A proposal to account for environmental effects in design of timber-concrete-composite beams

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Current design problem at the KBK

- retrofit of an existing timber bridge

- ski run bridge built in 1988

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Current design problem at the KBK

- retrofit of an existing timber bridge

design loads in 1988

- Pistenbully 240 D
  - dead load 5,2 to
  - maximum load 7.5 to
  - crawlers ≈ 1 to
  - maximum load per axle ?
  - breadth: 3,8 m
- snow:
  - natural snow 3,5 kN/m^2
  - limited by snow fall

- ski run bridge built in 1988

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Current design problem at the KBK

- retrofit of an existing timber bridge

today's "design" loads

- Pistenbully 600 D Polar
  - dead load 11.0 to
  - maximum load 12.5 to
  - crawlers $\approx$ 1 to
  - maximum load per axle: 23% of the total load
  - breadth: 4,2m – 5,5 m
- snow:
  - natural snow 3,5 kN/m^2
  - artifical snow
  - no limitation

- ski run bridge built in 1988

Current design problem at the KBK

- retrofit of an existing timber bridge

- ski run bridge built in 1988

	1988	today
snow	natural snow	artificial & natural snow
density	200 – 350 kg/m^3	450 – 550 kg/m^3
snow height	limited by snow fall	no limitation
snow groomer	PB 240 D	PB 600 Polar
dead load	5,5 to	11,5 to
maximum load	7,2 to	12,5 to
chains	1 to	1 to
maximum load per axle	?	23%
breadth	3.8m	4.2–5.5 m

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Current design problem at the KBK

- retrofit of an existing timber bridge

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chains	1 to	1 to
maximum load per axle	?	23%
breadth	3.8m	4.2–5.5 m

⇒ doubling the life load

⇒ increase of the breadth of the bridge necessary

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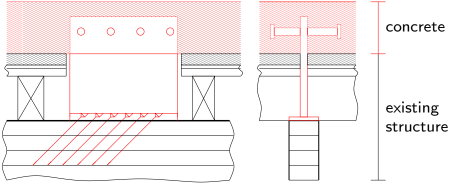
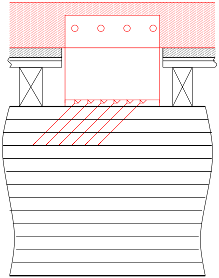
Concept

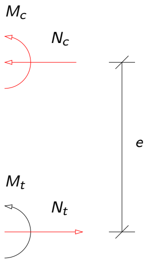


- concept
  - opening of the surface
  - installation of the connectors
  - additional concrete slab

  → timber-concrete-composite girder

Concept





- concept
  - increase of the load capacity

$$M_{res} = M_t + M_c + N \cdot e$$

Actions on the bridge

- dead loads
- snow loads
  - regular snow
  - artificial snow
- live loads
  - persons crossing the bridge
  - snow groomer Pistenbully 600D
- different inelastic strains due to
  - shrinkage of concrete
  - moisture variation of the timber cross section
  - temperature variation

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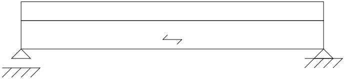
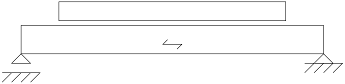
Influences of the inelastic strains

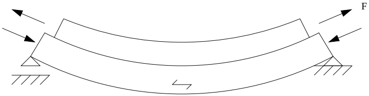
no concrete shrinkage



concrete shrinkage no connection



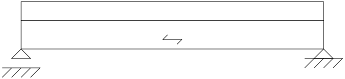
concrete shrinkage connection between timber and concrete



- different inelastic expansion due to
  - moisture variation
  - temperature variations
  - ...
- eigenstresses due to the different inelastic expansion

Influences of the inelastic strains

no concrete shrinkage



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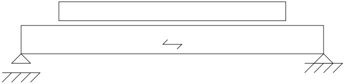

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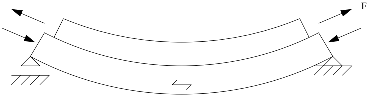

- different inelastic expansion due to
  - moisture variation
  - temperature variations
  - ...
- eigenstresses due to the different inelastic expansion
- brittle behaviour of timber in tension
- no reduction of the eigenstresses due to yielding comparable to steel or concrete

→ consideration in analysis necessary

→ how to do it?

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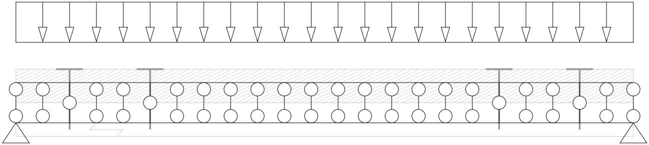
How to consider different expansion in the design?

- analysis by means of framework program



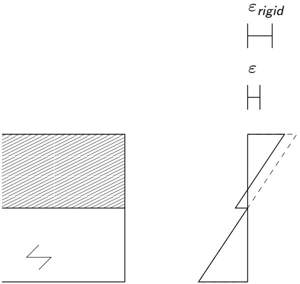
  \+ general application
  \- a lot of members
  \- difficult to verify
  \- complicated to optimise the structure

→ consideration of different expansion as an effective variation of temperature

How to consider different expansion in the design?

- analysis by means of framework program
- analysis by means of Eurocode 5 Annex B ("γ design method")

$$EJ_{eff} = \sum E_i \cdot J_i + \sum \gamma_i \cdot E_i \cdot A_i \cdot a_i^2$$



$$\gamma = \frac{\varepsilon}{\varepsilon_{rigid}}$$

+ simple
+ easy to implement in common spreadsheets

$\longrightarrow$ less errors

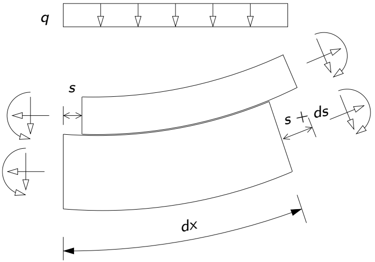
- limited to single span girders
- up-to-now no consideration of different expansion of the cross section i.e. due to shrinkage or temperature

$\longrightarrow$ expansion necessary

Expansion of the design methods of the consideration of shrinkage

- differential equation of the slip between timber and concrete

$$s'' - \alpha^2 \cdot s = -\alpha^2 \cdot \gamma \cdot q \cdot x$$



- deformation

$$w(x) = -\frac{1}{E_a \cdot J_v} \cdot \left(\frac{K \cdot a_{St}}{e_{||}} \cdot \left(\frac{1}{24} \cdot \gamma \cdot q \cdot x^4 - \frac{\gamma \cdot q}{\alpha^4} \cdot \frac{1}{cosh\left(\alpha \cdot \frac{L}{2}\right)} \cdot cosh\left(\alpha \cdot x\right) \right) - \frac{1}{24} \cdot q \cdot x^4 \right) - \frac{1}{2} \cdot c_q \cdot x^2 - c_w$$

$\rightarrow$ solution hardly practical for designers

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Expansion of the design methods of the consideration of shrinkage

- differential equation of the slip between timber and concrete
- 2 different approaches
  - superposition of the stresses and deformation caused by
    - external loads $\longrightarrow$ EC 5 Annex B
    - shrinkage $\longrightarrow$ solution of the differential equation

$$
\begin{aligned}
w_{max} &= w_{max,full} \cdot \gamma_M \\
w_{max,full} &= \frac{\Delta\varepsilon}{z} \cdot \frac{EJ_{full} - EJ_{abs}}{EJ_{full}} \\
\gamma_M &= 1 - \frac{8}{(\alpha \cdot L)^2} \cdot \left(1 - \frac{1}{cosh\,(0.5 \cdot \alpha \cdot L)}\right)
\end{aligned}
$$

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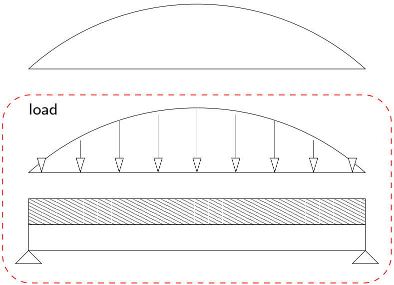
Expansion of the design methods of the consideration of shrinkage

- differential equation of the slip between timber and concrete
- 2 different approaches
  - superposition of the stresses and deformation caused by
    - external loads → EC 5 Annex B
    - shrinkage → solution of the differential equation
  - shrinkage as fictious load

$\Delta\varepsilon = \varepsilon_{timber} - \varepsilon_{concrete}$



→ fictious load

→ EC 5 Annex b

Expansion of the design methods of the consideration of shrinkage

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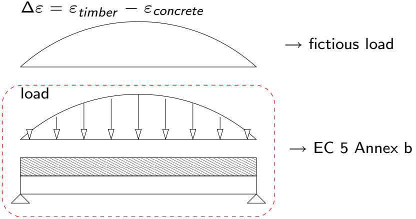

- fictious load

$$p_{sls} = \pi^2 \cdot \frac{E_1 \cdot A_1 \cdot E_2 \cdot A_2 \cdot z \cdot \gamma}{(E_1 \cdot A_1 + E_2 \cdot A_2) \cdot L^2} \cdot \Delta\varepsilon$$

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Expansion of the design methods of the consideration of shrinkage

- differential equation of the slip between timber and concrete
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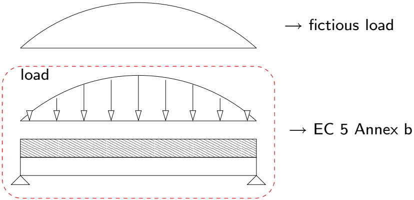


  - fictious load

$$p_{sls} = \pi^2 \cdot \frac{E_1 \cdot A_1 \cdot E_2 \cdot A_2 \cdot z \cdot \gamma}{(E_1 \cdot A_1 + E_2 \cdot A_2) \cdot L^2} \cdot \Delta\varepsilon$$

⇒ consideration of inelastic strains due to temperature variation, shrinkage etc. in the design possible

Input values for the design

- known parameters
  - geometry
  - strength and stiffness
  - loads
- unknown parameters
  - variation of temperature
  - shrinkage/swelling of timber → moisture variation
  - shrinkage of concrete

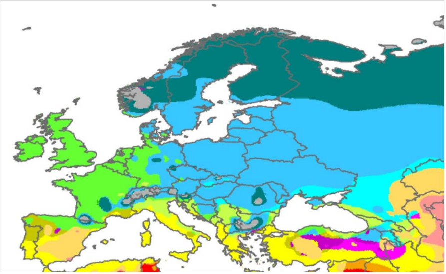
→ difference in the inelastic strains

$$\Delta\varepsilon = \varepsilon_{timber} - \varepsilon_{concrete}$$

→ dependent on the local climate

Concept

- definition of the climate according to the Köppen-Geiger-maps



Bsk: Cold semi-arid climate (Madrid, Salamanca, Albacete)
Csa: Warm Mediterranean climate (Lisbon, Cagliari, Palermo, Athens)
Csb: Temperate Mediterranean climate (Potenza, Marsilia, Coruna, Porto)
Cfa: Warm oceanic//humid subtropical climate (Zagreb, Brescia, Torino, Bologna, Roma, Foggia.)
Cfb: Temperate oceanic climate (Stuttgart, Zurich, Paris, London)
Dfa: Warm / humid continental climate (Kosice, Odessa, Zaporozhe)
Dfb: Temperate//humid continental climate (Moscow, Warsaw, Helsinki)
Dfc: Cool continental climate/subarctic climate (Rovaniemi, Lulea, Tampere)
ET: Tundra climate (Chambery, Zurich, Sofia)

$\longrightarrow$ variation of temperature and relative humidity

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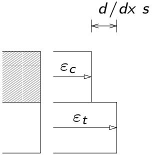
Local vs. average moisture variation

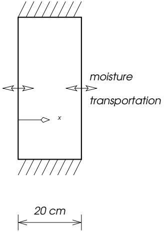
- differential equation

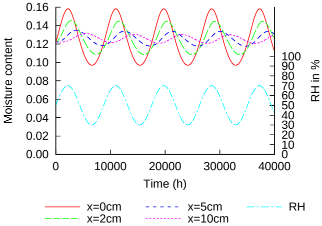
$$\frac{d}{dx}s = \varepsilon_c + \varepsilon_t = \frac{1}{K} \cdot \frac{d}{dx}N$$

$$N = \int_A \sigma \; dA = \sigma_{average} \cdot A$$



→ average moisture variation of interest
→ dependent on the cross section dimensions





Local vs. average moisture variation

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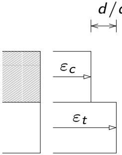
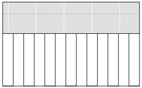
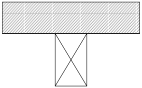
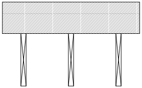


→ average moisture variation of interest

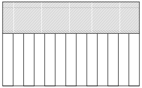
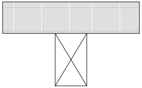
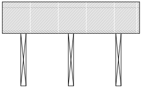
→ dependent on the cross section dimensions

- proposal for warm oceanic/humid subtropical climate (characteristic values)

Type of exposure	ΔT	Δu in % solid decks (continous)	medium breadth (b ≈ 125mm)	narrow section (b ≈ 38mm)
				
outdoor protected	-33	2.3	3.3	9.0
indoor unheated	-22	1.7	2.5	6.7
indoor heated	-11	1.2	1.7	4.5

Resulting inelatic strains

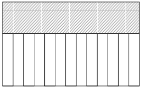
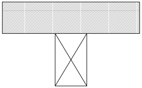
- resulting difference in the inelastic strains

Type of exposure	solid decks (continous)	$(\Delta\varepsilon_t - \Delta\varepsilon_c) \cdot 10^{-6}$ medium breadth (b $\approx$ 125mm)	narrow section (b $\approx$ 38mm)
			
outdoor protected	709	769	1111
indoor unheated	621	666	921
indoor heated	533	563	731

$\rightarrow$ characteristic input values for the consideration of the climate variation in the determination of the deflections

Need for consideration of inelastic strains?

- inelastic strains often neglected
- determination of the fictious load for different beams

Type of exposure	solid decks Fort Collins beam		medium breadth Florence beam	
				
	$\gamma_1 = 0.6$		$\gamma_1 = 0.31$	
	$g + \psi_2 \cdot p = 17.7 kN/m^2$		$g + \psi_2 \cdot p = 4.14 kN/m^2$	
	p_s	$\frac{p_s}{g+\psi_2 \cdot p}$	p_s	$\frac{p_s}{g+\psi_2 \cdot p}$
outdoor protected	6.63	38%	0.29	7%
indoor unheated	5.60	33%	0.26	6%
indoor heated	4.98	29%	0.22	5%

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Need for consideration of inelastic strains?

- inelastic strains often neglected
- determination of the fictious load for different beams

$\longrightarrow$ influence of the inelastic strains on the deformation and the internal forces

$\longrightarrow$ dependent on the γ-value and the geometry

$\longrightarrow$ calulation of the deformation with respect to the inelastic strains ✓

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Open questions

- determination of the characteristic inelastic strains
  - → eigenstresses
  - → consideration as a load in the ULS
  - → γ_F for the inelastic strains in general?

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Open questions

- determination of the characteristic inelastic strains
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  - → consideration as a load in the ULS
  - → γ_F for the inelastic strains in general?
- γ_F for shrinkage of concrete?
  - DIN Fachbericht 104 steel-concrete-composite bridges:
  - → $\gamma_{F,s} = 1{,}0$
  - useable in timber-concrete composite?
    - brittle failure in tension in timber instead of ductile failure of steel
    - redistribution of eigenstresses hardly possible

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Open questions

- determination of the characteristic inelastic strains
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  - $\rightarrow$ consideration as a load in the ULS
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    - brittle failure in tension in timber instead of ductile failure of steel
    - redistribution of eigenstresses hardly possible
  - German technical approval Z. 9.1.473 Brettstapel-Beton-Verbunddecken mit Flachstahlschlössern
    - shrinkage $\rightarrow$ temperature
    - $\gamma_{F,s} = \gamma_{F,T}$ [?]
    - $\gamma_{F,T} = 1.35$ and $= 0$ resp. according to DIN Fachbericht 104

$\rightarrow$ Which γ_F-value for shrinkage should be used?

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Which γ_F-value should be used?

- probabilistic design according to JCSS
- procedure
  - assumption of γ_F
  - determination of the required cross section dimension
  - Monte-Carlo-simulation with input values according to JCSS
  - frequency of failure

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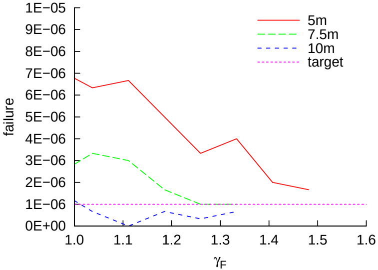
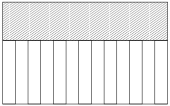
- results of the very first studies





- indoor climate
- residential building
- C24; C20/25;
- $\gamma_1 \approx 0.8$

$\Rightarrow$ $\gamma_{F,S} > 1.0$ as in DIN Fachbericht 104

$\Rightarrow$ $\gamma_{F,S} > 1.35$ as in German technical approval Z. 9.1.473 Brettstapel-Beton-Verbunddecken mit Flachstahlschlössern

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Which γ_F-value should be used?

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- results of the very first studies

$\Rightarrow$ $\gamma_{F,S} > 1.0$ as in DIN Fachbericht 104

$\Rightarrow$ $\gamma_{F,S} > 1.35$ as in German technical approval Z. 9.1.473 Brettstapel-Beton-Verbunddecken mit Flachstahlschlössern

- further studies necessary
  - different cross-sections
  - interaction with creep (?)
  - different approaches instead of Monte-Carlo-simulations
  - ...

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Conclusions and Outlook

- inelastic strains as a fictious load ✓
- determination of characteristic inelastic strains depending on
  - climate
  - cross-section dimensions

→ characteristic values for inelastic strains ✓

→ determination of the deformation possible

Conclusions and Outlook

- inelastic strains as a fictious load ✓
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→ characteristic values for inelastic strains ✓

→ determination of the deformation possible

- several different proposals for γ_F in the German standards

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