Acoustics and Vibration in Mass Timber Structures: Design & Performance

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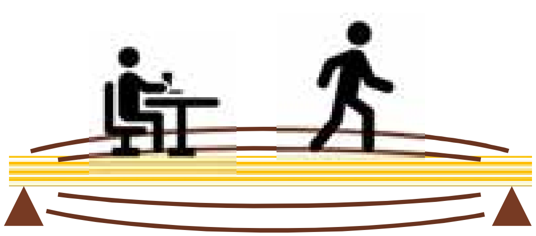
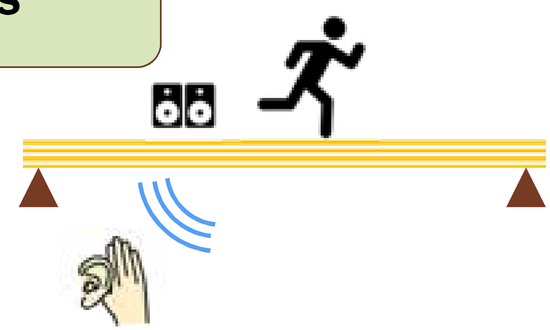
Photo Structurlam

Vibrations vs Acoustics

Structural Vibrations	Acoustic Vibrations
1 Hz – 100 Hz	20 Hz – 15,000 Hz
Transmitted through structure or through ground	Transmitted through air, walls, floors, windows
Physical effects	Audible effects





US Building Code Requirements for Vibration

None

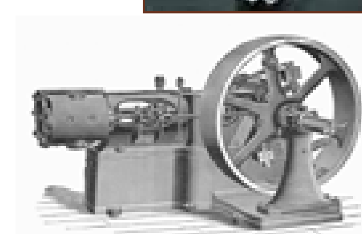
Barely mentioned in IBC, ASCE 7, NDS, etc.

ASCE 7 Commentary Appendix C has some discussion, no requirements

Common Vibration Sources for Buildings

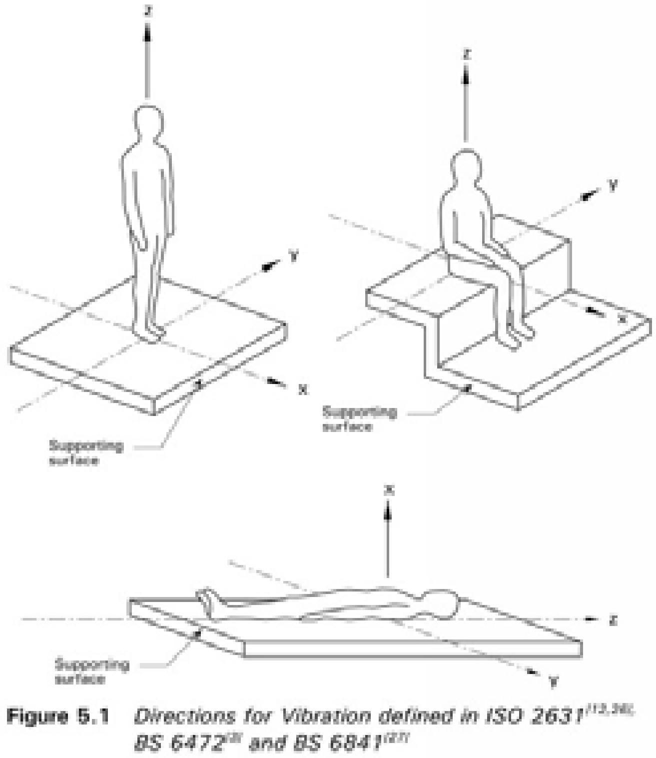
Vibration sources are complex:

- Footfall, running, aerobics, etc.
- Machinery and equipment
- Vehicular traffic, rail traffic, forklifts
- Ground-borne, structure-borne, air-borne
- Steady-state, episodic, periodic
- Harmonic, pulse, random
- Moving, stationary



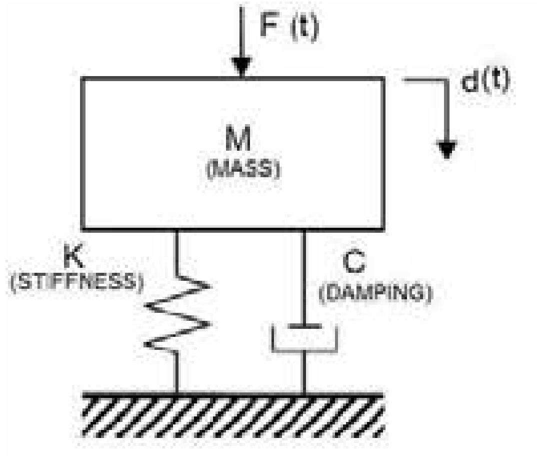
Vibration Sensitivities

- People
  - Sitting, Standing, Laying
- Equipment



Direction of Vibration in ISO 2631

Simple Vibration Dynamics

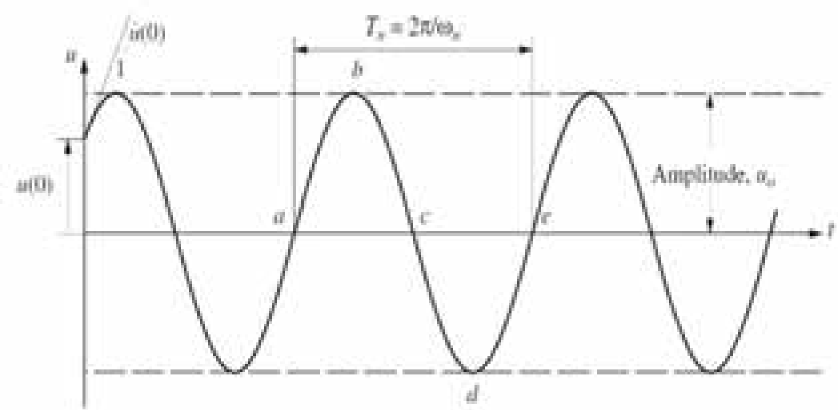


Natural Frequency

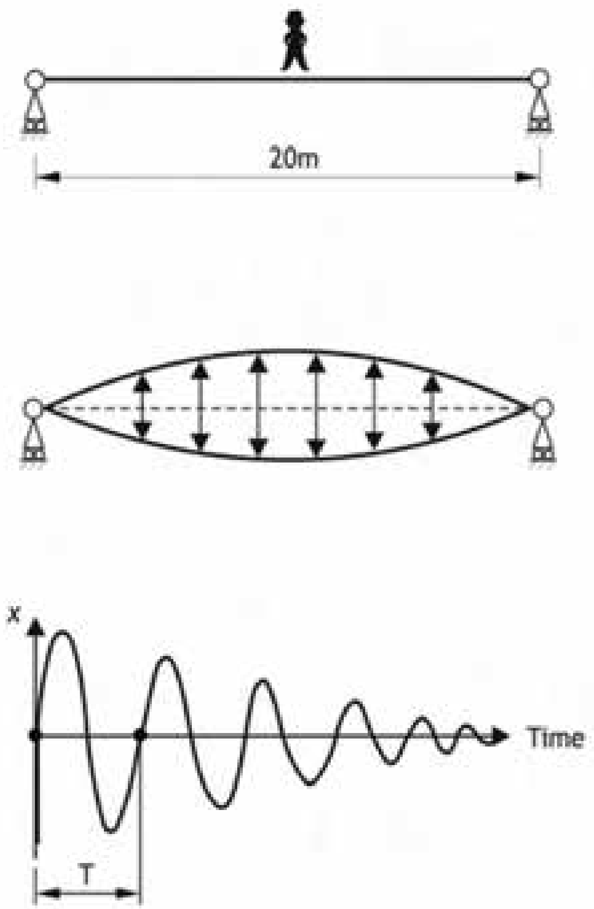
$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

Undamped Free Response

Period T = 1 / f_n Frequency



Vibration of a Simple Beam



(a) A bridge as a simply supported beam

(b) The first mode of vibration

(c) The displacement of mid-span after someone jumps once at mid-span

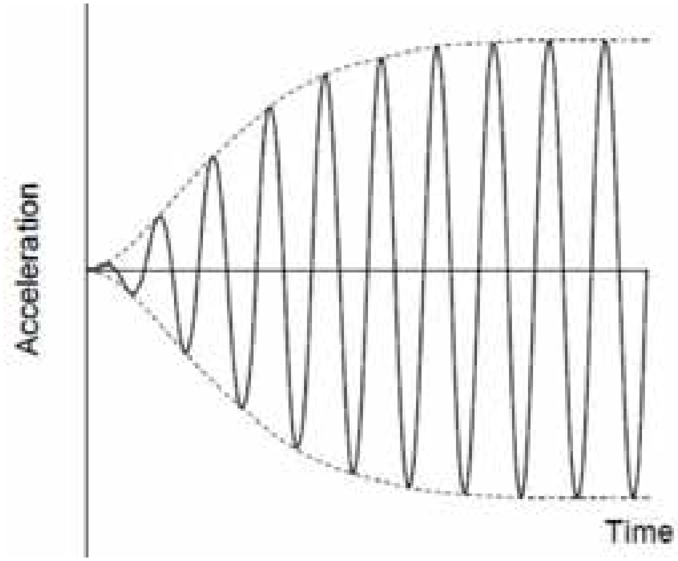
CCIP-016 (2006)

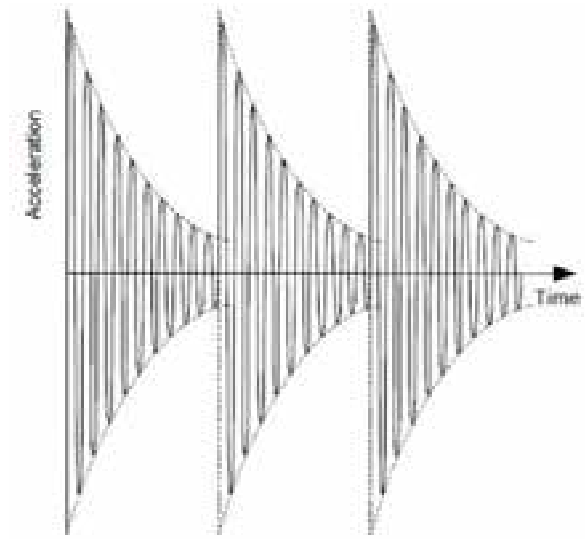
$$f_n = \frac{\pi}{(2L)^2}\sqrt{\frac{EI}{m}}$$

Practical floor frequencies from 5 to 15+ Hz.

Generally the higher the better

Resonant vs Impulsive Response





Excitation Frequency not >> Natural Frequency
Excitation Creates Resonant Build-up of Vibration

<u>Low Frequency Floor</u>

Excitation Frequency >> Natural Frequency
Responses decays out between load cycles

<u>High Frequency Floor</u>

f_n ~< 8 Hz For Walking Excitation f_n ~> 8 Hz

CCIP-016 (2006)

Floor Vibration Concepts: Resonance

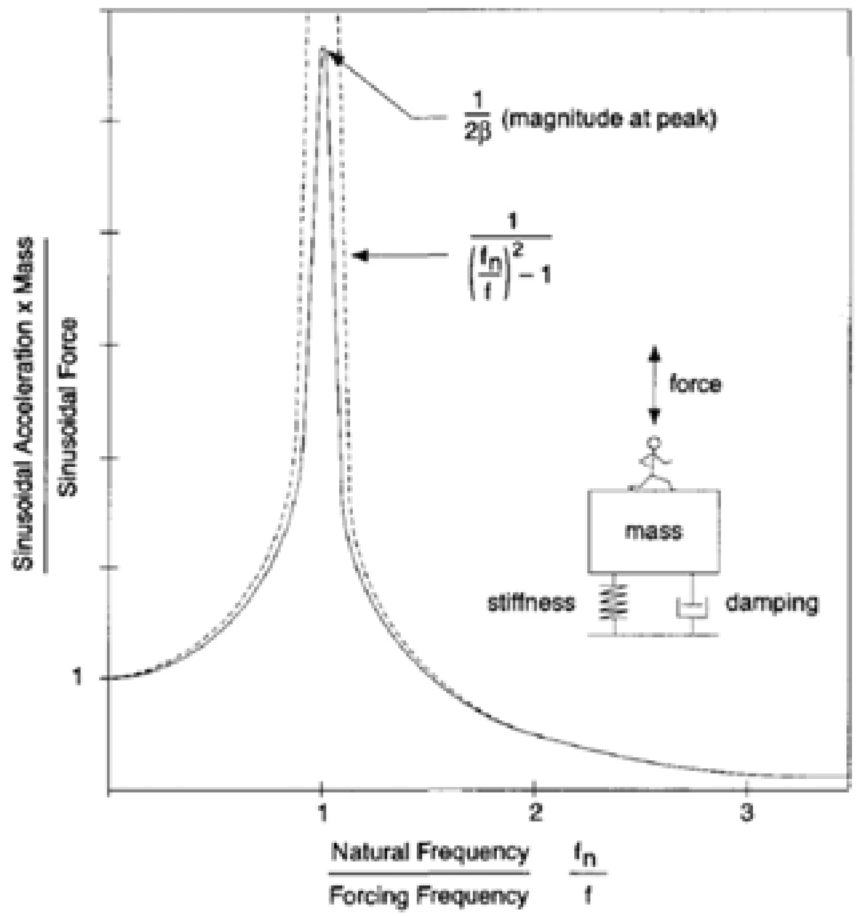


Illustration: Murray et al., 1997

Natural Frequency: f_n

Forcing Frequency: f

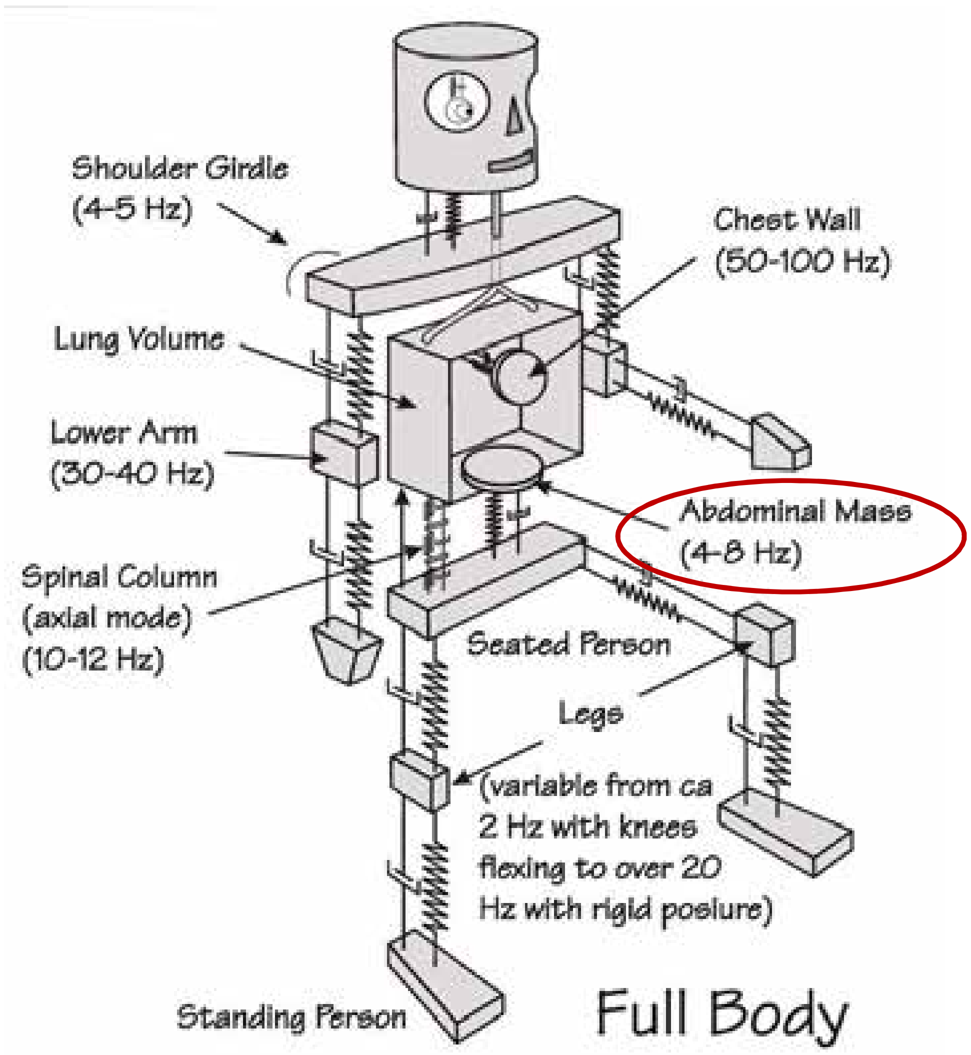


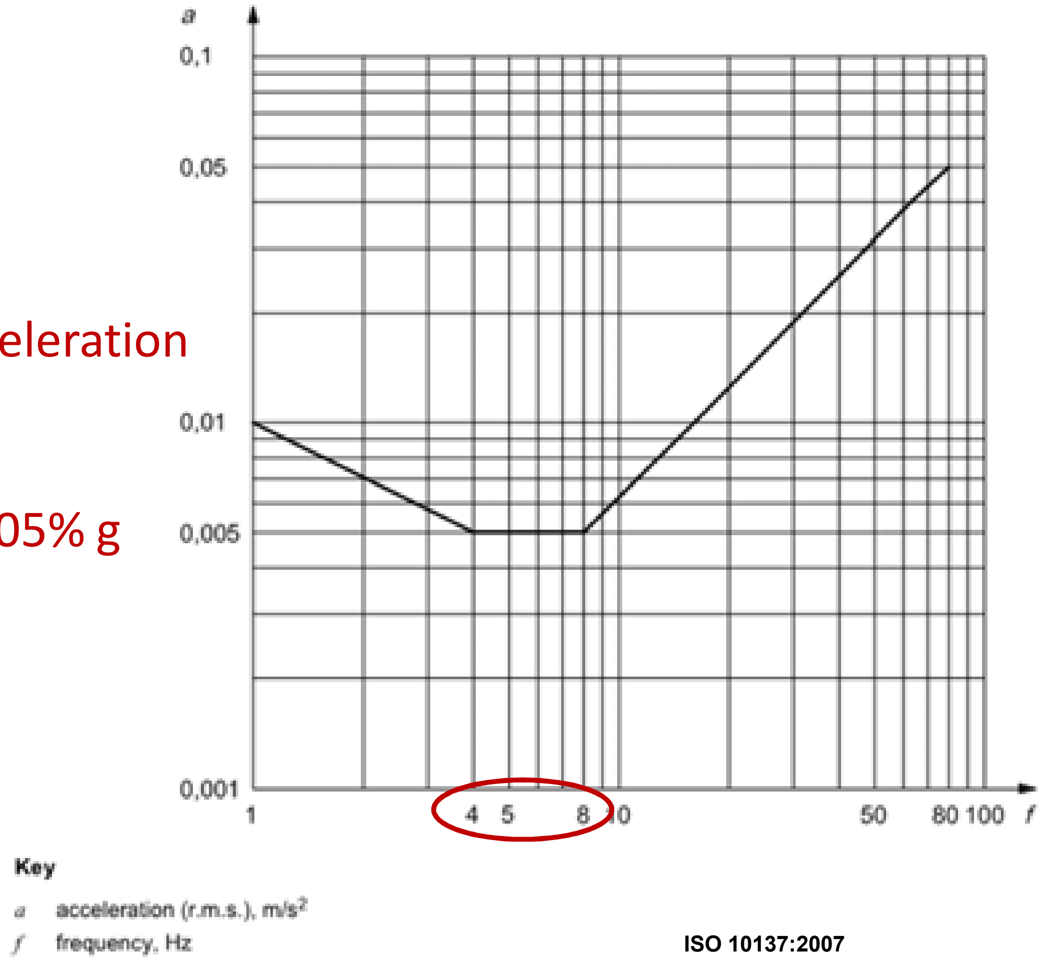
Illustration: Sven-Olof Emanuelsson

Human Body Dynamics

Floor Vibration Criteria – Human Comfort

Acceleration

0.05% g



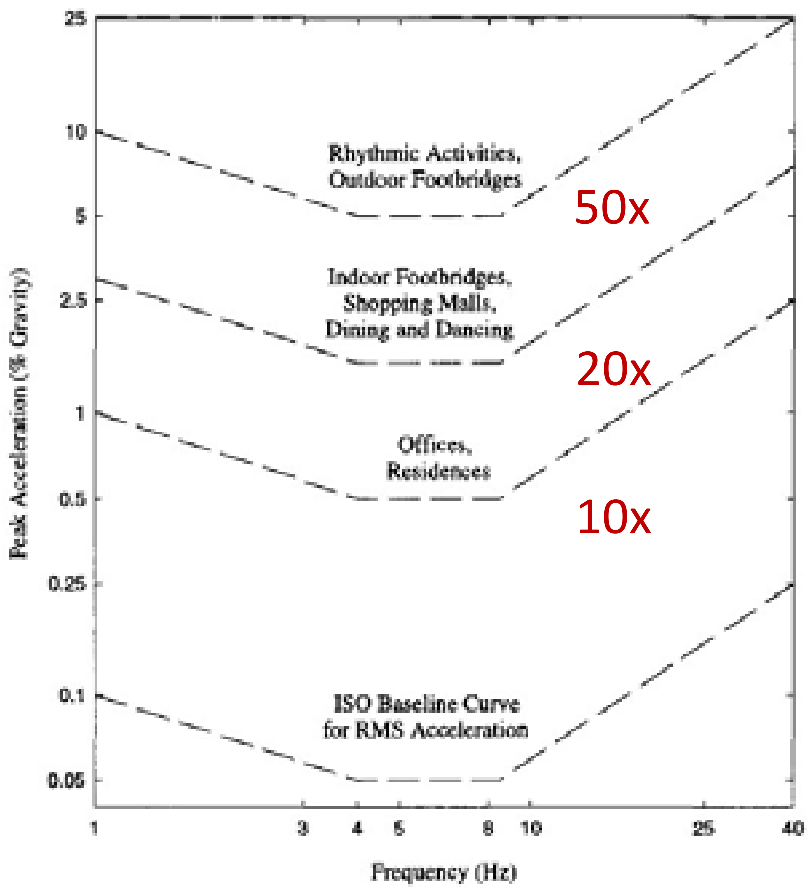
ISO 10137:2007

Limits of Human Perception of Acceleration

~.05% g (vertical) in 4-8 Hz

Floor Vibration Criteria – Human Comfort

Acceleration



0.05% g

Illustration: Murray et al., 1997

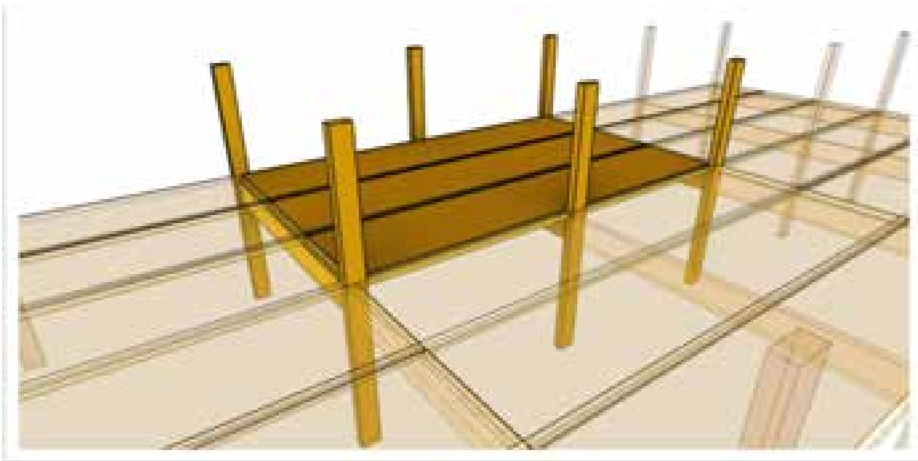
Range of Acceptable Perception of Acceleration

0.5% to 5% g (vertical)

Framing Materials Properties for Vibration

Material	Floor Weight (psf)	Damping	Material Stiffness (10^6 psi)	Material Mass (pcf)	Example Floor System
Concrete	100-150	1-5%	3.2-5.8	120-150	2-way slab on columns
Steel	50-100	0.5-5%	30	490	Concrete on metal deck on purlins and girders
Mass Timber	15-65	1-6%	1.2-1.8	30-40	Beam *or* wall supported
Wood Frame	10-40	2-12%	1.2-2.0	30-40	Wall supported

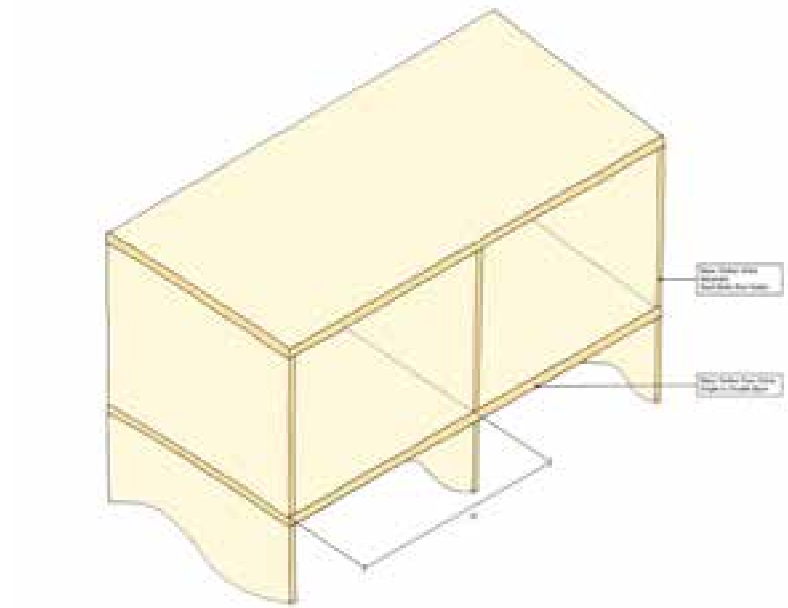
Beam vs Wall Supported Floors



Mass Timber Panels on Grid of Beams.
Frequency of Floor < Frequency of Panel
Vibration of Floor > Vibration of Panel
Vibration Design Depends on Beams

Low Frequency Floor?

Maybe, depends on system



Mass Timber Panels on Bearing Walls

High Frequency Floor?

Yes, for most floor spans < ~22 ft

Vibration Design Methods

Rules of Thumb → Empirical Methods → Simplified Analytical → FEM/Modal → FEM/Time History

$\Delta < L/480$

$f_n > 14$ Hz

Woeste & Dolan — ***Wood Frame***

FPI/CLT Handbook — ***Mass Timber***

AISC Design Guide 11 — ***Steel***

CCIP 016 — ***Concrete***

SCI P354 — ***Steel***

CRSI Design Guide 10 — ***Concrete***

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FPI/CLT Handbook Method

Calculated natural frequency of simple span of bare CLT:

$$f = \frac{2.188}{2L^2}\sqrt{\frac{EI_{app}}{\rho A}}$$

Where:

EI_{app} = apparent stiffness for 1 foot strip, pinned supported, uniformly loaded, simple span (K_s = 11.5) (lb-in^2)

ρ = specific gravity of the CLT

A = the cross section area (thickness x 12 inches) (in^2)

Reference: US CLT Handbook, Chapter 7

FPI/CLT Handbook Method

Limit CLT Floor Span such that

Frequency $f > 9.0$ Hz

Span $L \le \dfrac{1}{12.05} \dfrac{(EI_{app})^{0.293}}{(\rho A)^{0.122}}$

Based on:
- Un-topped CLT
- Single, Simple span
- Bearing wall supports.

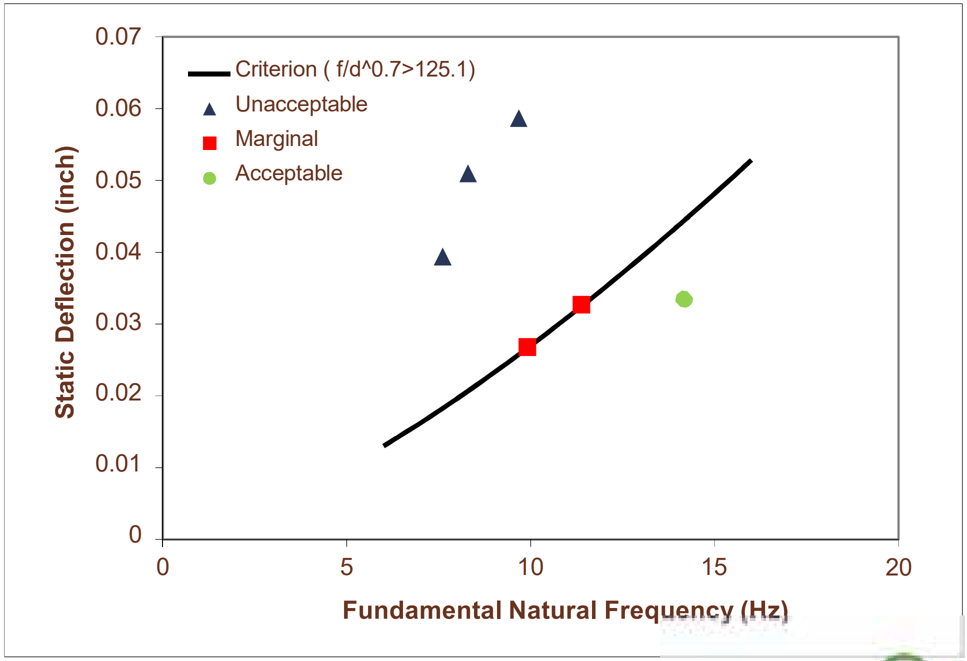
Does not account for:
- Supporting beam flexibility
- Multi-span conditions
- Additional floor mass (topping slab, etc)

Reference: US CLT Handbook, Chapter 7

FPI/CLT Handbook Method

CLT Handbook, Chapter 7 Recommendations

Experimental Verification – Results



Research by Lin Hu, et al. at FPInnovations

FPI/CLT Handbook Method

Calculation of Recommended Span Limit

$$\text{Span } L \leq \frac{1}{12.05}\frac{(EI_{app})^{0.293}}{(\rho A)^{0.122}}$$

Recall: $$EI_{app} = \frac{EI_{eff}}{1+\frac{K_s EI_{eff}}{GA_{eff}L^2}}$$

Using spreadsheet & iterate:

1) Estimate L
2) Calculate EI_{app}
3) Calculate L limit
4) Repeat until converges (quickly)

OR Use values provided by Manufacturers, et al.

Reference: US CLT Handbook, Chapter 7

FPI Span Limit for Basic CLT Grades / Layups

Grade	Layup	Thickness	FPI Span Limit
E1	3ply	4 1/8”	12’ 5”
	5ply	6 7/8”	17’ 4”
	7ply	9 5/8”	21’ 8”
E2	3ply	4 1/8”	12’ 0”
	5ply	6 7/8”	16’ 8”
	7ply	9 5/8”	20’ 10”
E3	3ply	4 1/8”	11’ 7”
	5ply	6 7/8”	16’ 1”
	7ply	9 5/8”	20’ 1”
E4	3ply	4 1/8”	12’ 2”
	5ply	6 7/8”	17’ 0”
	7ply	9 5/8”	21’ 3”

Grade	Layup	Thickness	FPI Span Limit
V1	3ply	4 1/8”	12’ 2”
	5ply	6 7/8”	17’ 0”
	7ply	9 5/8”	21’ 3”
V2	3ply	4 1/8”	11’ 11”
	5ply	6 7/8”	16’ 8”
	7ply	9 5/8”	20’ 10”
V3	3ply	4 1/8”	12’ 0”
	5ply	6 7/8”	16’ 9”
	7ply	9 5/8”	21’ 0”

Approximate FPI Span Limits:

3-ply: 11 to 12 ft

5-ply: 16 to 17 ft

7-ply: 20 to 21 ft

Limitations:

- **Does not account for strength or deflections**
- **Does not account for beam flexibility**
- **Does not account for project specifics**

CLT Handbook In Practice

- Explicitly requires high-frequency floor (>9Hz)
- Is simple to implement
- Experience shown it can produce well performing floors for load bearing wall applications.
- Does not directly consider impact of
  - Multi-span panels (which can help)
  - Flexibility of supports (which can hurt)
  - Topping slabs (which can help or hurt)
  - Selection of level of performance (hospital vs budget hotel)

Vibration Design Methods

Rules of Thumb → Empirical Methods → Simplified Analytical → FEM/Modal → FEM/Time History

- $\Delta < L/480$
- $f_n > 14$ Hz

- Woeste & Dolan — *Wood Frame*
- FPI/CLT Handbook — *Mass Timber*

Model Based Vibration Design

- Mass Timber Design Guide (in development) — *Mass Timber*
- AISC Design Guide 11 — *Steel*
- CCIP 016 — *Concrete*
- SCI P354 — *Steel*
- CRSI Design Guide 10 — *Concrete*

US Mass Timber Vibration Design Guide

USDA Wood Innovations Grant funded project in progress

US Mass Timber Floor Vibration Design Guide

Approximate Outline

1 Introduction
- 1.1 Preface
- 1.2 Scope of this Guide
- 1.3 Terminology
- 1.4 Symbols
- 1.5 Vibration Characteristics of Floor Structures
- 1.6 Building Codes and Standards

2 Understanding Floor Vibration
- 2.1 Structural Response to Footfall Forces
- 2.2 Vibration Background
- 2.3 Methods for Evaluating Vibration
- 2.4 Human Perception of Vibration

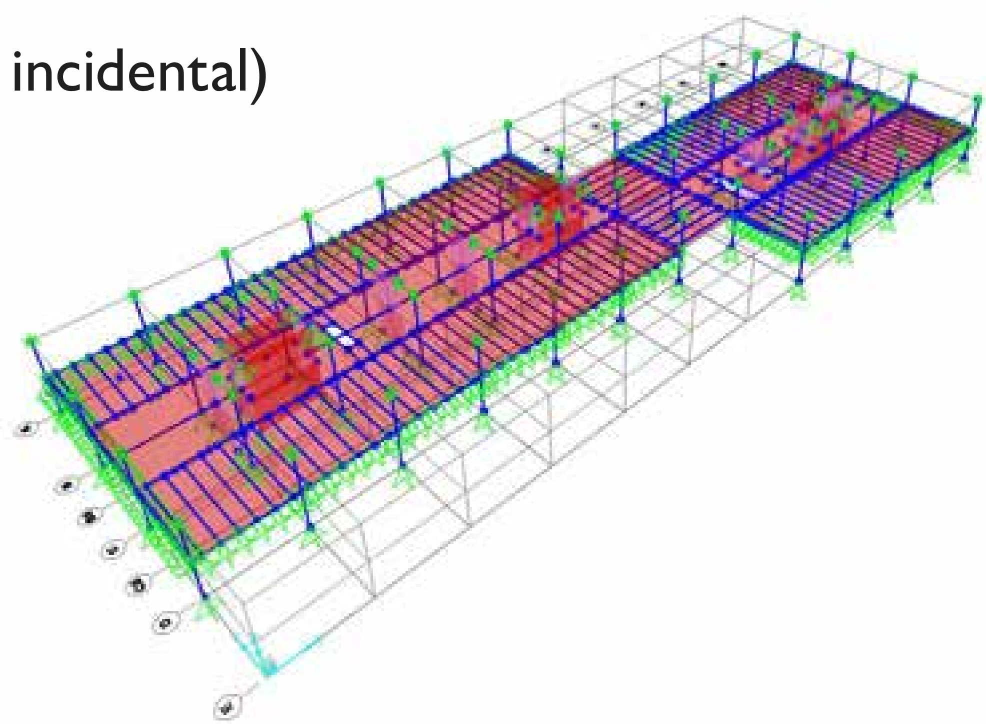
3 Vibration Design Considerations
- 3.1 Floor Loading / Mass
- 3.2 Damping
- 3.3 Component Stiffness
- 3.4 Composite Behavior
- 3.5 Structural and Floor Configurations
- 3.6 Excitation Parameters
- 3.7 Floor Vibration Performance Targets

Guide to be published by WoodWorks in early 2020

Project Team: WoodWorks, KPFF, Aspect, StructureCraft, & Fast+Epp

Model Based Vibration Design Considerations

- Dedicated Vibration Dynamics Model
- Floor Mass including Live Loading
- Component Stiffness
- Composite Behavior (explicit or incidental)
- Damping
- Walking Frequencies
- Boundary Conditions
- Acceptance Criteria



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Questions?

This concludes The American Institute of Architects Continuing Education Systems Course

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