Mass Timber Floor Design for Walking-Induced Vibrations

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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

Equal Loudness Contours by Phon

SPL (dB)

Frequency (Hz)

1,000 Hz
100 Hz
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**

RMS Amplitude $= \frac{u_0}{\sqrt{2}}$

Frequency $f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$
Understanding Floor Vibration

FIGURE 2-3: Vibration mode shapes
### Understanding Floor Vibration

<table>
<thead>
<tr>
<th>Walking Speed</th>
<th>Walking Frequency (Hz)</th>
<th>Steps Per Minute (SPM)</th>
<th>Potential Occupancies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very slow (uncommon)</td>
<td>1.25</td>
<td>75</td>
<td>Laboratories, surgical theaters</td>
</tr>
<tr>
<td>Slow</td>
<td>1.6</td>
<td>95</td>
<td>Bedrooms, hotel rooms</td>
</tr>
<tr>
<td>Moderate</td>
<td>1.85</td>
<td>110</td>
<td>Residential living areas, office work areas</td>
</tr>
<tr>
<td>Fast</td>
<td>2.1</td>
<td>126</td>
<td>Corridors, shopping malls, airports</td>
</tr>
</tbody>
</table>
Understanding Floor Vibration

1.5 Hz Walking
2 Hz Walking
3 Hz Running
6 Hz “Running”

6 Hz Floor
3rd Harmonic
(=18 Hz x 3 Hz x 3)
Understanding Floor Vibration

**Resonant Response**
Low Frequency ($f_n < 8-10$ Hz) Floors

**Increased Damping**

**Transient Response**
High Frequency ($f_n > 8-10$ Hz) Floors

**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

<table>
<thead>
<tr>
<th>Place</th>
<th>Peak Acceleration Target</th>
<th>RMS Velocity Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices or residences</td>
<td>0.5% g</td>
<td>16,000 - 32,000 mips</td>
</tr>
<tr>
<td>Premium offices or luxury residences</td>
<td>0.3% g</td>
<td>8,000 - 16,000 mips</td>
</tr>
</tbody>
</table>
# Floor Vibration Criteria

<table>
<thead>
<tr>
<th>Designation</th>
<th>RMS Velocity Limit</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>6,000 mips</td>
<td>Hospital patient rooms</td>
</tr>
<tr>
<td>N/A</td>
<td>4,000 mips</td>
<td>Surgery facilities, laboratory robots, bench microscopes up to 100x, operating rooms</td>
</tr>
<tr>
<td>VC-A</td>
<td>2,000 mips</td>
<td>Microbalances, optical comparators, mass spectrometers, industrial metrology laboratories, spectrophotometers, bench microscopes up to 400x</td>
</tr>
<tr>
<td>VC-B</td>
<td>1,000 mips</td>
<td>Microsurgery, microtomes and cryotomes for 5-10 μm slices, tissue and cell cultures, optical equipment on isolation tables, bench microscopes greater than 400x, atomic force microscopes</td>
</tr>
<tr>
<td>VC-C</td>
<td>500 mips</td>
<td>High-precision balances, spectrophotometers, magnetic resonance imagers, microtomes and cryotomes for &lt; 5 μm slides, chemotaxis, electron microscopes at up to 30,000x</td>
</tr>
<tr>
<td>VC-D</td>
<td>250 mips</td>
<td>Cell implant equipment, micromanipulation confocal microscopes, high-resolution mass spectrometers, electron microscopes at greater than 30,000x</td>
</tr>
<tr>
<td>VC-E</td>
<td>125 mips</td>
<td>Unisolated optical research systems, extraordinarily sensitive systems</td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Category</th>
<th>Range of Damping (% critical)</th>
<th>Discussion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightly damped</td>
<td>1-2%</td>
<td>The lower end includes bare floors without topping and with minimal furnishing. The higher end includes floors with concrete topping and furnishings.</td>
</tr>
<tr>
<td>Moderately damped</td>
<td>2-4%</td>
<td>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.</td>
</tr>
<tr>
<td>Heavily damped</td>
<td>4-5%</td>
<td>Floors in this range represent the upper limit of inherent damping. These floors likely include floating topings, raised floors, suspended ceilings, furnishings, fixtures and/or permanent partitions not otherwise taken into account.</td>
</tr>
<tr>
<td>Explicit damping control</td>
<td>5%+</td>
<td>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.</td>
</tr>
</tbody>
</table>

TABLE 3-2 Proposed mass timber floor damping ratios
Mass Timber Floor Vibration Design Decisions

“Free” Stiffness

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

\[ EI_{\text{eff}} = EI_1 + EI_2 + \gamma_1 \cdot EA_1 \cdot a_1^2 + \gamma_2 \cdot EA_2 \cdot a_2^2 \]

\[ a_1 = \frac{\gamma_2 \cdot (EA)_2 \cdot r}{\gamma_1 \cdot (EA)_1 + \gamma_2 \cdot (EA)_2} \]

\[ a_2 = \frac{\gamma_1 \cdot (EA)_1 \cdot r}{\gamma_1 \cdot (EA)_1 + \gamma_2 \cdot (EA)_2} \]

\[ \bar{z} = \frac{\gamma_1 \cdot (EA)_1 \cdot \bar{z}_1 + \gamma_2 \cdot (EA)_2 \cdot \bar{z}_2}{\gamma_1 \cdot (EA)_1 + \gamma_2 \cdot (EA)_2} \]

\[ r = \frac{(h_1 + h_2)}{2} \]

*FIGURE 3-1: Two-component composite system*

*\( \gamma \)* only when centroid of component centered on depth of component
**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**

<table>
<thead>
<tr>
<th>Case</th>
<th>Partial Composite Action Factor ($\gamma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete topping on mass timber panel detailed as a TCC system with explicit composite action</td>
<td>From testing or detailed analysis</td>
</tr>
<tr>
<td>Concrete topping cast directly on mass timber floor with nominal connection</td>
<td>N/A</td>
</tr>
<tr>
<td>Concrete topping cast directly on mass timber floor with no connection</td>
<td>N/A</td>
</tr>
<tr>
<td>Concrete topping on acoustic mat or slip-sheet on mass timber panel</td>
<td>N/A</td>
</tr>
<tr>
<td>Mass timber panel in direct contact with timber beam with clamping connection</td>
<td>N/A</td>
</tr>
</tbody>
</table>

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

\[
L_{\text{lim}} \leq \frac{1}{12.05} \left( \frac{\text{EI}_{\text{eff}}^{0.293}}{\bar{\rho} A^{0.122}} \right) \text{ (ft)}
\]

\[
L_{\text{lim}} \leq \frac{1}{13.34} \left( \frac{\text{EI}_{\text{eff}}^{0.293}}{\text{w}^{0.122}} \right) \text{ (ft)}
\]

**“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

<table>
<thead>
<tr>
<th>Grade</th>
<th>3-ply</th>
<th>5-ply</th>
<th>7-ply</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>E</td>
<td>210 GPa</td>
<td>210 GPa</td>
<td>210 GPa</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>$A$</td>
<td>9.625</td>
<td>9.625</td>
<td>9.625</td>
</tr>
</tbody>
</table>

Note: The above table provides a summary of the vibration span limits for different grades of CLT panels.
Mass Timber Floor Vibration Design Methods and Modeling

**FIGURE 4-1: Vibration design flow chart**

- **Start**
  - Response to human walking? **YES**
  - Typical occupant comfort performance target **YES**
  - Panels supported on bearing walls **YES**
    - Use CLT Handbook method (Section 4.2.2)
  - Panels supported on bearing walls **NO**
    - Use CLT Handbook method for preliminary panel selection (Section 4.2.2)
    - Evaluate system with modal response analysis method (Section 4.3)
  - Typical occupant comfort performance target **NO**
  - Response to human walking? **NO**
    - Outside scope of this guide
Mass Timber Floor Vibration Design Methods and Modeling

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

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Property Modification Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong axis axial</td>
<td>$f_{11} = \frac{E_{A_{11}}}{E_{eff}} \cdot \alpha_{11}^{geom}$</td>
</tr>
<tr>
<td>Weak axis axial</td>
<td>$f_{12} = \frac{E_{A_{12}}}{E_{eff}} \cdot \alpha_{12}^{geom}$</td>
</tr>
<tr>
<td>In-plane shear</td>
<td>$f_{12} = \frac{G_{A_{12}}}{G_{eff}} \cdot \alpha_{12}^{geom}$</td>
</tr>
<tr>
<td>Strong axis flexure</td>
<td>$m_{11} = \frac{E_{I_{11}}}{E_{eff}} \cdot \alpha_{11}^{geom}$</td>
</tr>
<tr>
<td>Weak axis flexure</td>
<td>$m_{22} = \frac{E_{I_{22}}}{E_{eff}} \cdot \alpha_{22}^{geom}$</td>
</tr>
<tr>
<td>Out-of-plane torsion*</td>
<td>$m_{12} = \min(v_{13}, v_{23})$</td>
</tr>
<tr>
<td>Strong axis out-of-plane shear</td>
<td>$v_{13} = \frac{G_{A_{13}}}{G_{eff}} \cdot \alpha_{13}^{geom}$</td>
</tr>
<tr>
<td>Weak axis out-of-plane shear</td>
<td>$v_{23} = \frac{G_{A_{23}}}{G_{eff}} \cdot \alpha_{23}^{geom}$</td>
</tr>
</tbody>
</table>

* 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 5-1: Example floor vibration model in SAP2000

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

\[ a_{\text{real},h,m} = \left( \frac{f_h}{f_m} \right)^2 \frac{F_{h,m} \mu_{r,m} \mu_{e,m} \rho_{h,m}}{m_m} \frac{A_m}{\left(A_m^2 + B_m^2\right)} \]

\[ a_{\text{imag},h,m} = \left( \frac{f_h}{f_m} \right)^2 \frac{F_{h,m} \mu_{r,m} \mu_{e,m} \rho_{h,m}}{m_m} \frac{B_m}{\left(A_m^2 + B_m^2\right)} \]

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

\[ B_m = 2f_h f_m \]

\[ a_{\text{real},h} = \sum_{m=1}^{N} a_{\text{real},h,m} \]

\[ a_{\text{imag},h} = \sum_{m=1}^{N} a_{\text{imag},h,m} \]

\[ a_h = \sqrt{a_{\text{real},h}^2 + a_{\text{imag},h}^2} \]

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

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

\[ \dot{v}_m = \mu_{r,m} \mu_{e,m} \frac{I_{\text{eff,m}}}{m_m} \]

\[ v_m(t) = \dot{v}_m e^{-2\pi f_m t} \sin(2\pi f_m t) \]

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

\[ v_{\text{RMS}} = \sqrt{\frac{1}{T_w} \int_0^{T_w} (v(t))^2 \, dt} \]

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

FIGURE 6-1: Example post-processor resonance response calculations.
Mass Timber Floor Vibration Design Examples
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
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
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

![Diagram of floor vibration analysis](image)

**Mode 7**

\[ f_7 = 16.16 \text{ Hz} \]

**FIGURE 9-3: Isometric view**

**FIGURE 9-5: Shell property/stiffness modification factors**

**FIGURE 9-1: Floor assembly considered in this example**
Thank You

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