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
  - $V_1=4.7\,\text{Hz}$, $V_2=15\,\text{Hz}$, $V_3=28\,\text{Hz}$

- **FB2:**
  - Girder, similar span (15m), similar modes
  - $V_1=4.8\,\text{Hz}$, $V_2=17.1\,\text{Hz}$, $T_1=8.3$, $9.5$ and $13.8\,\text{Hz}$

- **FB3:**
  - Simple truss, similar span (14.5m), quite stiff
  - $V_1=16.6\,\text{Hz}$, $V_2=28.8\,\text{Hz}$, $T_1=20.7\,\text{Hz}$, $T_2=22.1\,\text{Hz}$

- **FB4:**
  - Suspended (steel cables), “big” span (51m), 5 vertical flexural modes up to 5Hz
  - $V_1=1.0\,\text{Hz}$, $V_2=1.5\,\text{Hz}$, $V_3=2.2\,\text{Hz}$, $V_4=2.7\,\text{Hz}$, $V_5=3.9\,\text{Hz}$

- VERTICAL FLEXURAL modes analysed only!

---

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

Expect about 5x larger vibration response!

Mass of FRP structures

- FB1_girder (L=16.9m): w=0.76m, m’=110kg/m, 150kg/m²
- FB2_girder (L=15.0m): w=2.00m, m’=310kg/m, 155kg/m²
- FB3_truss (L=14.5m): w=2.20m, m’=380kg/m, 170kg/m²
- FB4_suspension (L=51.3m): w=2.20m, m’=610kg/m, 280kg/m²

*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
One mode below 5Hz only.

Typical response to walking at 2Hz:

Note visibility of forcing harmonics
**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)

Subjective judgement by the testing team:
This is liveliest bridge we tested!
Vib. Performance: FB2, L=15.0m

FB2 (L=15.0m)

One mode below 5Hz

Mode 1: 8.3 Hz, 2.6%
Mode 2: 4.8 Hz, 1.2%
Mode 3: 9.5 Hz, 2.0%
Mode 4: 17.1 Hz, 1.2%
Mode 5: 13.8 Hz, 1.7%
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

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

<table>
<thead>
<tr>
<th>Vibration Mode</th>
<th>Frequency [Hz]</th>
<th>Damping ratio [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical 1</td>
<td>16.6</td>
<td>0.79</td>
</tr>
<tr>
<td>Torsion 1</td>
<td>20.7</td>
<td>1.44</td>
</tr>
<tr>
<td>Torsion 2</td>
<td>22.1</td>
<td>0.97</td>
</tr>
<tr>
<td>Vertical 2</td>
<td>28.8</td>
<td>1.38</td>
</tr>
</tbody>
</table>
FB3 (L=14.5m)

Not very perceptible at 16.6Hz.

FB3 (L=14.5m): crowd of 15

Not very perceptible at 16.6Hz.
Vib. Performance: FB4, L=51.3m

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

FB4 (L=51.3m)
FB4 (L=51.3m)

Typical response to walking at 1.9Hz:

Note contributions above 5Hz.

Energy: walking at 1.9Hz vs running at 3.0Hz

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

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

<table>
<thead>
<tr>
<th>Activity</th>
<th>Harmonic number, n</th>
<th>Common range of forcing frequency, f, Hz</th>
<th>Numerical coefficient for vertical direction, κv</th>
<th>Numerical coefficient for horizontal direction, κh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking</td>
<td>1</td>
<td>1.2 to 2.4</td>
<td>0.37 (−1.0)</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.4 to 4.8</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3.6 to 7.2</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.8 to 9.5</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6.0 to 12.0</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>Running</td>
<td>1</td>
<td>2 to 4</td>
<td>1.4</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4 to 8</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6 to 12</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

* 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?)
Thank you

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