Bending-active structures: a review of design principles

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VRIJE UNIVERSITEIT BRUSSEL

NOVEL STRUCTURAL SKINS
COST ACTION TU1303

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

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

Stiffening techniques
define how stiffness is developed withing 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

a. ReciPlyDome - KADK +
Vrije Universiteit Brussel

b. Dermoid - CITA + SIAL

c. ICD/ITKE pavilion 2015-2016
University of Stuttgart

Self-restraining systems maintain
bending through the component interaction

d. Panikkar - CODA

e. ICD/ITKE pavilion 2010 -
University of Stuttgart

f. Undulatus -
Vrije Universiteit Brussel

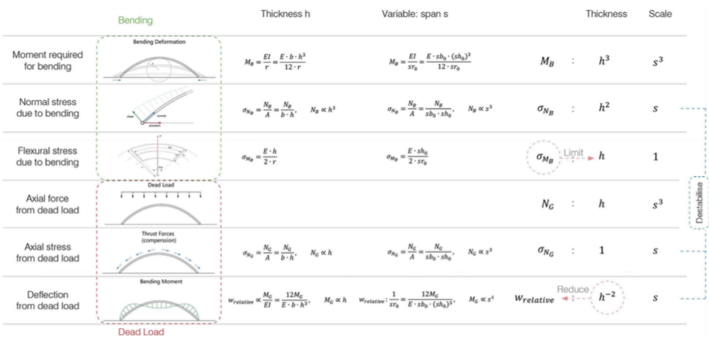
Post-restrained structures can be assembled on the ground

g. SheltAir - UdK Berlin

h. TorUs - CODA

i. Pavilion - EmTech (AA) + ETH

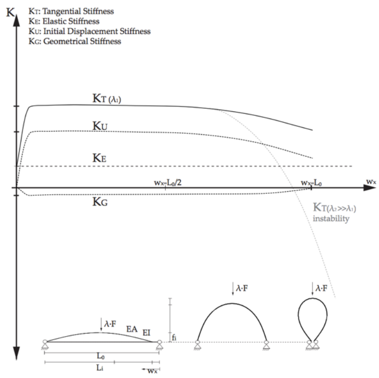
The stiffness is defined by three components: elastic, initial displacement and geometric stiffness



	Bending	Thickness h		Variable: span s				Thickness	Scale
Moment required for bending	Bending Deformation	$M_B = \frac{EI}{r} = \frac{E \cdot b \cdot h^3}{12 \cdot r}$		$M_B = \frac{EI}{sr_0} = \frac{E \cdot sb_0 \cdot (sh_0)^3}{12 \cdot sr_0}$		M_B	:	h^3	s^3
Normal stress due to bending		$\sigma_{N_B} = \frac{N_B}{A} = \frac{N_B}{b \cdot h}$,	$N_B \propto h^3$	$\sigma_{N_B} = \frac{N_B}{A} = \frac{N_B}{sb_0 \cdot sh_0}$,	$N_B \propto s^3$	σ_{N_B}	:	h^2	s
Flexural stress due to bending		$\sigma_{M_B} = \frac{E \cdot h}{2 \cdot r}$		$\sigma_{M_B} = \frac{E \cdot sh_0}{2 \cdot sr_0}$		σ_{M_B}	Limit	h	1
Axial force from dead load	Dead Load					N_G	:	h	s^3
Axial stress from dead load	Thrust Forces (compression)	$\sigma_{N_G} = \frac{N_G}{A} = \frac{N_G}{b \cdot h}$,	$N_G \propto h$	$\sigma_{N_G} = \frac{N_G}{A} = \frac{N_G}{sb_0 \cdot sh_0}$,	$N_G \propto s^3$	σ_{N_G}	:	1	s
Deflection from dead load	Bending Moment	$w_{relative} \propto \frac{M_G}{EI} = \frac{12M_G}{E \cdot b \cdot h^3}$,	$M_G \propto h$	$w_{relative} : \frac{1}{sr_0} = \frac{12M_G}{E \cdot sb_0 \cdot (sh_0)^3}$,	$M_G \propto s^4$	$w_{relative}$	Reduce	h^{-2}	s

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

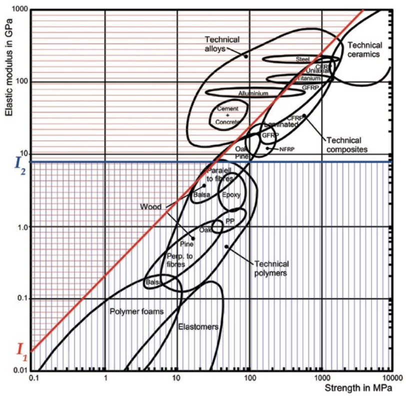
The stiffness is defined by three components: elastic, initial displacement and geometric stiffness



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

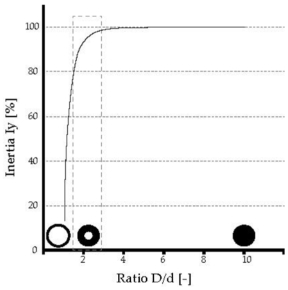
The elastic stiffness is
constant throughout the deformation

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



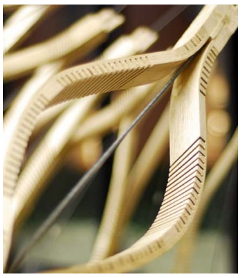
$$\frac{1}{r} = \frac{M}{E \cdot I} \quad (1) \qquad \sigma = \frac{E \cdot I}{r \cdot w} = \frac{E \cdot t}{2 \cdot r} \quad (2)$$

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

Lienhard, Schleicher & Knippers (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

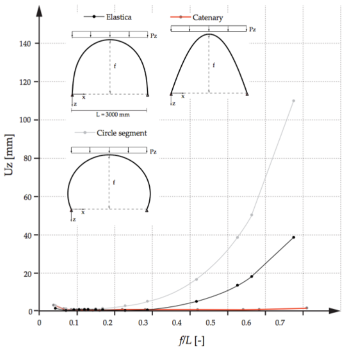
Anisotropic properties can be interesting when separating direction of bending from loading

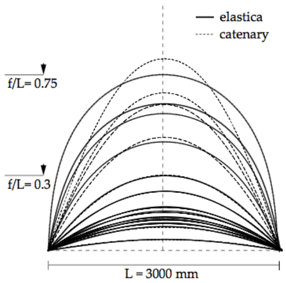
Neula - CODA

TorUs - CODA

The initial displacement stiffness is defined by the deformed geometry

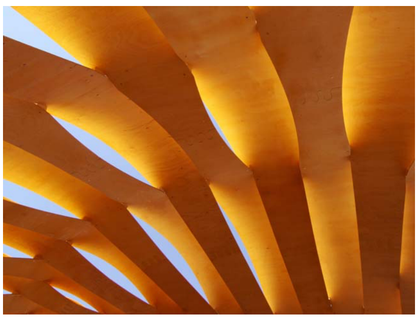
Different curved geometries lead to varying load-bearing behaviour

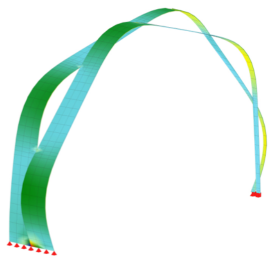




Lienhard (2014) - Bending-active structures, form-finding strategies using elastic deformation in static and kinematic systems and the structural potential therein

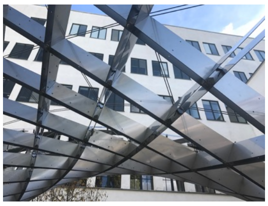
Coupling can improve the behaviour by increasing the structural height





ICD/ITKE research pavilion 2010

Coupling can increase the moment of inertia while maintaining the residual stress



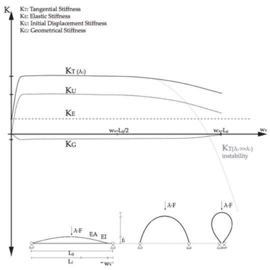
Layering
Asymptotic pavilion – Eike Schling

Bundling
Sensory Playscape – Sean Ahlquist

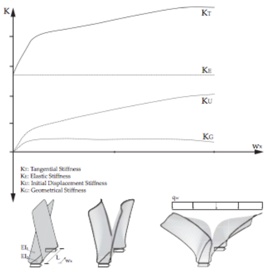
Insertion
TwoDtoThreeD – KOGE (Günther Filz)

The geometric stiffness is the result of the stress-stiffening effect

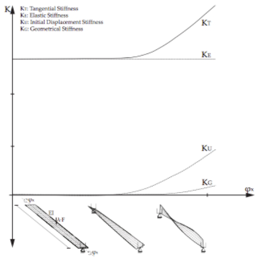
The stress-stiffening is defined by the flow of forces



Compression



Tension



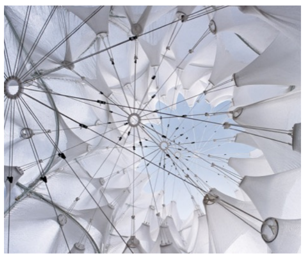
Torsion

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)