COST Action FP1004
Final Meeting

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Vibration Serviceability Performance of Timber Floors

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Outline

- Background
- Technical Considerations
- Review of design methods
- Accuracy of design calculations
- Conclusions
- Outlook

Background

Structural systems vibrate

- Due to impacts and repetitive loading
- Resulting in motions that must be controlled
- Tend to be prone to intolerable resonance and acceleration levels if light-weight

Technical Considerations

Classification of timber floor systems

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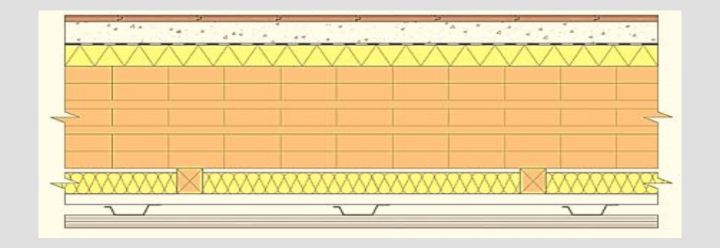


Cross-section normal to span

Technical Considerations

Human perception of floor vibrations

- Aggregate perceptions from audio, visual and motion cues
  - ➡Cues taken relate to two or three sense than just motion
- Laboratory studies often carried out under conditions that deprive observers of cues other than motion
- Under field conditions no cues are blocked from occupants
  - ➡Aggregation of effects

Technical Considerations

Human perception of floor vibrations

Questions for correlating occupant satisfaction with response parameters

1) Are laboratory studies contaminated by the perspective of humans' relationship to perception of motion of floors?

2) Is combining results from laboratory and field studies reliable?

3) Are proposed design criteria based on building occupant perceptions consistent for all types of floors?

Design methods for floor vibrations

Static deflection limitation methods

Limiting max deflection from dead load plus uniformly distributed live load

- Span/360 for floors with sawn lumber joists
- Span/480 or span/600 for floors with engineered timber joists *(APA 2004)*

Alternative: Limiting max deflection under a concentrated load

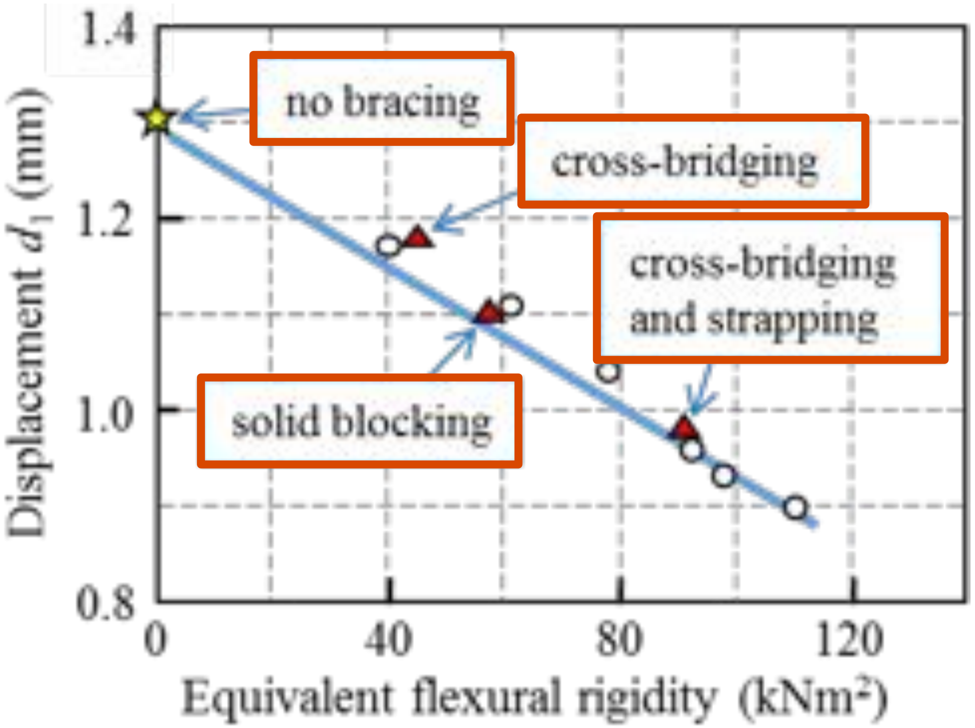
- $d_1 \le 2mm$ for $l < 3$ m, and $d_1 \le \frac{8}{l^{1.3}}$ for $l \ge 3$ m *(APA 2004, IRC 2010)*
- $d_1 \le \frac{2.55}{l^{0.63}}$ for 5.5 m $\le l < 9$ m, and $d_1 \le 0.6mm$ for $l \ge 9$ m for engineered wood joist products *(CWC 1997)*

Simple, hence static deflection-based methods still popular for design

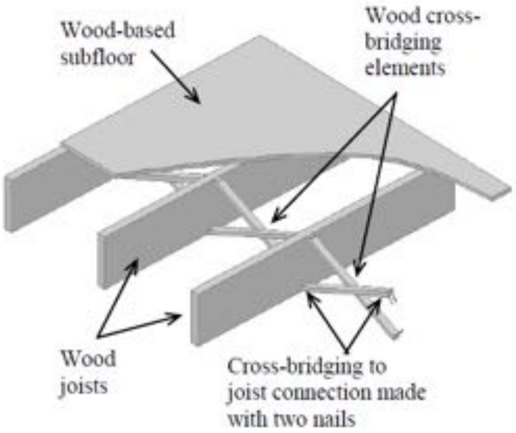
Design methods for floor vibrations

Static deflection limitation methods

Impact of mid-span bracing elements tested (traditional floor) *(Khokhar et al. 2012)*



Strong reduction in deflection

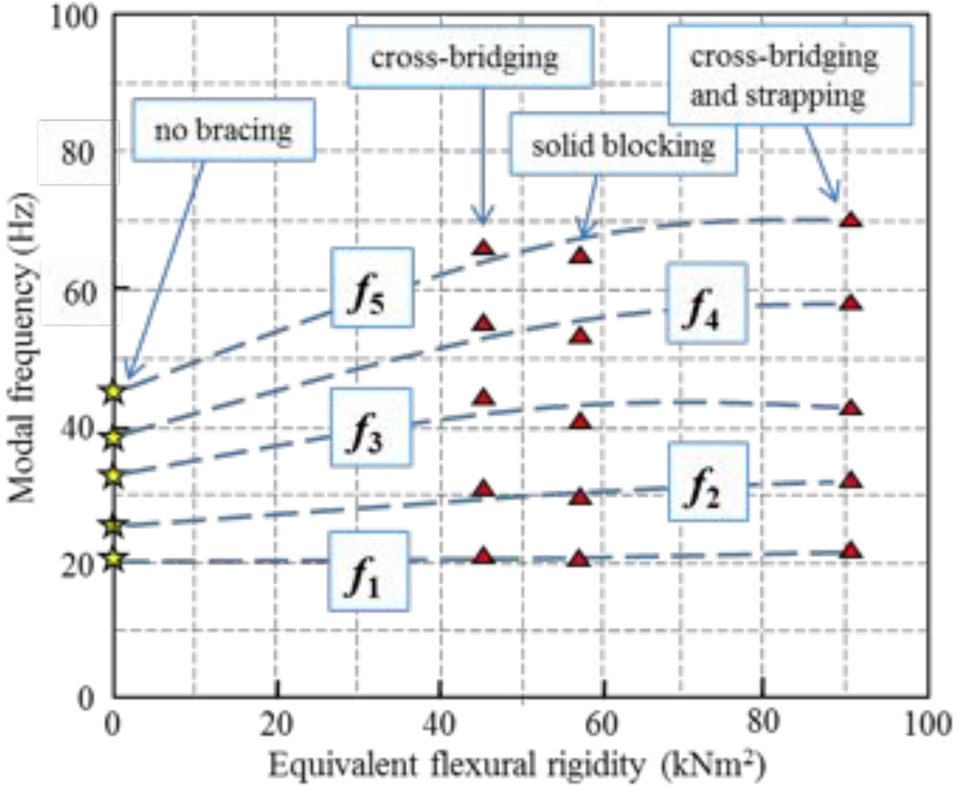


(from Khokhar et al. 2012)

Design methods for floor vibrations

Static deflection limitation methods - (Transverse) flexural stiffness

Impact of mid-span bracing elements tested (traditional floor) *(Khokhar et al. 2012)*



- Little effect on f_1
- Stronger effects on f_2 - f_5
- Augmentation of f_s

Design methods for floor vibrations

Static deflection limitation methods - (Transverse) flexural stiffness

Low transverse stiffness increases the likelihood of:

- Clustering of modal frequencies
- Amplification of acceleration levels at floor surfaces

➡ *Greater chance of disturbing vibrations*

➡ *Not reliably assessable with static deflection checks*

Design methods for floor vibrations

Subjective assessments-based methods

- Opinion surveys on response parameters suggested
  - static deflection correlates with occupant perceptions,
  - occupant satisfaction correlates with fundamental frequencies

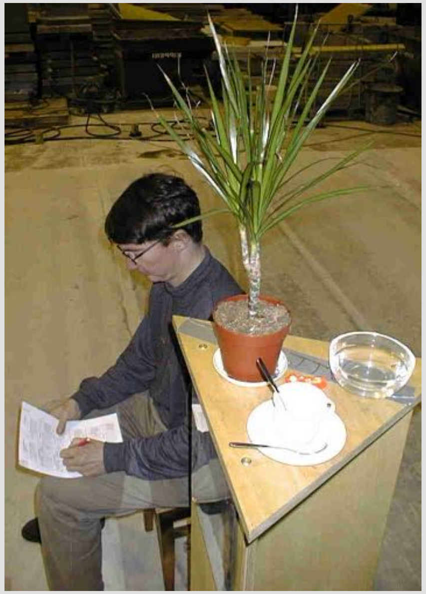
  (Onysko 1985; Ohlsson 1988a, 1988b; Hu 2000).
- Design criteria proposed based on separate/combined application of static deflection and natural frequency *(Hu 2000, Chui 1987, Dolan et al. 1999)*.
- Methods of subjective and empirical nature

Design methods for floor vibrations

Subjective assessments and measurement combination methods

Vibration serviceability method (Toratti and Talja 2006) based on

- Subjective assessment of floor performance
- Physical response characteristics of floors
- 50% laboratory tests, 50% in-situ tests
- Observations made from body sensing and from visual or audio cue impressions of vibrating objects
- Data collected over 10 years


Talja, Toratti and Jarvinen (2002)

Design methods for floor vibrations

Subjective assessments and measurement combination methods

Potential issues identified

- Only deflection and fundamental frequency can be expected to be estimated accurately by engineering formulas.
- Parameters like dynamic displacement/velocity/acceleration have to be obtained by testing.
- FE analysis yielded uncertain results due to issues related to:
  - definition of boundary conditions,
  - estimation of structural damping.

Design methods for floor vibrations

Dynamic response-based methods: TRADA design method

$$f_1 = \frac{\pi}{2l^2}\sqrt{\frac{E_j I_j (n_j - 1)}{\rho_s t b + \rho_j A (n_j - 1)}} > 8 \text{ Hz} \qquad \text{(Eq. 1)}$$

$$A_r = \frac{2000K}{M \pi f_0^2} \leq 0.45 \text{ m/s}^2 \qquad \text{(Eq. 2)}$$

correlating field measurements with occupant opinions *(Chui and Smith, 1990)*

0.30 - 0.45 m/s² according to BS 6472 *(BSI 1984)*

- High-tuning of most energetic components
- Avoids acceleration levels not tolerable to most occupants

Design methods for floor vibrations

Dynamic response-based methods: EC5 Criteria

- Serviceability Limit States (SLS) in Eurocode 5

  Requiring fundamental frequency to be > 8 Hz

  - Limiting unit point load deflection
  - Limiting unit impulse velocity response

    - including a damping ratio for design

$$v = \frac{4(0.4+0.6n_{40})}{mbl+200} \leq b^{(f_1\xi-1)} \text{ [m/Ns}^2\text{]}$$

$$f_1 = \frac{\pi}{2l^2}\sqrt{\frac{EI}{m}} \geq 8 \text{ [Hz]}$$

$$\frac{w}{F} \leq a \text{ [mm/kN]}$$

n_{40} [illegible] *'For a rectangular floor simply supported along all four edges'* (EC5)

- [illegible] supported beam (Toratti and Talja 2006; [illegible] 2010) (Zhang et al. 2013)
  - 0.71 mm/kN *(Jarnero 2014)*

Design methods for floor vibrations

Damping

- Often referred to the first mode of vibration (but higher modes can contribute to unsatisfactory floor vibrations)
- Hard to be determined reliably
  - variation due to measurement procedures
  - variation due to analysing methods
  - variation due to test environment (laboratory/in-situ)

➡ Different proposals for damping ratios exist

Design methods for floor vibrations

Damping

Joisted floors *CLT floors*

Suggestions for damping ratios

- Ohlsson (1988b): 1.0% for normal light-weight floors
  0.8% for floors of large span or weight
- Smith and Chui (1988): 3.0%
- EC5 (2004): 1.0%
- UK NA to EC5 (2004): 2.0%
- CLT Handbook (Canada*): 1.0%
- CLT Handbook (Europe**): 2.5 - 4.0% depending on floor lay-up (considers presence of a person on the floor)

**Hu and Gagnon (2011)* ***Schickhofer et al. (2009)*

Design methods for floor vibrations

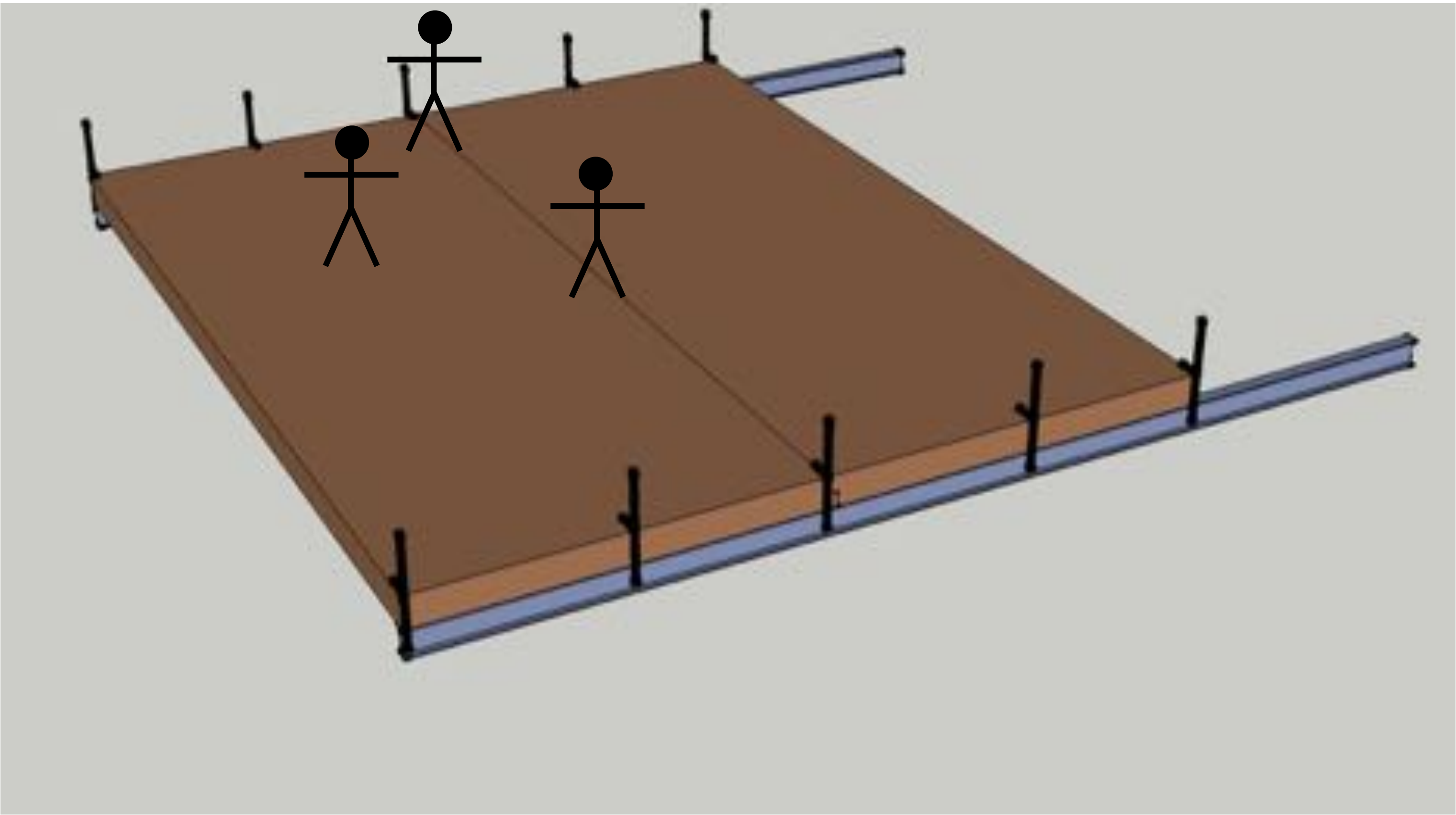
Damping

Recent studies *(Jarnero 2014, 2015)*

- In-situ test: 6.0% for finished floor in building
- Laboratory test: between quarter and half of in-situ test

Design methods for floor vibrations

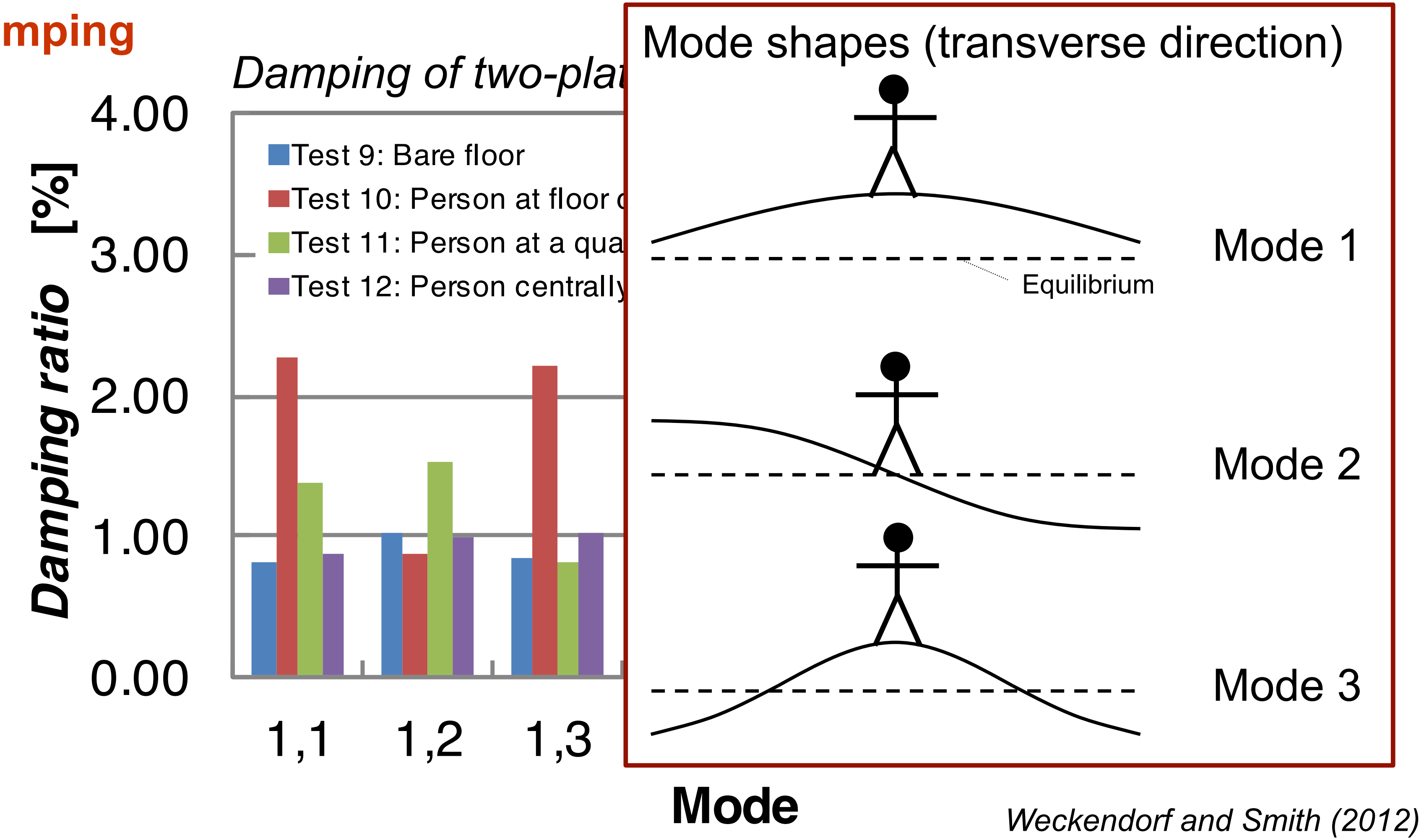
Damping



Weckendorf and Smith (2012)

Design methods for floor vibrations

Damping



Weckendorf and Smith (2012)

Design methods for floor vibrations

Damping

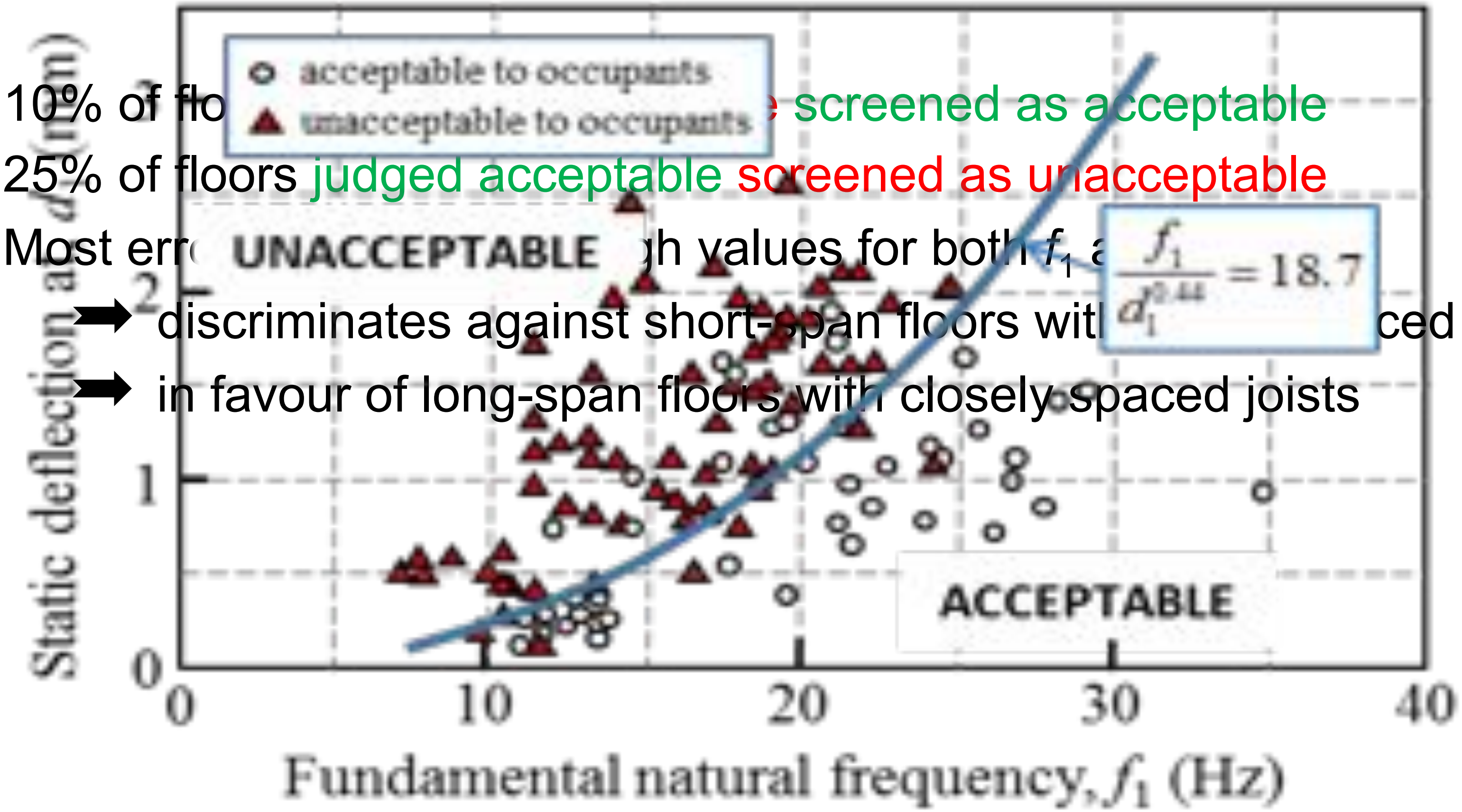
EC5 limit of velocity response:

$$v_d = b_f^{\left(f_1 \boxed{\xi} - 1\right)}$$

- Limit much dependent on damping assumed
- High damping = By-passing velocity criterion

Accuracy of design calculations

Subjective assessment-based design criteria



- 10% of flo screened as acceptable
- 25% of floors judged acceptable screened as unacceptable
- Most err gh values for both f_1 a
  - ➡ discriminates against short-span floors wit ced joists
  - ➡ in favour of long-span floors with closely spaced joists

using data from Hu and Chui (2004)

Accuracy of design calculations

Modal characteristics and time history responses

Floor system	Fundamental modal frequency (f_1) Hz		# of first-order modes up to 40 Hz (n_{40})	
	Eurocode 5	**Experimental**	**Eurocode 5***	**Experimental**
No bracing	21.9	20.8	6	4
Solid blocking	20.7	20.8	3	2
Cross bridging	21.2	20.5	3	2
Cross bridging & strap	21.0	21.8	2	2
One segment	11.5	12.0	1	2
Two jointed segments	11.5	11.5	2	3

Joisted floors
(Khokhar et al. 2012)

CLT floor slabs
(Ussher and Smith 2015)

* rounded

Unreliable predictions

Possible explanations for n_{40}

- EC5 formula developed based on joisted floors, not slab systems
- CLT floor slabs typically have hinge-like joints

➡ tends to overestimate # of modes for light-weight systems

➡ tends to underestimate # of modes for heavy timber systems

Nonetheless equal unreliability for predictions for CLT slabs and joisted floors

Accuracy of design calculations

Modal characteristics and time history responses

Floor	Approach	Response parameters		
		f_1 (Hz)	n_{40}	v (mm/s/Ns)
Chui (1987): Floor 2	Test	22.3	3	--
	Chui model (1987)	21.1	2	--
	Eurocode 5	18.5	3	22.8
	Hu model (1992)	21.6	2	21.1
Hu (1992) Floor 2	Test	11.2	6	--
	Eurocode 5	10.4	5	20.0
	Hu model	10.9	6	11.2
Hu (1992) Floor 4	Test	13.1	5	--
	Eurocode 5	13.9	5	21.8
	Hu model	14.1	5	12.2
Hu (1992) Floor 6	Test	17.1	4	--
	Eurocode 5	24.9	5	26.9
	Hu model	22.0	4	13.9
Ohmart (1968) 1-5B	Test	18.8	--	--
	Ohmart model	16.8	--	--
	Eurocode 5	13.9	3	1.59
	Hu model	17.6	2	0.70
Ohmart (1968) 1-4B	Test	20.8	--	--
	Ohmart model	18.6	--	--
	Eurocode 5	14.8	2	1.41
	Hu model	19.3	2	0.67

Floor	Approach	Response parameters		
		f_1 (Hz)	n_{40}	v (mm/s/Ns)
Ohmart (1968) 1-3B	Test	25.9	--	--
	Ohmart model	22.8	--	--
	Eurocode 5	18.0	2	1.84
	Hu model	23.7	1	0.86
1-2B	Test	35.7	--	--
	Ohmart model	36.1	--	--
	Eurocode 5	30.5	1	1.66
	Hu model	37.5	1	0.95
2-5B	Test	15.6	--	--
	Ohmart model	15.3	--	--
	Eurocode 5	16.7	2	1.96
	Hu model	16.3	3	1.40
2-4B	Test	16.7	--	--
	Ohmart model	15.9	--	--
	Eurocode 5	18.2	2	2.37
	Hu model	16.9	2	1.42
2-3B	Test	18.5	--	--
	Ohmart model	17.7	--	--
	Eurocode 5	23.2	1	1.91
	Hu model	18.8	2	1.49
2-2B	Test	23.8	--	--
	Ohmart model	24.2	--	--
	Eurocode 5	41.7	1	2.69
	Hu model	25.6	1	2.22

Accuracy of design calculations

Modal characteristics and time history responses

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overestimated

Floor	Approach	Response parameters		
		f_1 (Hz)	n_{40}	v (mm/s/Ns)
Ohmart (1968) 1-3B	**Test**	**25.9**	**--**	**--**
	Ohmart model	22.8	--	--
	Eurocode 5	**18.0**	2	1.84
	Hu model	23.7	1	0.86
1-2B	**Test**	**35.7**	--	--
	Ohmart model	36.1	--	--
	Eurocode 5	**30.5**	1	1.66
	Hu model	37.5	1	0.95
2-5B	Test	15.6	--	--
	Ohmart model	15.3	--	--
	Eurocode 5	16.7	2	1.96
				0
2-4B				
	Ohmart model	15.9	--	--
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	Eurocode 5	**41.7**	1	2.69
	Hu model	25.6	1	2.22

underestimated

Accuracy of design calculations

Modal characteristics and time history responses

Floor	Approach	Response parameters		
		f_1 (Hz)	n_{40}	v (mm/s/Ns)

Floor	Approach	Response parameters		
		f_1 (Hz)	n_{40}	v (mm/s/Ns)

Hu model accounts for

- Plate orthotropy
- Bending and shear deformations
- Rotary inertia in joists
- Discontinuities in floor decking

Unit impulse velocity response only reliably estimated using complex numerical models

It has been verified as accurate (Smith et al. 1993)

Conclusions

Existing conundrums

When attempting to reduce complex issues to simplistic solutions:

How to tractably

- Reduce complexity of actual floor loads to levels of representation consistent with simple analysis,
- Represent geometries of floors that exist in practice as ones that can be easily analyzed (e.g. defining spans or support conditions, incorporate openings),
- Uncouple vibration responses of floor substructures from those of supporting and supported substructures,

Conclusions

Existing conundrums

When attempting to reduce complex issues to simplistic solutions:

How to tractably

- Uncouple influences that motion, sound and visual cues have on human perception of floor motion,
- Couple recommendations for best engineering design practices with recommendations for best floor construction practices?

Outlook

- Sophisticated calculation or test procedures are required to obtain comprehensive vibration characteristics of particular floor types.
- Existence of poorly defined boundary conditions and features like soft surfaces complicate even estimation of static deflection or fundamental frequencies *(which are the more easily obtainable).*
- Advanced products, stronger regulations for acoustic and fire, advanced construction, lead to more complex structural floor systems.

➡ *Need for appropriate engineering codes and standards applying to vibration serviceability of modern structures*

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Thank you

Thank you!