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Timber adaptive structures

Author : Vincent Lestang

Supervisors : Prof. Ian F.C. Smith [1] / Dr. G. Senatore [1] / Dr. Johannes Natterer

[1] Applied Computing and Mechanics Laboratory (IMAC) EPFL

Motivations

Minimization of energy is one of the ways to reduce use of resources, and restrict human impact on the environment. The total energy of a building is composed by the embodied energy from its materials and the operational energy to run over its service life. Zero net operational energy could be achieved in the next decades thanks to emerging green technologies (PV,…). Minimization of energy in structures appears consequently as a challenge in terms of embodied energy.

Design process

Statically indeterminacy of structures provokes additional self-stress states, in equilibrium and without provoking additional support forces, added to the equilibrium stress-state. Optimal forces into the structure are obtained by combining those with controlled change of length of selected structural elements.

Flowchart

Optimization of the embodied energy

Determination of an **optimal set of cross-sections** that comply ULS with **optimal geometric forces** that satisfy the equilibrium conditions

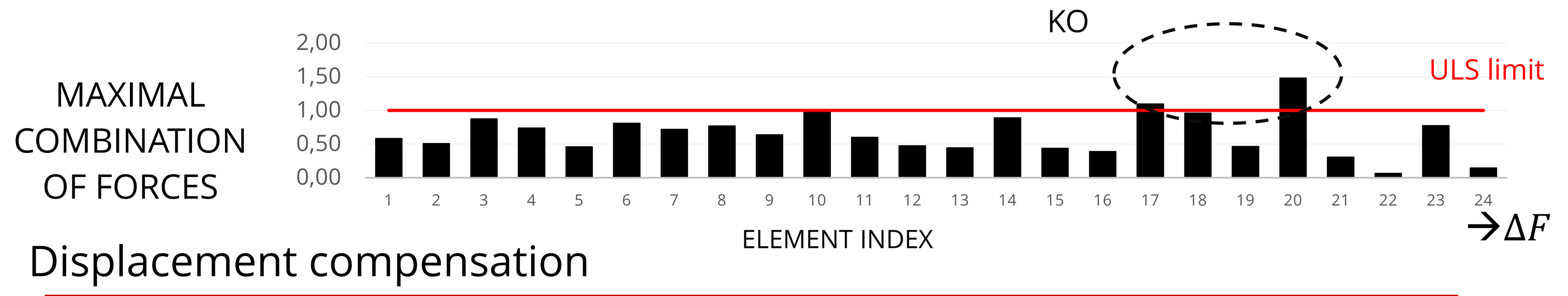
$$\min_{h,\varphi} EE(h_i) = \sum (h_i \cdot b \cdot L_i) PE_{timber} + \sum (A(\varphi_i) \cdot L_i) PE_{steel}$$

$$Equilibirum: \min_F ||B^{RED} \cdot F - P^{RED}||^2$$

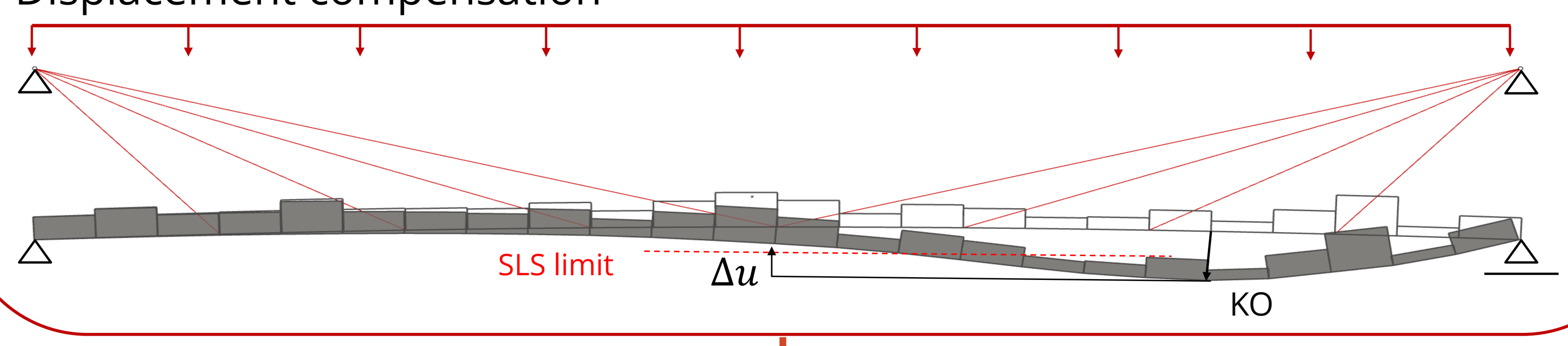
$$s.t\ ULS: \quad A^{ULS,B} \cdot F \leq 1$$

Check of the structure without control

Force redirection

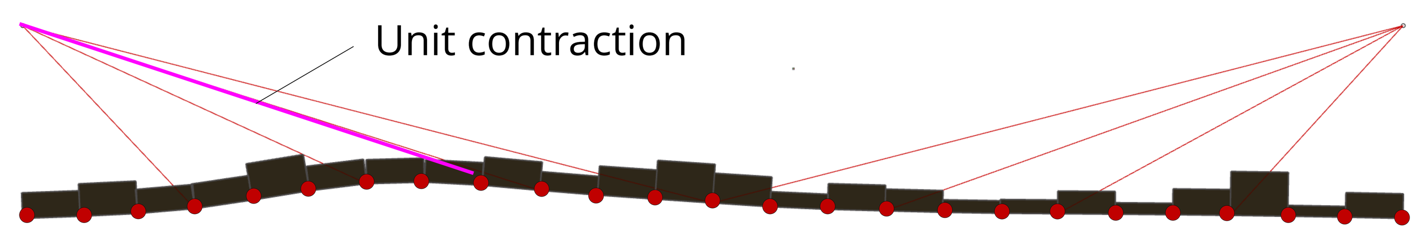


Displacement compensation



Optimal actuator layout

Evaluation of the sensitivity to the change of length of the actuators to determine the most efficient ones to redirect the forces and compensate the displacements regarding the structure without control.



Axial — Shear — Bending moment

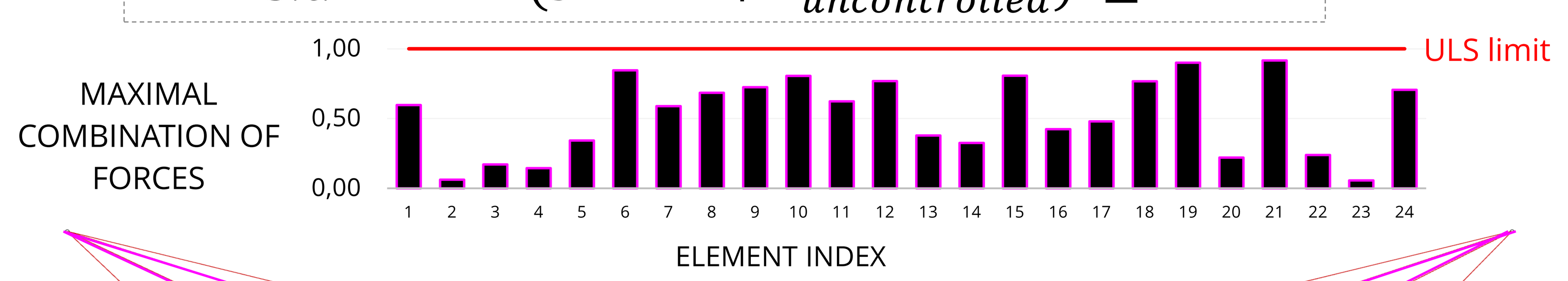
Sensitivity: Forces S^F — Displacements $S^{u|RED}$

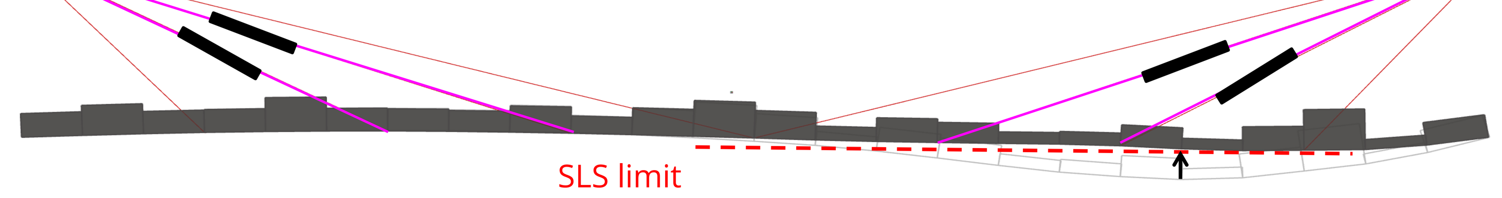
Efficiency → Selection by ranking

Control of the structure

$$\min_{\Delta L} \left|\left| \begin{bmatrix} S^{u|RED} \\ I \end{bmatrix} \cdot \Delta L - \begin{bmatrix} \Delta u_k^{RED} \\ 0 \end{bmatrix} \right|\right|^2$$

$$\text{s.t. } A^{ULS,B} \cdot (S^F \cdot \Delta L + F^{ULS}_{uncontrolled}) \leq 1$$





Objectives

- Develop an design tool for adaptive structures made of timber beams using the methodology proposed by Senatore & al., regarding the Swiss construction standards (SIA 260, 261, 265)
- Provide a relevant overview of the limits (span, height) and potential offered by timber for adaptive methodology application

Analysis method

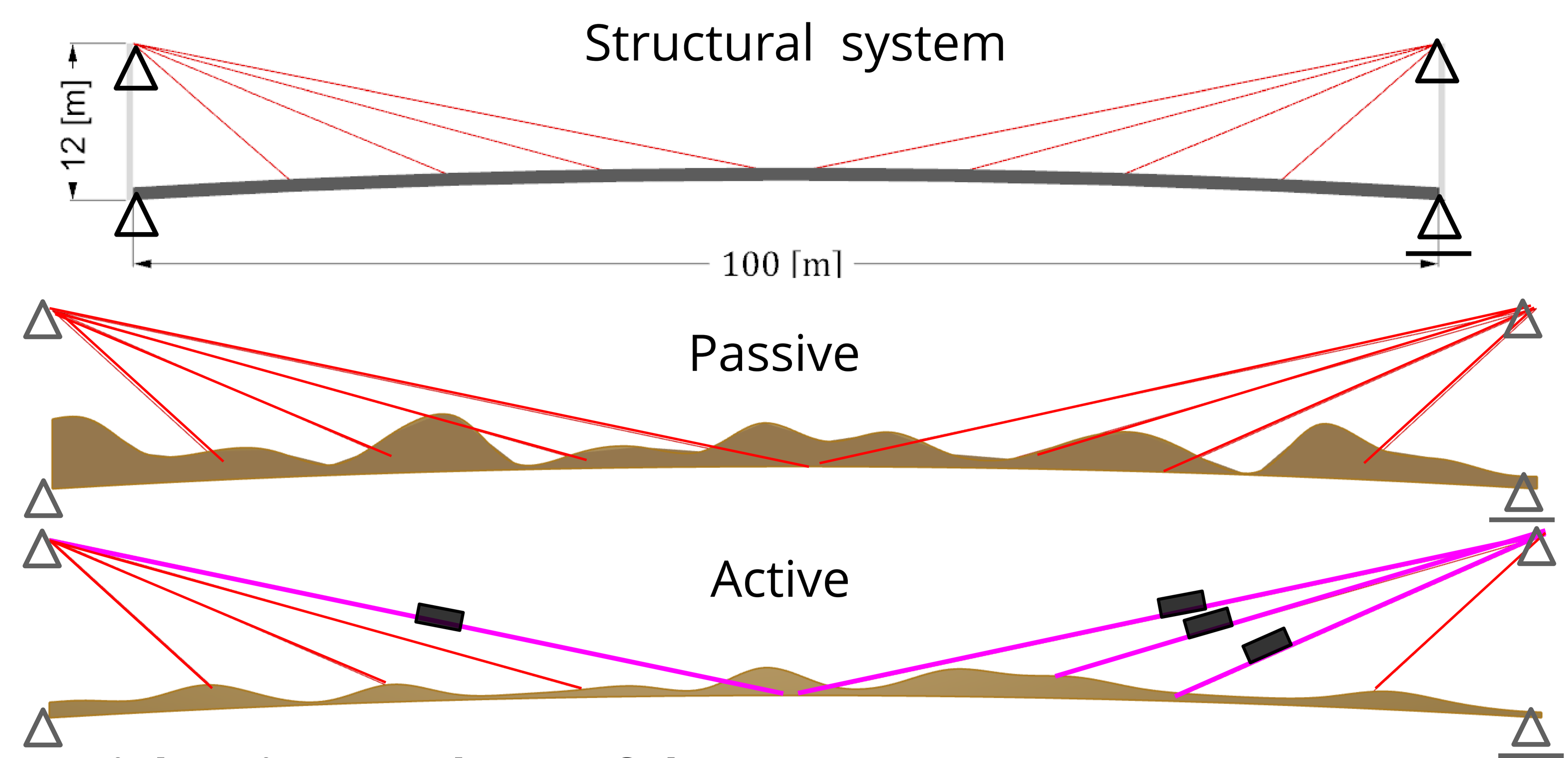
Structures were modeled with the Integrated Force Method that allows to dissociate equilibrium and compatibility conditions.

Governing matrix: $\begin{bmatrix} B \\ CG \end{bmatrix} F = \begin{bmatrix} P^{ext} \\ -C \cdot \Delta L \end{bmatrix}$

Case studies and results

The design process was applied on different structural systems to assess the potential savings in terms of material but also the influence of the dimensions and the structural systems. Both active and passive structures must be able to comply ultimate ULS and serviceability SLS limit states.

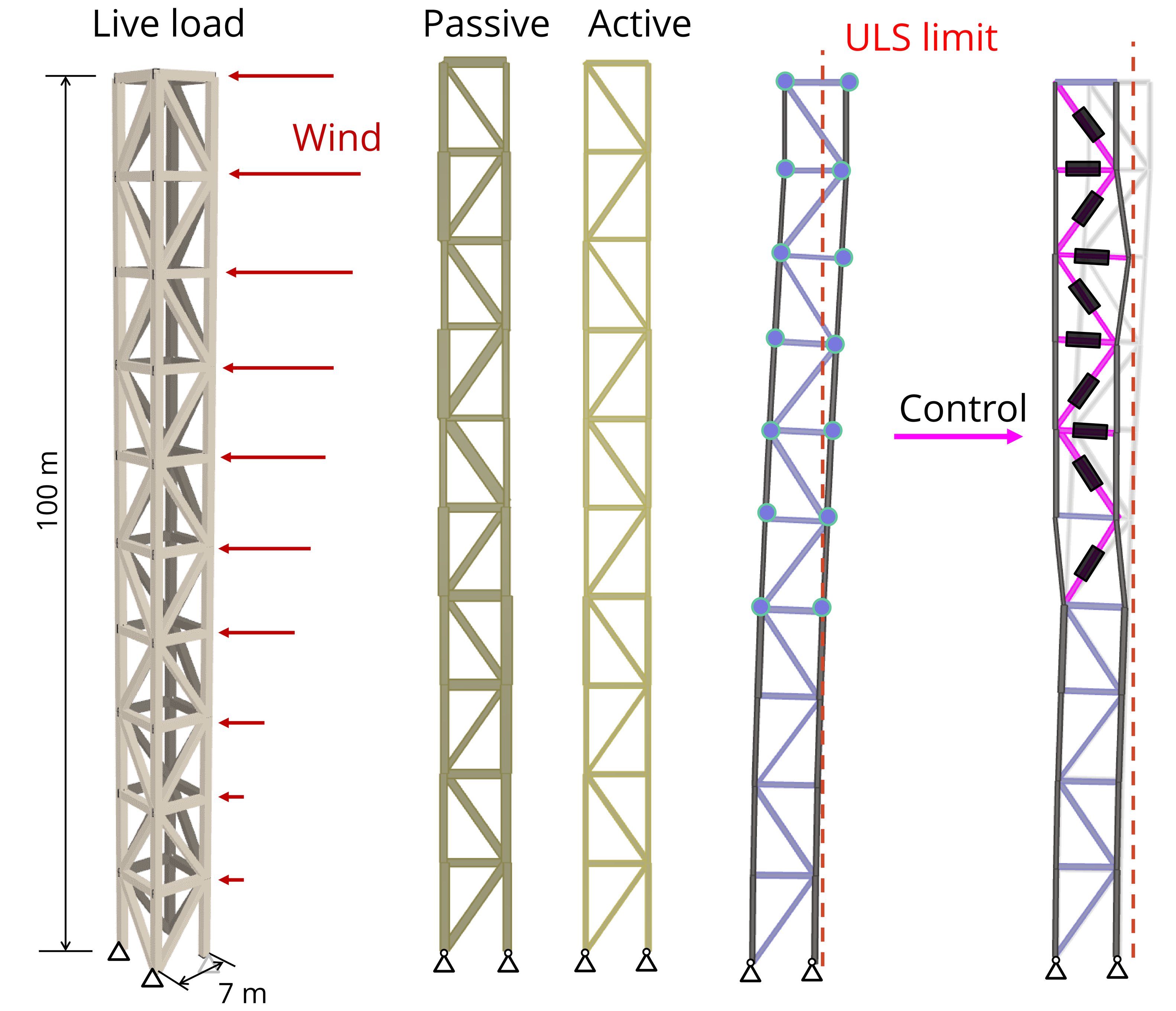
Pedestrian bridge



Material savings : Volume of the structures
Passive: 77 [m³] → Controlled: 35 [m³] Savings: 55 %

Maximal cross-section heigth (width = 400 [mm]):
Passive: 4.6 [m] → Controlled: 1.8 [m]

High-rise building



Material savings : Volume of the structures
Passive: 450 [m³] → Controlled: 120 [m³] Savings: 72 %

Maximal cross-section dimensions
Passive: 1580 x 1580 [mm] → Controlled: 840 x 840 [mm]

Conclusion

- Expansion of the methodology for beams requires to adapt steps of the design process to consider the higher number of transferred forces per element
- Savings are dependent on the structural systems, high reduction of embodied energy can be attained
- For structures with large dimensions, actuation allows to reduce the required cross-sections dimensions, fitting the actual timber cross-section production capacity