

Vibration Response to Human-Induced Dynamic Loading

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University of Warwick

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Aim

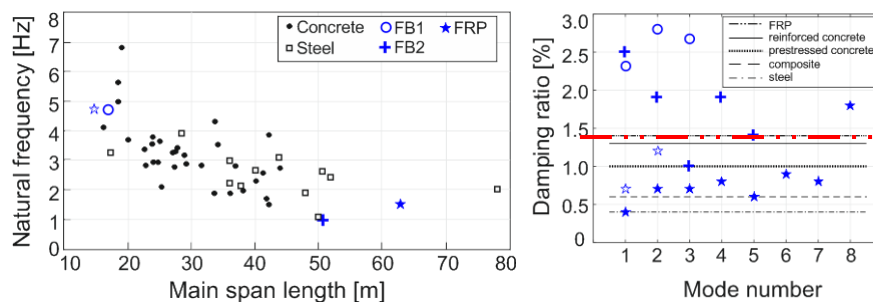
- Establish key differences in dynamics of FRP and non-FRP bridges
- Evaluate vibration performance of a subset (of four) bridges under dynamic actions by people
- Critically evaluate current vibration serviceability modelling

Four structures

- Footbridge 1 (FB1):
-Girder, 16.9m span
V1=4.7Hz, V2=15Hz, V3=28Hz
- FB2:
-Girder, similar span (15m), similar modes
V1=4.8Hz, V2=17.1Hz, T1 ("3x") = 8.3, 9.5 and 13.8Hz
- FB3:
-Simple truss, similar span (14.5m), quite stiff
V1=16.6Hz, V2=28.8Hz, T1=20.7Hz, T2=22.1Hz
- FB4:
-Suspended (steel cables), "big" span (51m), 5 vertical flexural modes up to 5Hz
V1=1.0Hz, V2=1.5Hz, V3=2.2Hz, V4=2.7Hz, V5=3.9Hz
- VERTICAL FLEXURAL modes analysed only!

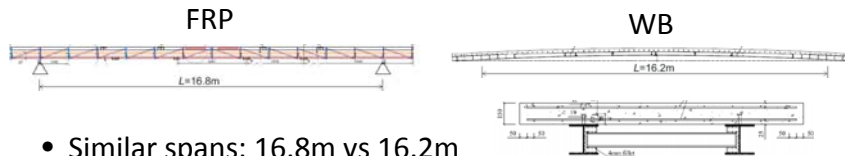
V-vertical flexural mode
T-torsion

Dynamics of FRP structures

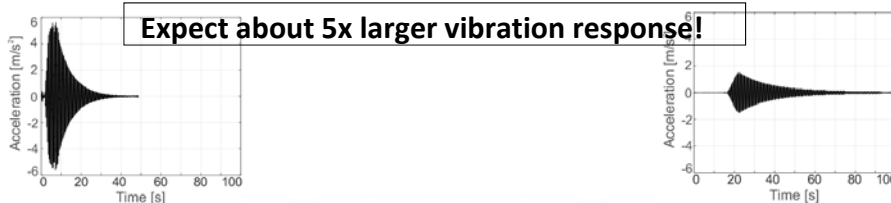


- Compared with non-FRPs: similar frequency, generally higher damping ratio
- **Key difference is the mass!**

Example: FRP Lab vs steel-concrete composite WB



- Similar spans: 16.8m vs 16.2m
- Similar natural frequencies: 2.5Hz vs 2.4Hz
- Higher (~2x) damping ratio for FRP: 0.9% vs 0.45%
- Lower (~11x) modal mass: 700kg vs 7700kg



Mass of FRP structures

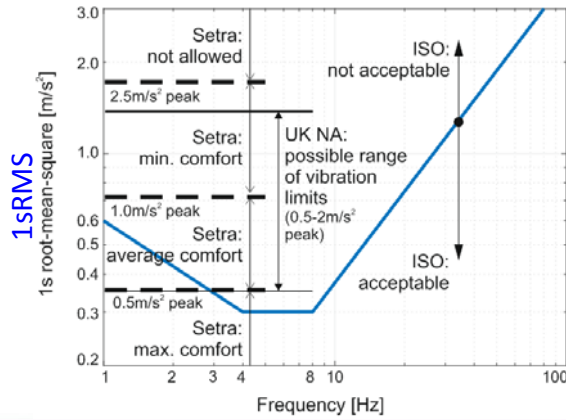
- FB1girder (L=16.9m): $w=0.76\text{m}$, $m'=110\text{kg/m}$, 150kg/m^2
- FB2girder (L=15.0m): $w=2.00\text{m}$, $m'=310\text{kg/m}$, 155kg/m^2
- FB3truss (L=14.5m): $w=2.20\text{m}$, $m'=380\text{kg/m}$, 170kg/m^2
- FB4* suspension (L=51.3m): $w=2.20\text{m}$, $m'=610\text{kg/m}$, 280kg/m^2

*includes concrete ballast, excludes mass of pylons/cables

- We had bridges from 100-600kg/m (90-300kg/m²)
- FRP Lab bridge is 66kg/m (27kg/m²)

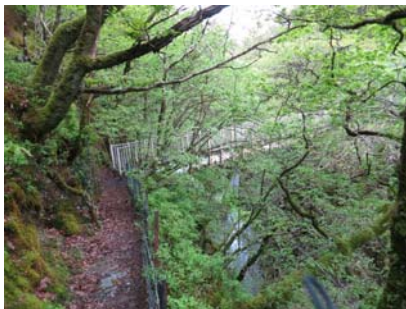
Targeted vibration performance?

- Fundamental natural frequency (vertical flexural) >5Hz?
- Vibration limits? (vertical)

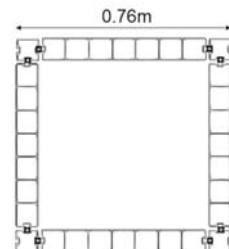


Peak = 1.4 * 1sRMS
acceleration
(for response at a single
frequency)

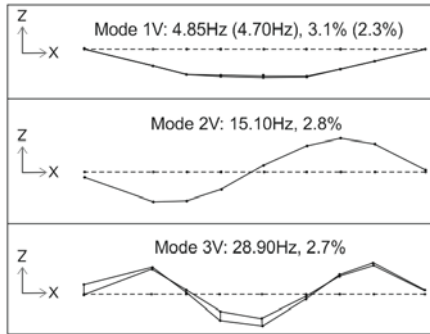
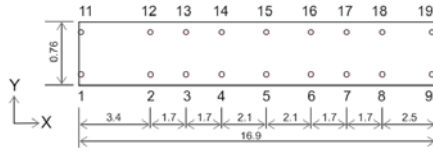
Vib. Performance: FB1, L=16.9m



Made of
ACCS
panels

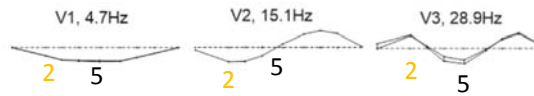


FB1 (L=16.9m)

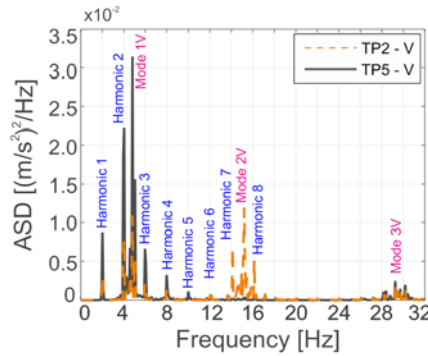
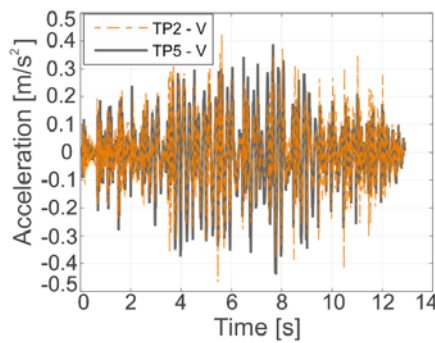


One mode below 5Hz only.

FB1 (L=16.9m)



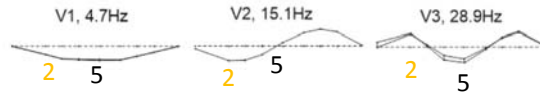
Typical response to walking at 2Hz:



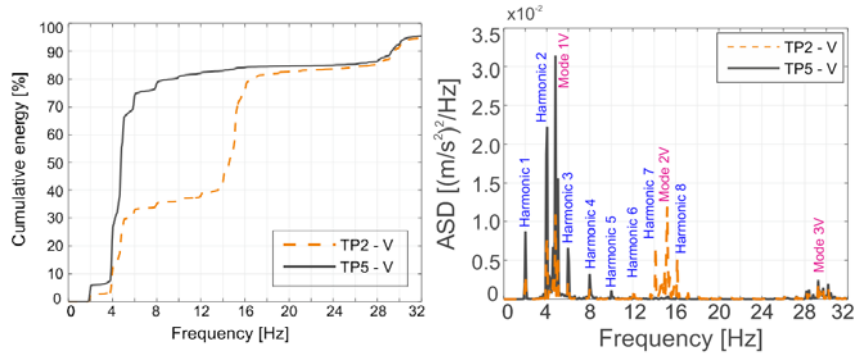
Note visibility of forcing harmonics

TP-test point

FB1 (L=16.9m)

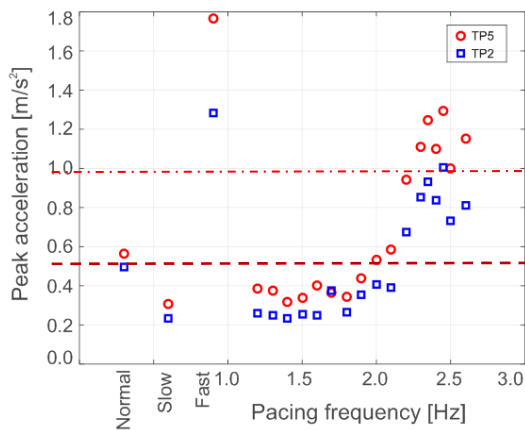
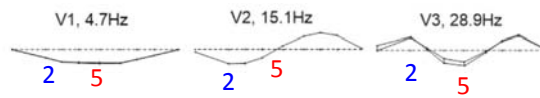


Typical response to walking at 2Hz:



Mode V1 contributes most at TP5, first two modes to TP2
 Individual harmonics add up to 5% (out-of-resonance)

FB1 (L=16.9m)



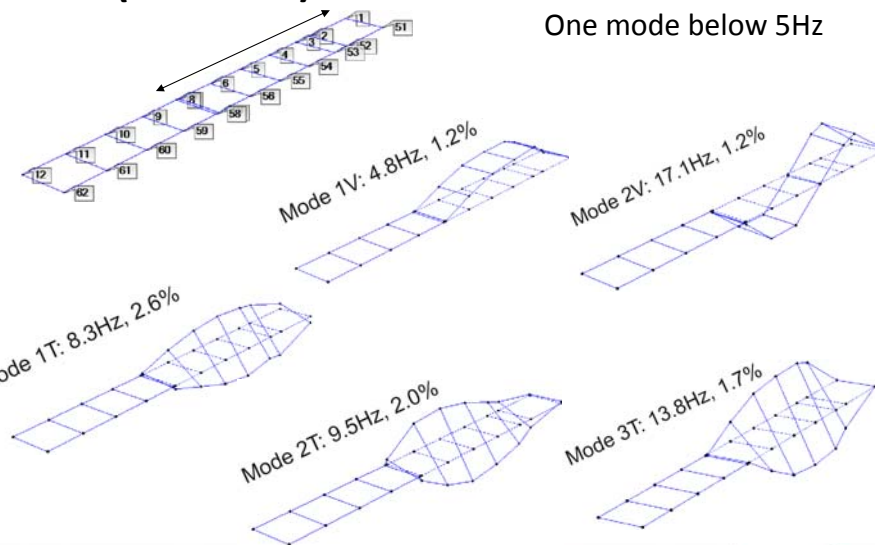
Subjective judgement by the testing team:

This is liveliest bridge we tested!

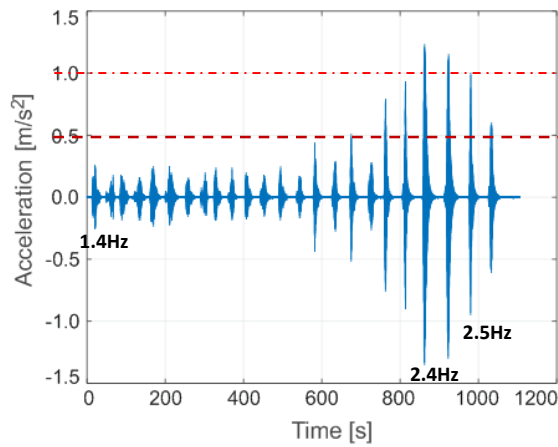
Vib. Performance: FB2, L=15.0m



FB2 (L=15.0m)



FB2 (L=15.0m)

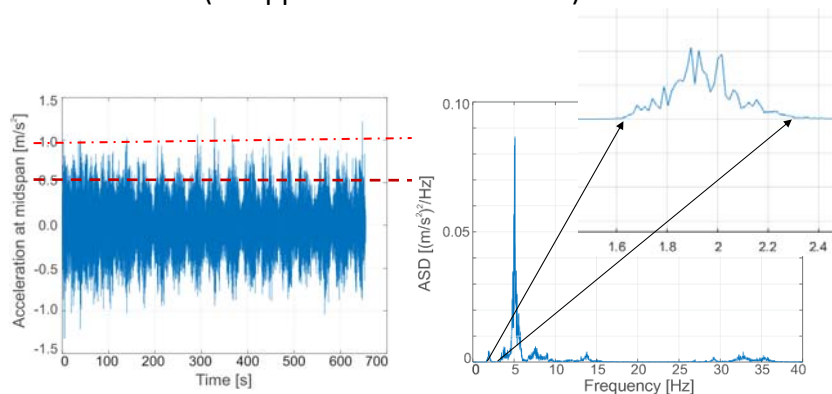


Typical response to walking at 1.4-2.5Hz

As before, Mode V1 contributes most, and vibration is large when close to resonance only!

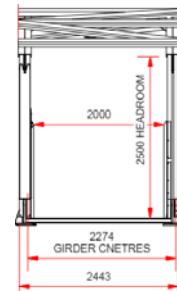
FB2 (L=15.0m): crowd of 15 (0.3ped/m²)

2m wide deck (as opposed to 0.76m in FB1)

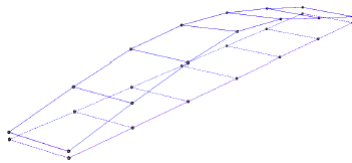


Sustained vibration of this level could attract adverse comments.

Vib. Performance: FB3, L=14.5m



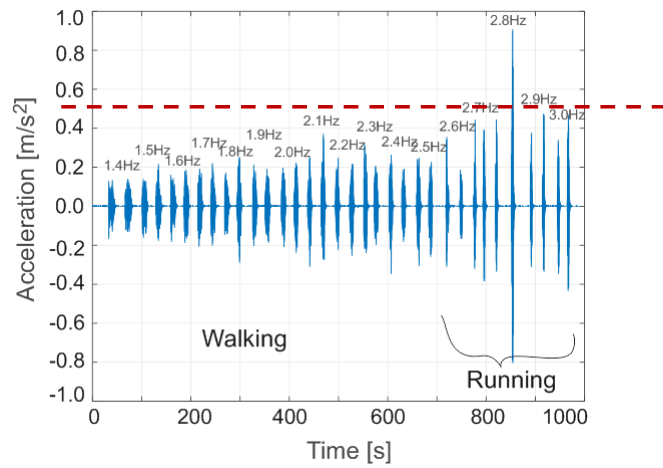
FB3 (L=14.5m)



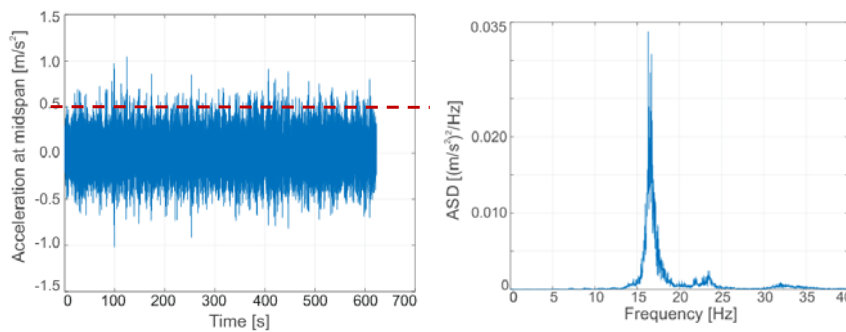
No mode below 5Hz.
Mode at 16.6Hz
dominates the
response.

Vibration Mode	Frequency [Hz]	Damping ratio [%]
Vertical 1	16.6	0.79
Torsion 1	20.7	1.44
Torsion 2	22.1	0.97
Vertical 2	28.8	1.38

FB3 (L=14.5m)

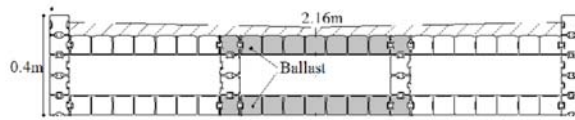


FB3 (L=14.5m): crowd of 15



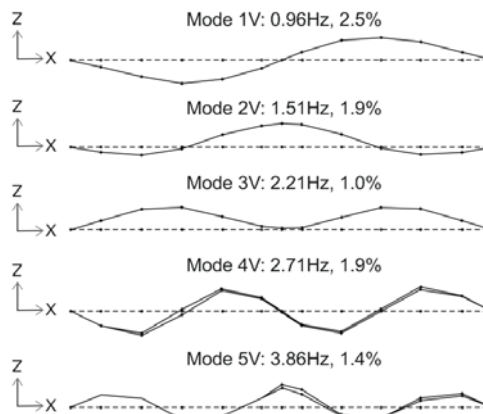
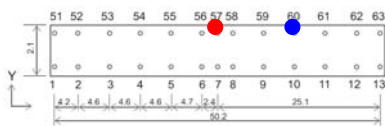
Not very perceptible at 16.6Hz.

Vib. Performance: FB4, L=51.3m



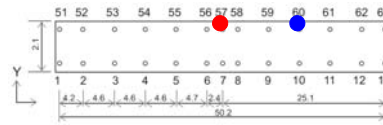
Made of ACCS panels

FB4 (L=51.3m)

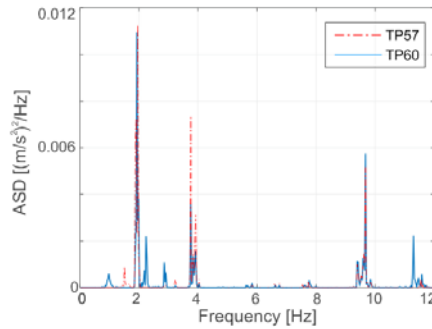
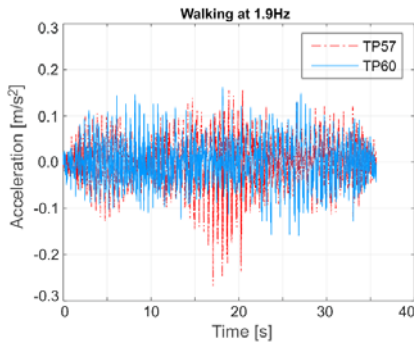


Five modes below 5Hz
(Torsion at 3.2Hz ignored!)

FB4 (L=51.3m)

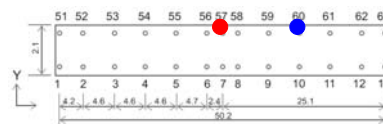


Typical response to walking at 1.9Hz:

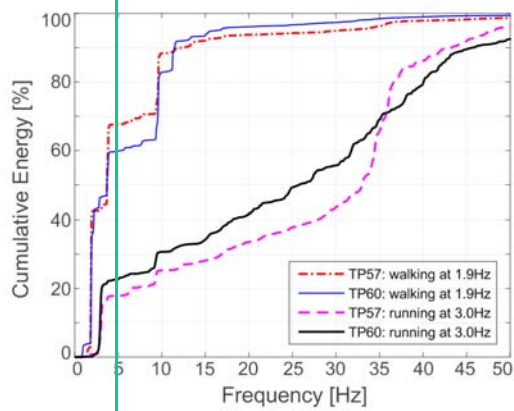


Note contributions above 5Hz.

FB4 (L=51.3m)

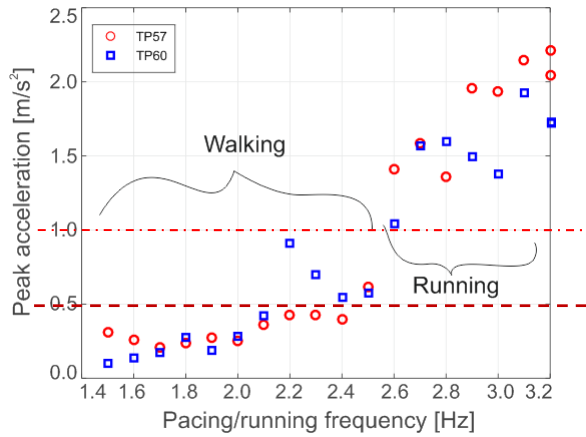


Energy: walking to 1.9Hz vs running at 3.0Hz



Note contributions above 5Hz, especially for running!!!

FB4 (L=51.3m)



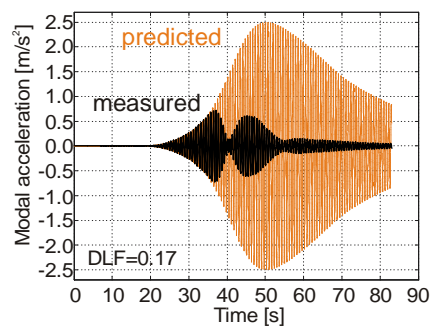
Running can produce large vibrations; modes above 5Hz do respond!

Vib. Performance: conclusion

Generally acceptable; each bridge has its own story:

- for fundamental frequency around 5Hz, liveliness would likely occur under crowds
- suspension bridge responds in a large number of modes

Did not experience the Aberfeldy bridge problem!
But we will have it on the Lab bridge



Vib. Performance: subjective evaluation by 2 members of testing team



FB1



FB2



FB3



FB4

1 – the most responsive
4 – the least responsive

WE CANNOT AGREE!!!

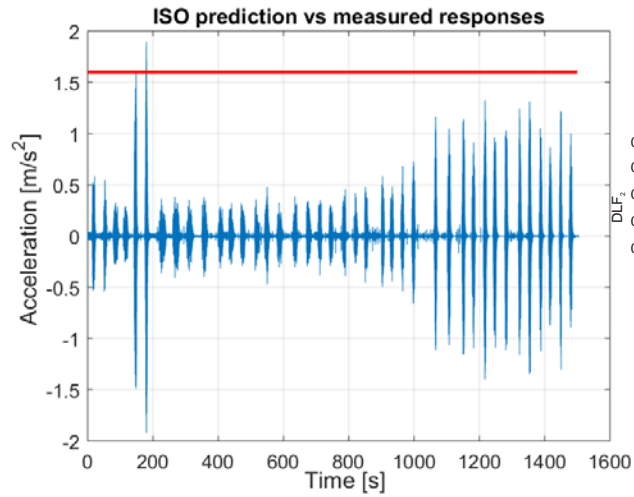
Vibration assessment according to ISO10137*

- Single person model in resonance (moving force, single mode)
- Up to 5 harmonics for walking and up to 3 for running

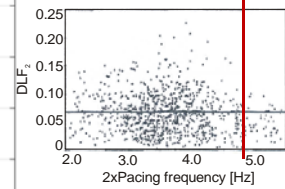
Activity	Harmonic number, n	Common range of forcing frequency, nf Hz	Numerical coefficient for vertical direction, $\alpha_{n,v}$	Numerical coefficient for horizontal direction, $\alpha_{n,h}$
Walking	1	1.2 to 2.4	$0.37(f-1.0)$	0.1
	2	2.4 to 4.8	0.1	
	3	3.6 to 7.2	0.06	
	4 ^a	4.8 to 9.6	0.06	
	5 ^a	6.0 to 12.0	0.06	
Running	1	2 to 4	1.4	0.2
	2	4 to 8	0.4	
	3	6 to 12	0.1	

^a These higher harmonics are rarely significant where human perception is of concern, but may be important for more sensitive building occupancies such as vibration-sensitive instrumentation.

ISO – FB1

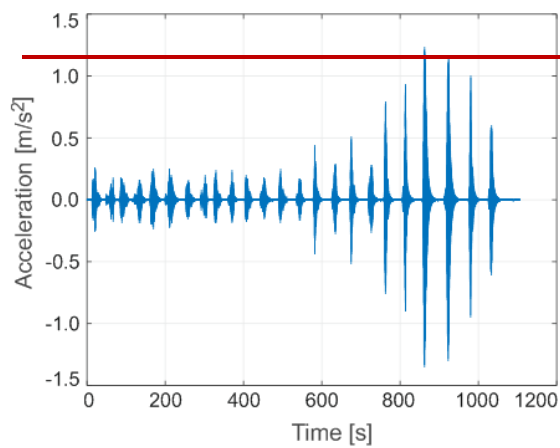


How good is this estimate?

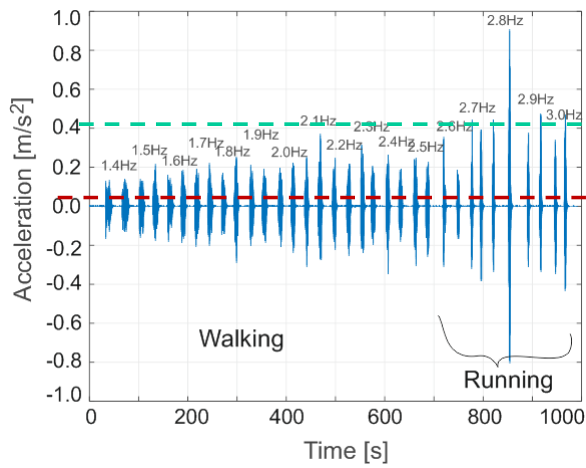


(Kerr, 1998)

ISO – FB2



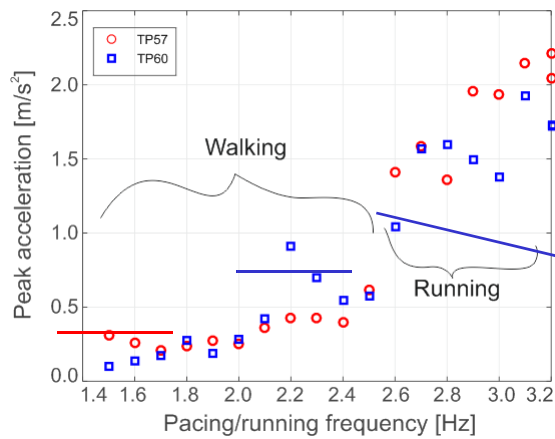
ISO – FB3



Extended ISO model of 8 harmonics (6-8: 3% of person's weight)

ISO model of 5 harmonics

ISO – FB4

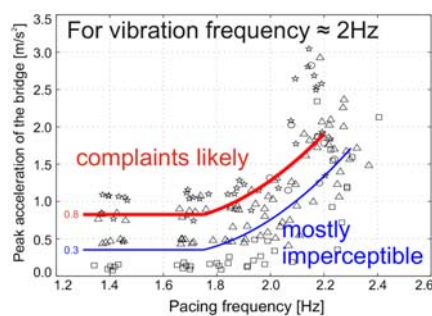


Walking – OK prediction.
But running not.

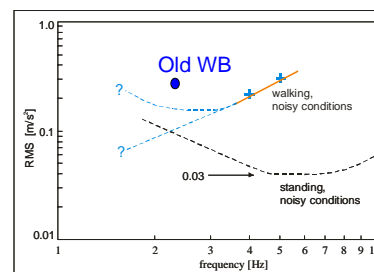
Conclusions

- To predict vibrations, multiple harmonic forcing model can be used provided:
 - all relevant modes are considered (those above 5Hz could be of interest, especially for running), and
 - all relevant harmonics are modelled.
- The simple forcing model can be used even for modes above 10Hz, e.g. FB3 (not so for floor structures).
- To improve vibration assessment, better modelling of vibration limits is required (requires probabilistic approach: people and site specific).

Where are the actual limits?



Note that some standards removed limits recently (low confidence in them?)



Perception – walking posture

Thank you

***Questions and
discussion/comments
on any aspect of the
workshop***

