibration.pdf

Thank You

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