On development of network arch bridges in timber

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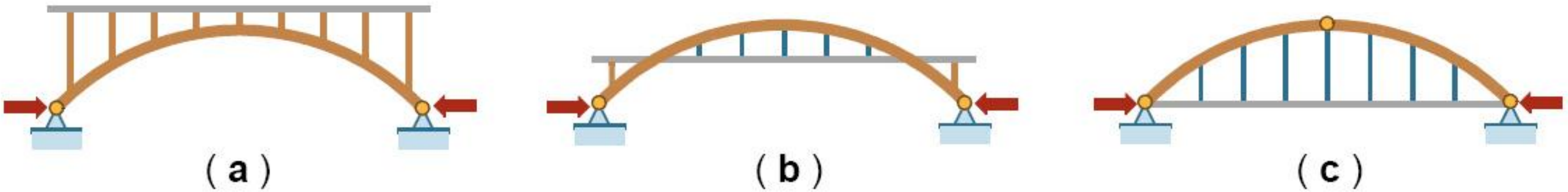
Plan of Presentation

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

Footbridge, Trømso, Norway (photo: SWECO)

Durability issues

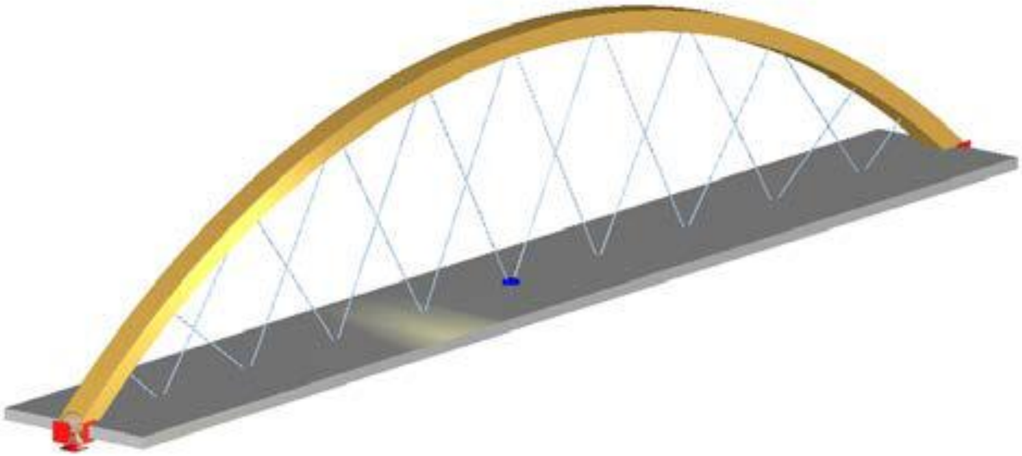
– Chemical treatment – environmental friendly?

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

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

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

Massive arch bridges – Inclined hangers



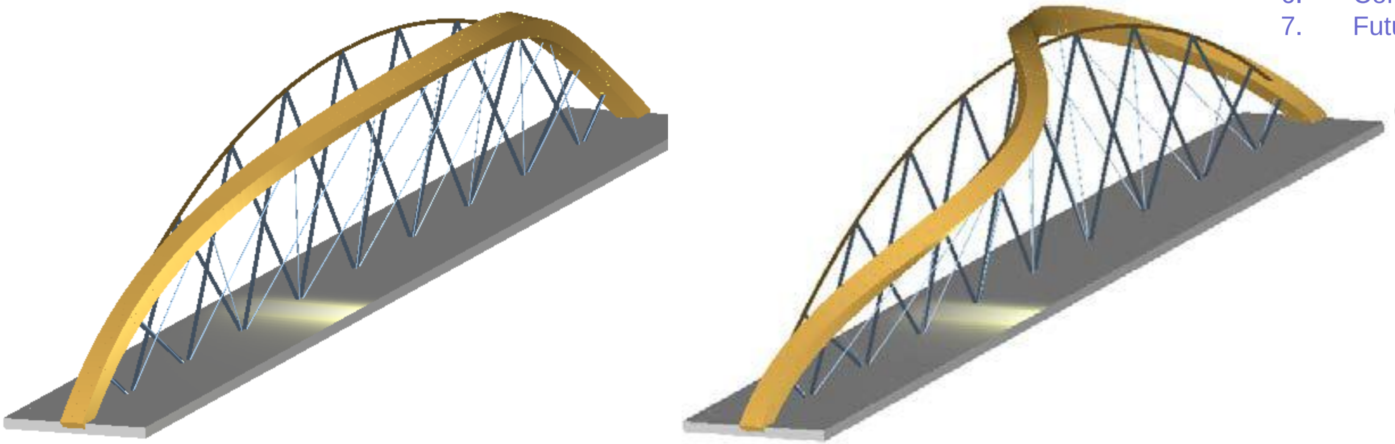
Inclined hangers

- 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;

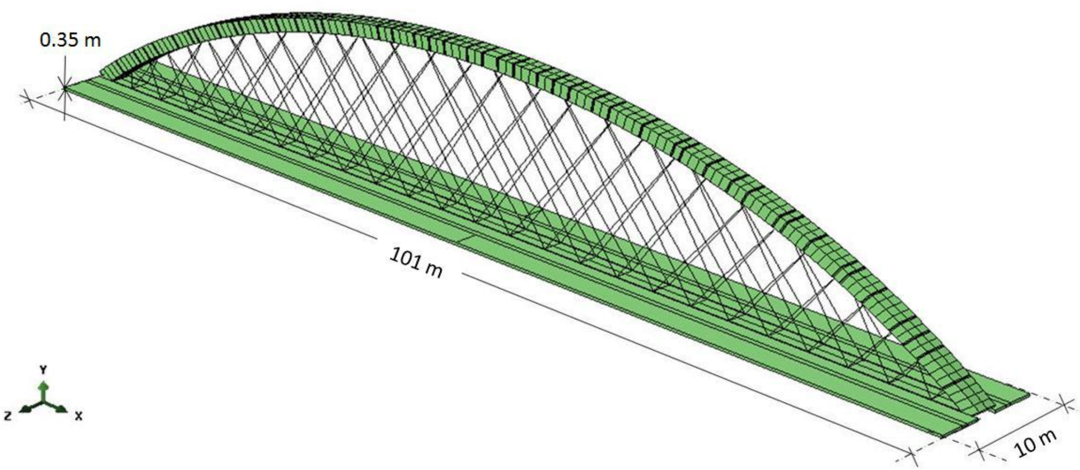
    moment action reduction: roughly one quarter

    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

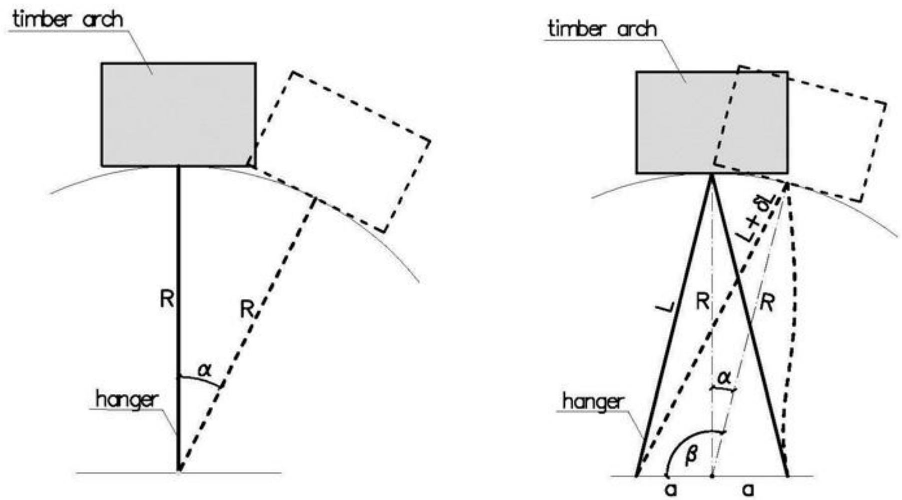


Fig. Lateral stiffness from spoked wheel configuration

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

Where:

- L – length of hangers
- δL – elongation
- a – half distance of hangers fastening points
- α – angle of rotation
- R – radius of rotation

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

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

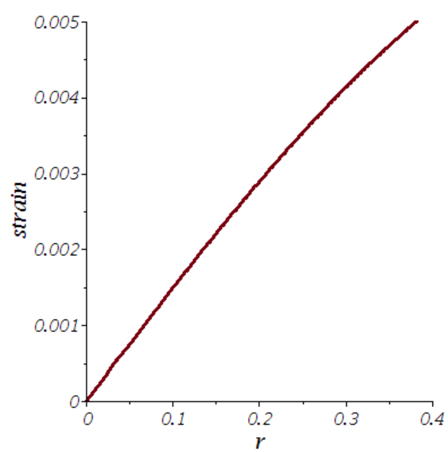


Fig. Strain in hanger

Where:

$r = a/R$ – geometric ratio

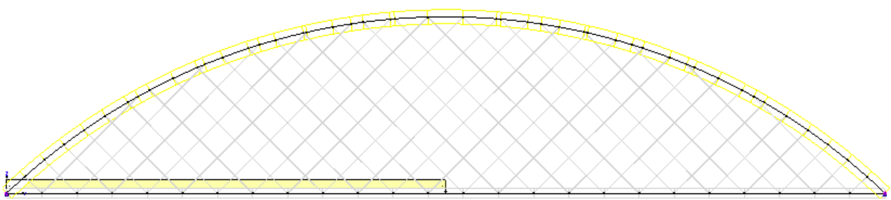
Bridge with spoked hangers – concept study

- 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

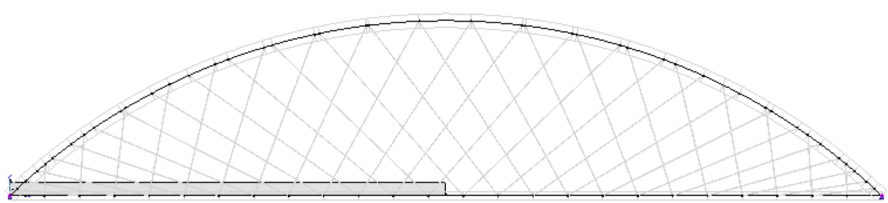
- Design requirements
  - Free span of 100m
  - 2 lines of road traffic
  - Width 10m
  - Glulam circular arches
  - Inclined network hangers
  - Spoked hangers configuration
  - Tension tie
  - No wind truss between arches
  - Timber stress laminated deck

Design consideration

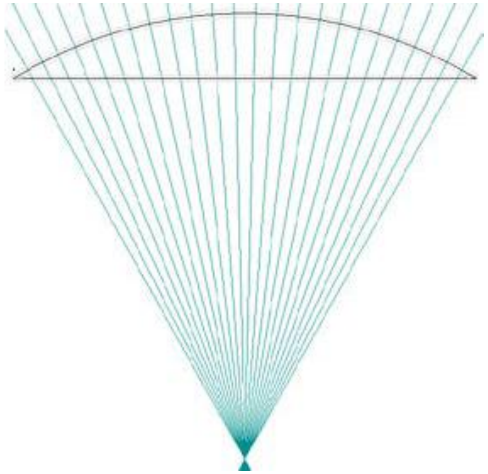
– Reduction of moment action in arches
  $\Longrightarrow$ reduction of material needed for the arch
– Relaxation of some hangers $\Longrightarrow$ buckling (both in hangers and in-plane)



Hanger layout with constant horizontal spacing and angle

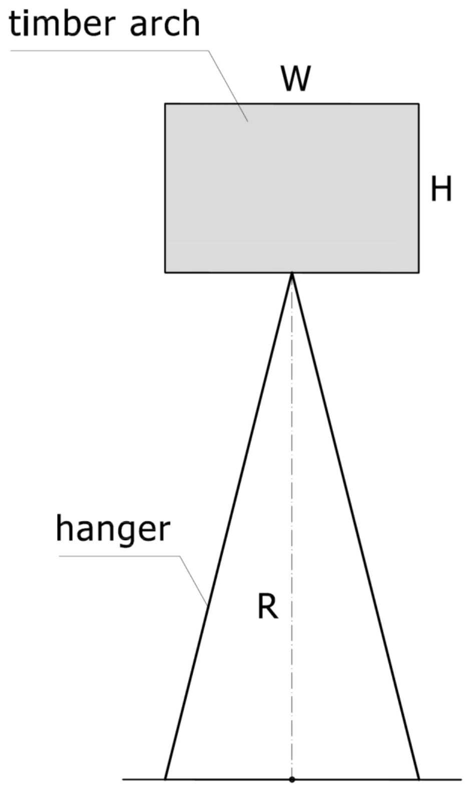


Hanger layout with radial resultants of pair of hangers



Design consideration

- Stability
  - Influence of height to width ratio (cross section)
    $\Longrightarrow$ width (W) > height (H)
  - Rise to span ratio
    $\Longrightarrow$ 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

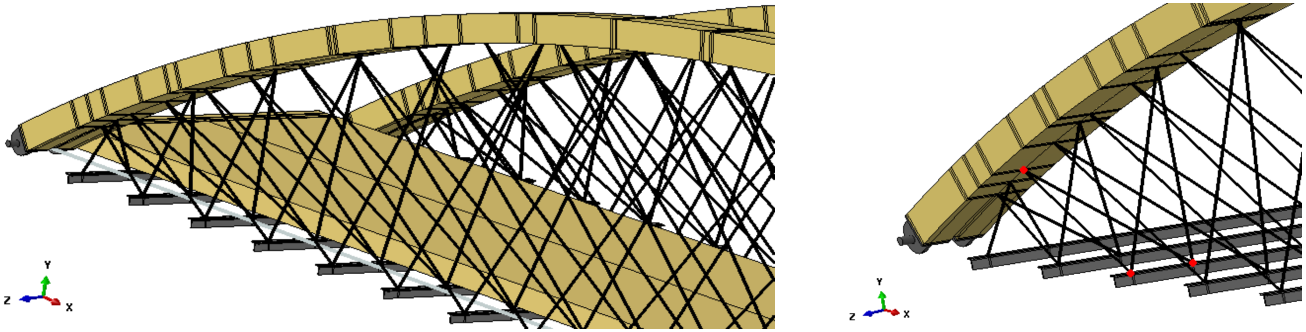


Fig. Fastening of hangers to the transvers beams (numerical model)

- 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

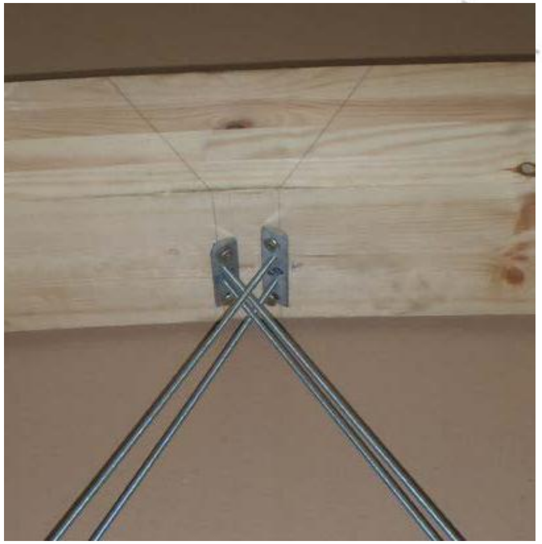
Scaled laboratory model

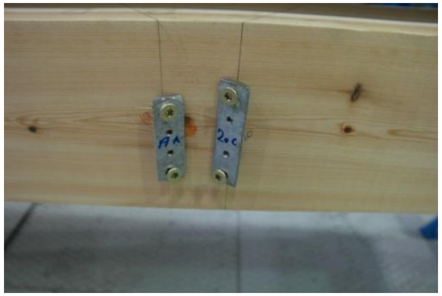
Experimental model in scale 1:10

Scaled laboratory model

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

Scaled laboratory model





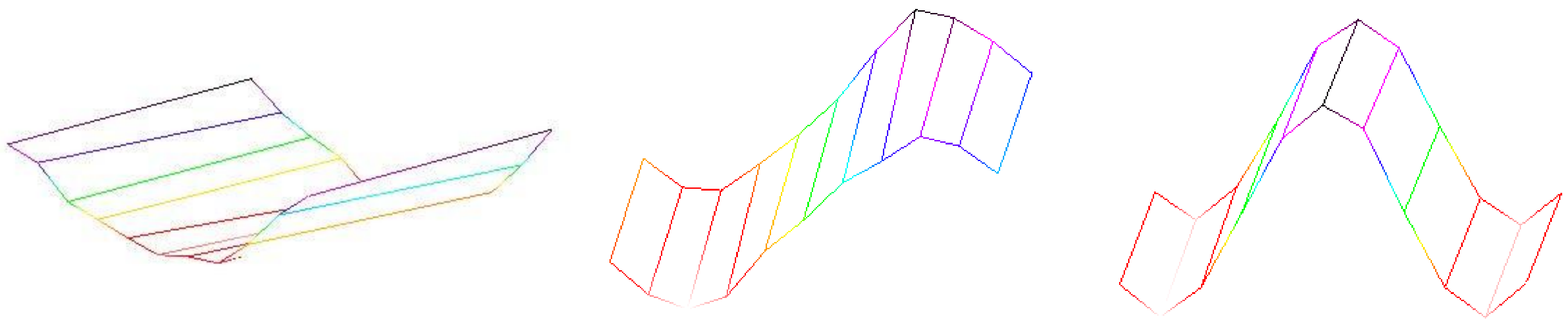
Fastening of hangers to the wooden arch

Structural behaviour of the bridge

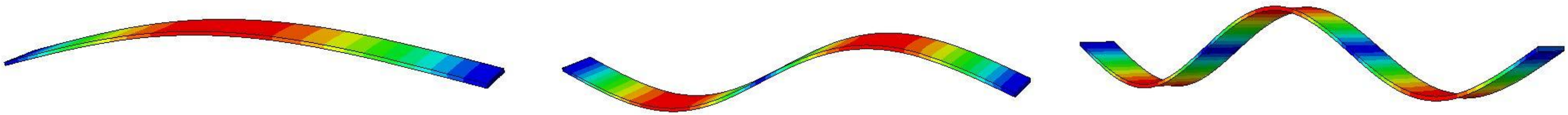
- Parameters for evaluation
  - Stiffness
  - Mass distribution
  - Eigenfrequencies and vibrational modes
  - Acceleration levels
  - Damping characteristics

- 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

Dymanic behaviour of the deck



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

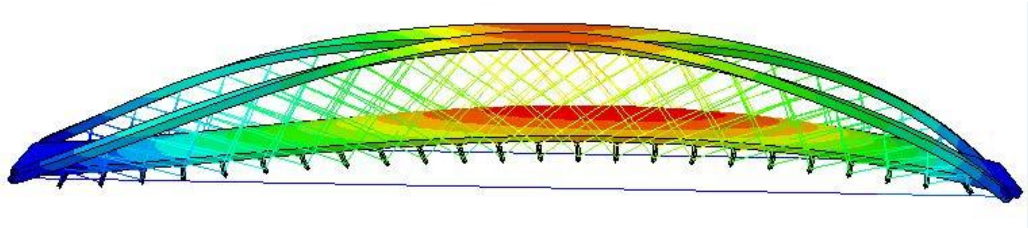
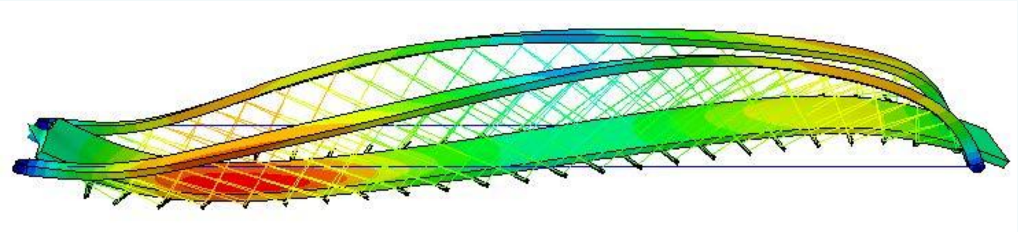
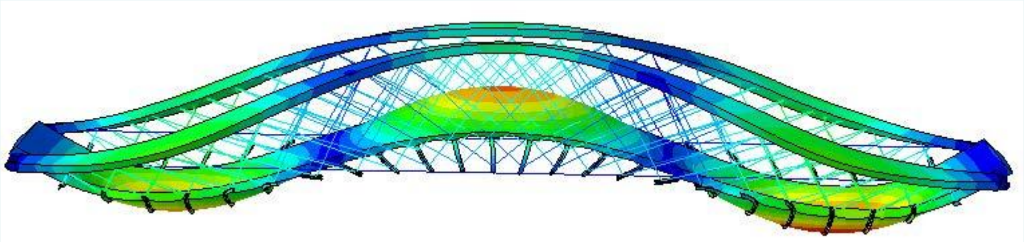
Table Measured damping, modes and frequencies compared to numerically obtained frequencies

Mode	Measured frequency [Hz]	Numerical frequency [Hz]	Measured damping [%]
Vertical 1	3.0	3.2	4.2
Vertical 2	8.0	7.5	0.63
Vertical 3	17.5	16.9	0.95
Horizontal 1	17.8	18.2	2.4

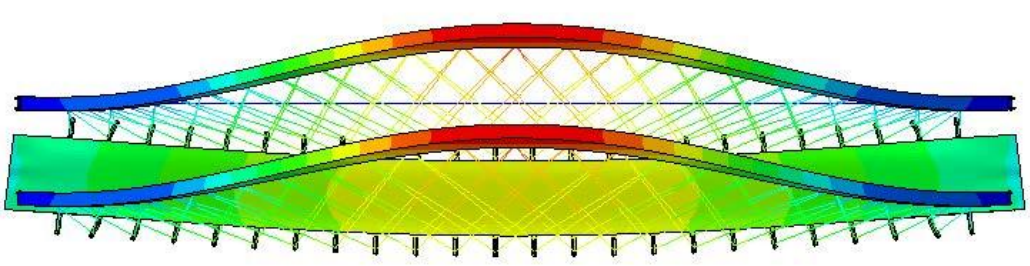
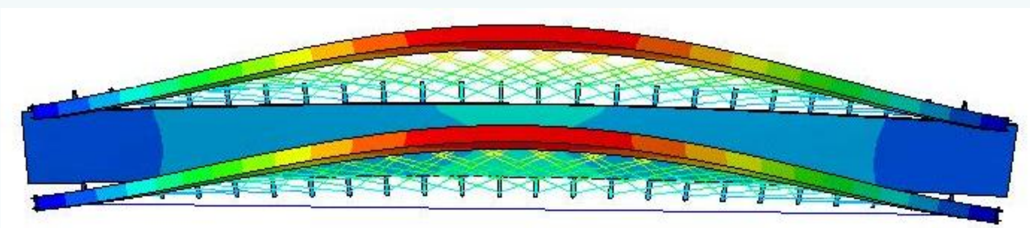
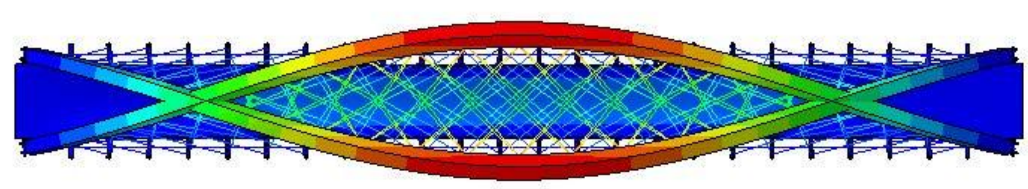
- Comment
  - stress-laminated deck behaves like a massive wooden block

  ⟹ pre-stressing is sufficient

Vertical vibrations of the deck

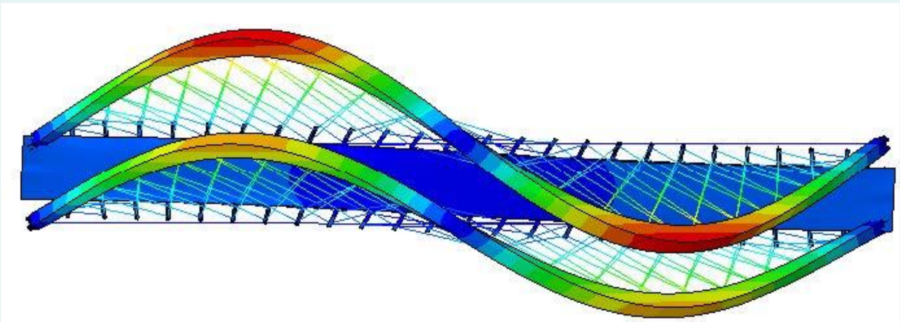
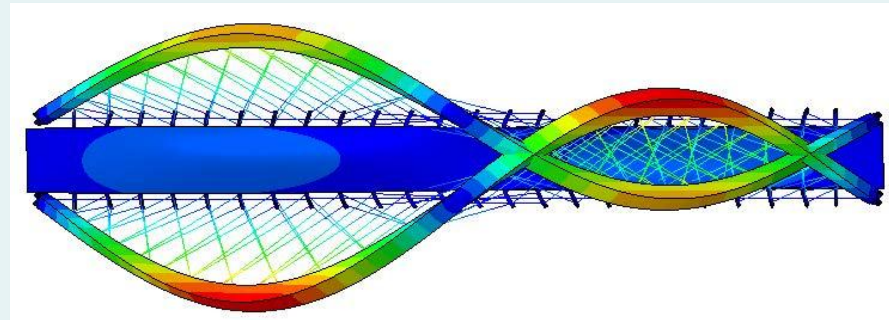
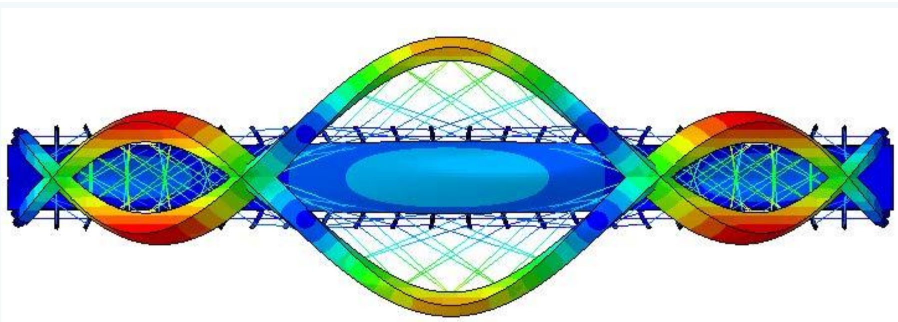
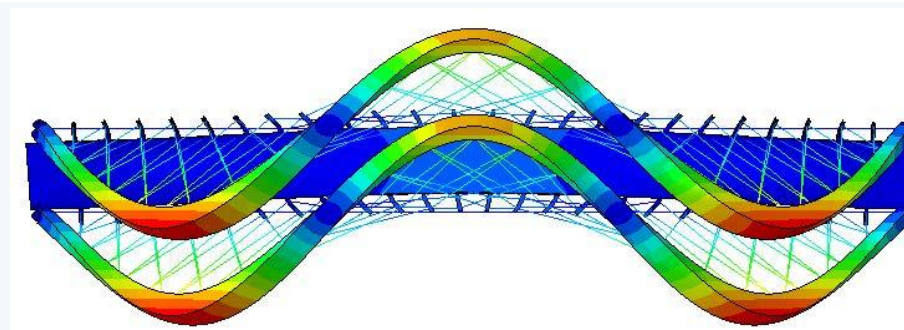
Mode shapes with deck vibrating in vertical direction	Mode	Experimental model scale (1:10) Frequency [Hz]	Numerical model scale (1:10) Frequency [Hz]	Numerical model full scale (1:1) Frequency [Hz]
	1	none	26,5	2,95
	2	28,5	24,7	2,27
	3	43,5	42,2	3,99

Horizontal vibrations of the deck

Mode shapes with vibrations mainly in horizontal direction	Mode	Numerical model scale 1:10 Frequency [Hz]	Numerical model full scale(1:1) Frequency [Hz]
 Horizontal deck impact Measured experimental model 1:10 ; Frequency: 15.9 – 16.4 [Hz]	1	15.9	1.98
	1a	8.66	0.809
	1b	9.29	0.814

Horizontal vibrations of the deck

Table Mode shapes and frequencies of vibrations in horizontal direction

Mode 2a	Mode 2b
	
Frequency in numerical model (scale 1:10): **16,83** [Hz] Frequency in numerical model (scale 1:1): **1.787** [Hz]	**16,86** [Hz] **1.802** [Hz]
Mode 3a	**Mode 3b**
	
Frequency in numerical model (scale 1:10): **32,18** [Hz] Frequency in numerical model (scale 1:1): **3,66** [Hz]	**32,59** [Hz] **3,67** [Hz]

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 m^3 / 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

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

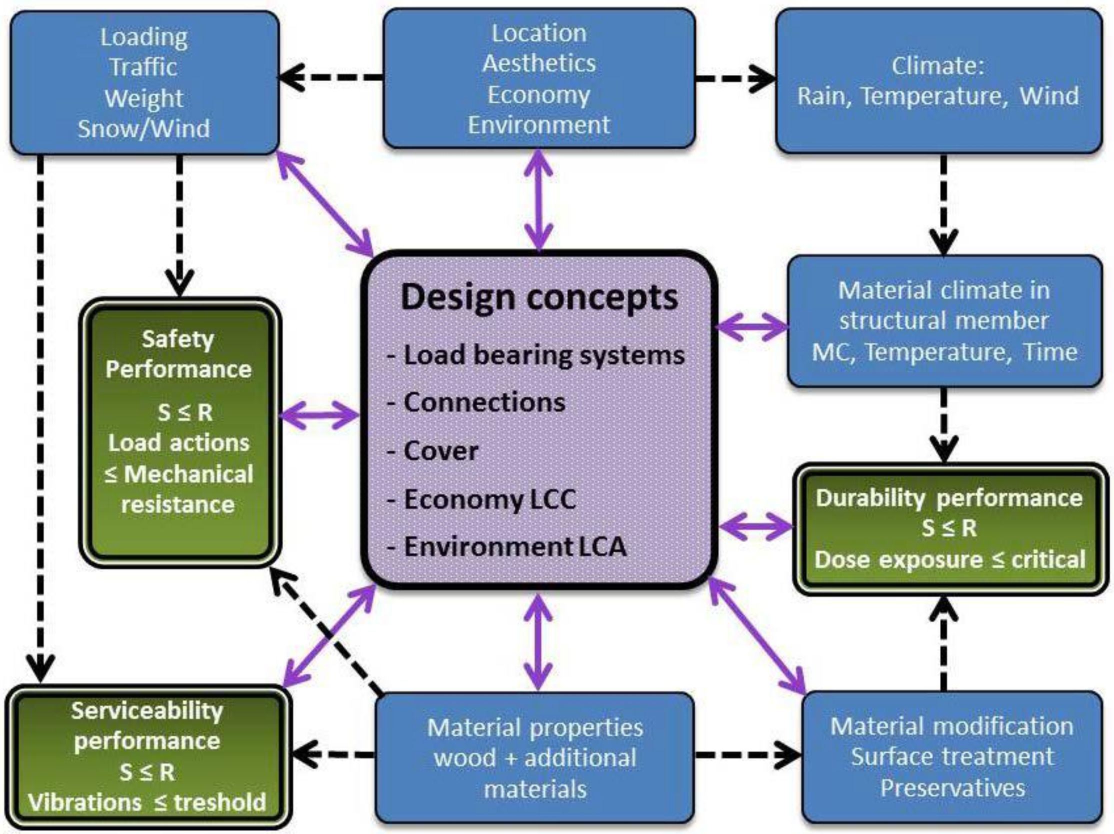


Fig. Performance model for durability

- Bridge design:
  - Safety - Seviceability
  - 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 architecs, designers, consultants, authorities

Thank you for your attention.