**Bending-active structures: a review of design principles**

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Tuesday 17 Oct 2017

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**Active bending** is the systemic use of elastic deformation

"Bending-active structures are structural systems that include curved beam or shell elements that base their geometry on the elastic deformation from an initially straight or planar configuration."

Knippers et al. (2011) - Construction manual for polymers + membranes  
Lienhard et al. (2013) - Active Bending, a review on structures where bending is used as a self-formation process
Existing structures are very varied but do touch some common design principles
**Existing structures** are very varied but do touch some common design principles.

Restraint techniques
define how bending is induced and maintained in the system

Stiffening techniques
define how stiffness is developed within the system

1. Introduction
2. Elastic formation in design and construction
3. Form through force: restraining bending-active systems
   - Pre-bent members
   - Self-restraining system
   - Post-restrained structure
4. Stiffness through flexibility: manipulating elastic behaviour
   - Elastic stiffness
   - Initial displacement stiffness
   - Geometric stiffness
5. Conclusions
Existing structures differ in the way bending is induced and maintained in the system

Pre-bent components can be pre-assembled in the workshop

Self-restraining systems maintain bending through the component interaction

Post-restrained structures can be assembled on the ground
Pre-bent components can be pre-assembled in the workshop

Self-restraining systems maintain bending through the component interaction
Post-restrained structures can be assembled on the ground
**The stiffness** is defined by three components: elastic, initial displacement and geometric stiffness.

Takahashi et al. (2016) – Scale effect in bending-active plates and a novel concept for elastic kinetic roof systems

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Lienhard (2014) - Bending-active structures, form-finding strategies using elastic deformation in static and kinematic systems and the structural potential therein
The elastic stiffness is constant throughout the deformation

Materials for active bending should have high elasticity to strength ratios

Kotelnikova-Weiler et al. (2013) - Materials for actively-bent structures
Cross-sections and component geometry define stiffness and residual stress

\[ \frac{1}{r} = \frac{M}{E J} \quad (1) \]
\[ \sigma = \frac{E J}{r^2} - \frac{E J}{2r} \quad (2) \]

Ahlquist & Lienhard (2016) - Extending Geometric and Structural Capacities for Textile Hybrid Structures with Laminated GFRP Beams and CNC Knitting

Lienhard, Schleicher & Niemeyer (2011) - Bending-active structures - Research Pavilion ICD/ITKE

Manipulating the components allows customising for a certain geometry or behaviour

EmTech (AA) – ETH pavilion

Kerf-based complex wood systems – Achim Menges
Anisotropic properties can be interesting when separating direction of bending from loading.

The initial displacement stiffness is defined by the deformed geometry.
Different curved geometries lead to varying load-bearing behaviour

Coupling can improve the behaviour by increasing the structural height
**Coupling** can increase the moment of inertia while maintaining the residual stress.

The geometric stiffness is the result of the stress-stiffening effect.
The stress-stiffening is defined by the flow of forces

**Compression**  
**Tension**  
**Torsion**

Lienhard (2014) - Bending-active structures, form-finding strategies using elastic deformation in static and kinematic systems and the structural potential therein

**Tension** can increase the stiffness of bending-active (hybrid) structures considerably

M1 Tour de l’architecte – Lienhard & Ahlquist  
Sensory Playscape – Sean Ahlquist  
Hybrid Tower – UdK (Berlin) + CITA (Copenhagen)