On development of network arch bridges in timber

Department of Structural Engineering
NTNU Norwegian University of Science & Technology
Plan of Presentation

1. Introduction
2. Massive arch bridges
3. Bridge with spoked hangers
4. Scaled laboratory model
5. Bridge structural behaviour
6. Conclusive remarks
7. Future work
Introduction - Arch bridges

Different types of arch bridges

- Bridge part prefabrication limitations:
  - Chemical treatment
  - Transport
  - Max. Element length 30-35m
Arch bridges

Tynset bridge, Norway (photo: K. Bell)

- **Truss-work type arches:**
  - Use of truss connections as mounting connection
  - Connections in truss exposed to axial forces

- **Bridges with vertical hangers:**
  - Vertical hangers – point load in the arch
  - Large moment action in the arch
Sideway stability

• Issues
  - Slender arch ⇒ need sideway support
  - Connection at support ⇒ clamped ?
  - Wind bracing at the top of arches ⇒ force transfer to the support
    (Tynset bridge – no horizontal forces transfer from arch to the deck)
  - Small spans ⇒ prestressed decks carry horizontal forces
  - Small spans ⇒ hangers replaced by rigid portal frames; increased
    transverse stability

Footbridge, Trømso, Norway (photo: SWECO)
Durability issues

- Chemical treatment – environmental friendly?

- Fretheim bridge:
  - Copper cladding on the top faces
  - Ventilated venetian blinds – side faces

Fretheim bridge, Flåm, Norway, (photo: SWECO)

- General durability issues:
  - Keep water out of wooden material (moisture content < 18-20%)
  - Susceptible points: upward surfaces, cracks, around details, in connections
  - Rapid transport of liquid water
  - Covered bridges, possible solution
Inclined hangers

• Traffic loading:
  – Heavy loading in skew position
  – Vertical hangers: loading as point loads; results in large moments in arch
  – Remedies: ‘network arch bridge’ with inclined hangers;
    moment action reduction: roughly one quarter
    vertical displacement reduction: nearly one sixth
Stability of network arch

The two lowermost buckling modes for an arch; hangers in one plane

Network arch with double hangers in spoked wheel configuration
Stability of network arch

Fig. Lateral stiffness from spoked wheel configuration

\[(L + \delta L)^2 = a^2 + R^2 + 2aR \sin(\alpha)\]

Where:
- \(L\) – length of hangers
- \(\delta L\) – elongation
- \(a\) – half distance of hangers fastening points
- \(\alpha\) – angle of rotation
- \(R\) – radius of rotation

\[\varepsilon = \sqrt{1 + \frac{2aR}{a^2 + R^2}} \sin(\alpha) - 1\]

\[\varepsilon = \frac{r}{r^2 + 1}\alpha\]

Where:
- \(r = a/R\) – geometric ratio
Bridge with spoked hangers – concept study

- Conceptual design
  - Combination of network arch and light-weight deck in long timber bridge concept
  - Network arch with inclined hangers
  - Numerical analysis (full and scaled) and experimental model (scale 1:10)
  - Eurocode requirements

- Design requirements
  - Free span of 100m
  - 2 lines of road traffic
  - Width 10m
  - Glulam circular arches
  - Inclined network hangers
  - Spoked hangers configuration
  - Tension tie
  - No wind truss between arches
  - Timber stress laminated deck
Design consideration

- Reduction of moment action in arches
  ⇒ reduction of material needed for the arch
- Relaxation of some hangers ⇒ buckling (both in hangers and in-plane)

*Hanger layout with constant horizontal spacing and angle*

*Hanger layout with radial resultants of pair of hangers*
Design consideration

- Stability

  - Influence of height to width ratio (cross section)
    \[ \text{width (W)} > \text{height (H)} \]
  - Rise to span ratio
    \[ \text{rise = (0.1 - 0.2) span} \]
    (our case: 0.14)
  - Out-of-the-plane support conditions
  - Distance between fastening point of spoked hangers limited to projection of cross section

Cross section of the bridge with spoked hangers
Design for full scale 100 m bridge

- distance between supports: 100 m
- rise of arch: 14 m
- two hinge arches: glulam; GL 32c
- constant cross-section of arches: width-1.8 m, height: 1.2 m
- stress-laminated timber deck: width 10 m, thickness 1 m
- transverse steel beams, IPE 400 (spacing of 4 m)
- hangers in double pairs: in-plane and transverse direction
- hangers: steel rods d=40 mm, fastening axial screws in wood in the same direction as hangers

Fig. Fastening of hangers to the transverse beams (numerical model)
Scaled laboratory model

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Experimental model in scale 1:10
Scaled laboratory model

Support conditions; hinged in the plane of the arch, transversely rigid
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Scaled laboratory model

Fastening of hangers to the wooden arch
Structural behaviour of the bridge

- Parameters for evaluation
  - Stiffness
  - Mass distribution
  - Eigenfrequencies and vibrational modes
  - Acceleration levels
  - Damping characteristics

- Scaled model of the deck
  - Amount of wood material in the timber deck is roughly twice of that in the arches
  - Measured self weight - 560 kg
  - Stress-laminated deck height is 98 mm
  - Pre-stressed to nominal stress of 1.0 MPa
Dyanmic behaviour of the deck

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Measured vibrational modes in vertical direction, experimental model of timber deck

Numerically obtained vibrational modes in vertical direction of timber deck
Dymanic behaviour of the deck

Table  Measured damping, modes and frequencies compared to numerically obtained frequencies

<table>
<thead>
<tr>
<th>Mode</th>
<th>Measured frequency [Hz]</th>
<th>Numerical frequency [Hz]</th>
<th>Measured damping [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical 1</td>
<td>3.0</td>
<td>3.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Vertical 2</td>
<td>8.0</td>
<td>7.5</td>
<td>0.63</td>
</tr>
<tr>
<td>Vertical 3</td>
<td>17.5</td>
<td>16.9</td>
<td>0.95</td>
</tr>
<tr>
<td>Horizontal 1</td>
<td>17.8</td>
<td>18.2</td>
<td>2.4</td>
</tr>
</tbody>
</table>

• Comment
  – stress-laminated deck behaves like a massive wooden block
  ⇒ pre-stressing is sufficient
Vertical vibrations of the deck

<table>
<thead>
<tr>
<th>Mode shapes with deck vibrating in vertical direction</th>
<th>Mode</th>
<th>Experimental model scale (1:10) Frequency [Hz]</th>
<th>Numerical model scale (1:10) Frequency [Hz]</th>
<th>Numerical model full scale (1:1) Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>none</td>
<td>26,5</td>
<td>2,95</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>28,5</td>
<td>24,7</td>
<td>2,27</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>43,5</td>
<td>42,2</td>
<td>3,99</td>
</tr>
</tbody>
</table>

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Anna W. Ostrycharczyk
Horizontal vibrations of the deck

Mode shapes with vibrations mainly in horizontal direction

<table>
<thead>
<tr>
<th>Mode</th>
<th>Numerical model scale 1:10 Frequency [Hz]</th>
<th>Numerical model full scale(1:1) Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.9</td>
<td>1.98</td>
</tr>
<tr>
<td>1a</td>
<td>8.66</td>
<td>0.809</td>
</tr>
<tr>
<td>1b</td>
<td>9.29</td>
<td>0.814</td>
</tr>
</tbody>
</table>

Horizontal deck impact
Measured experimental model 1:10 ; Frequency: 15.9 – 16.4 [Hz]
Horizontal vibrations of the deck

Table Mode shapes and frequencies of vibrations in horizontal direction

<table>
<thead>
<tr>
<th>Mode 2a</th>
<th>Mode 2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Mode 2a Image]</td>
<td>![Mode 2b Image]</td>
</tr>
<tr>
<td>Frequency in numerical model (scale 1:10):</td>
<td>16.83 [Hz]</td>
</tr>
<tr>
<td>Frequency in numerical model (scale 1:1):</td>
<td>1.787 [Hz]</td>
</tr>
<tr>
<td></td>
<td>16.86 [Hz]</td>
</tr>
<tr>
<td></td>
<td>1.802 [Hz]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode 3a</th>
<th>Mode 3b</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Mode 3a Image]</td>
<td>![Mode 3b Image]</td>
</tr>
<tr>
<td>Frequency in numerical model (scale 1:10):</td>
<td>32.18 [Hz]</td>
</tr>
<tr>
<td>Frequency in numerical model (scale 1:1):</td>
<td>3.66 [Hz]</td>
</tr>
<tr>
<td></td>
<td>32.59 [Hz]</td>
</tr>
<tr>
<td></td>
<td>3.67 [Hz]</td>
</tr>
</tbody>
</table>
Conclusive remarks

• Network arch bridges are
  – Competitive to other type of timber bridges
  – Very stiff in the plane of the arches
  – It is possible to use this concept to build long bridges without the need for truss-work for wind forces or stability, by using hangers in a spoked configuration
  – Reduction of moment action in arches due to better load distribution

• Acknowledgements
  – This work has been made possible by a project grant gratefully received from The Research Council of Norway (208052) and financial and technical support from The Association of Norwegian Glulam Producers, Skogtiltaksfondet and Norwegian Public Road Authorities.
Future work – durable timber bridges

Norway:
- 16 000 existing bridges
- 400 in planning/construction
- 300 timber bridges after 1996

Timber bridges:
- Crossing of roads and rivers
- Full traffic load or pedestrian
- Wood: 1000 m³ / bridge

Future:
- Existing bridges need replacement or renovation
- Less maintenance costs
- Less environmental costs
- Minimum closing time
- Most spans: 10 – 120 m
- Considerable market potential for timber bridges
**Introduction**

**Massive arch bridges**

**Bridge with spoked hangers**

**Scaled laboratory model**

**Bridge structural behaviour**

**Conclusive remarks**

**Future work**

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**Durable timber bridges**

*Tynset bridge, Norway (photo: K. A. Malo)*

**To-day:**
- Free span < 80 m
- Many connections
- Preservatives
- Wood or concrete deck
- Labor - Wood consumption?
- No tool for evaluation of durability

**Future - timber bridges ?**
- Most span. 10 – 150 m ?
- No toxic preservatives?
- Life time: > 100 years
- Low maintenance costs
- Documented environmental impact
- Quick installation on site
Durable timber bridges

- Bridge design:
  - Safety
  - Serviceability
  - Aesthetics
  - Economy
  - Durability

- Distribution of moisture and temperature in wooden bridge members

- Moisture traps?

- Performance model to evaluate durability

- Design concepts for short and long spans for durability

- Cover lacking info (fatigue, durability classification)

- Input to EN 1995-2 Timber Bridges

- Output to architects, designers, consultants, authorities

Fig. Performance model for durability
Thank you for your attention.