MŰEGYETEM 1782
Budapest University of Technology and Economics

Department of Structural Engineering

Durability-design of pre-cast concrete structural members

PhD thesis

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Research objectives

The importance of durability of structures is continuously increasing due to economical reasons.

Main objective of the research was to provide a calculation method for the durability-design of pre-cast concrete members, that is:

- Based on state of the art probabilistic approach with arbitrary number of stochastic parameters
- Considering the loads as a function of time
- Considering the decrease of load carrying capacity (F_u) in time due to slow deformations, degradation of structural geometry and aging of materials
- Fast and accurate enough for practical application
- Results are easy to use for practicing designers

Why pre-cast concrete members?

The research was focusing on the analysis of prefabricated prestressed concrete girders because:

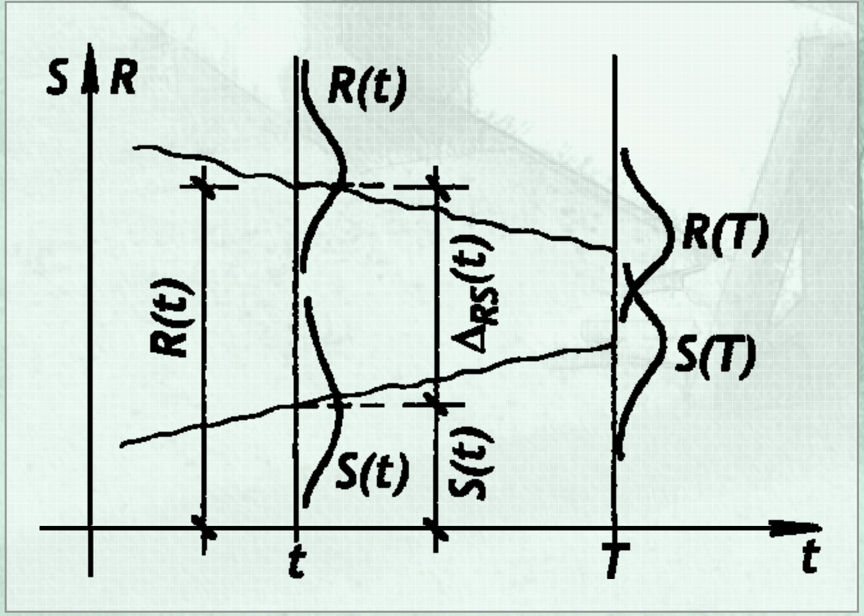
- They are widely used for the construction of residential houses and industrial buildings
- The stochastic characteristics of process parameters (mean values and standard deviations of structural geometry and material properties) can be obtained from the results of quality control
- Manufacturing conditions of the members can be more precisely controlled and modified if necessary

Probabilistic approach for the durability-design

Durability: The structure is durable enough (functions properly) if the desired level for the **probability of failure** is not exceeded during its life-span.

Probability of failure: $p_G = prob[(R-S)<0]$

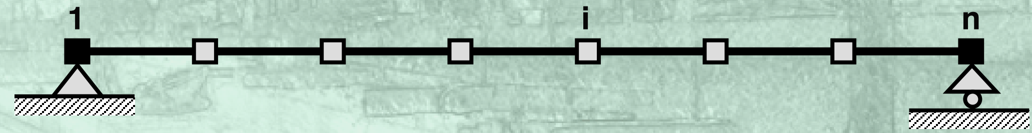
The probability that the load effect (**S**) is exceeding the structural resistance (**R**).



Changes of the stochastic distribution of external loads (**S**) and the structural resistance (**R**) in time causing the increase of failure probability.

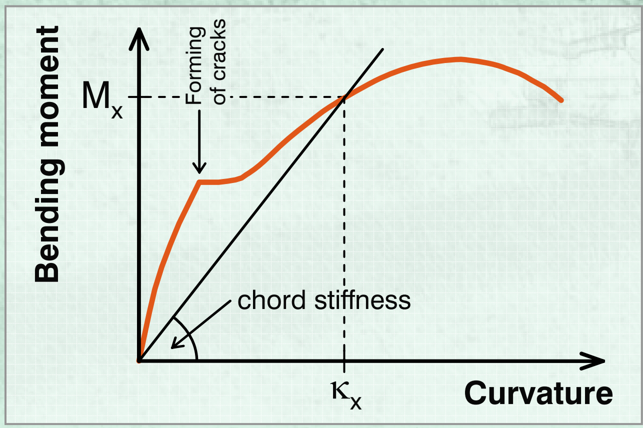
Applied calculation method

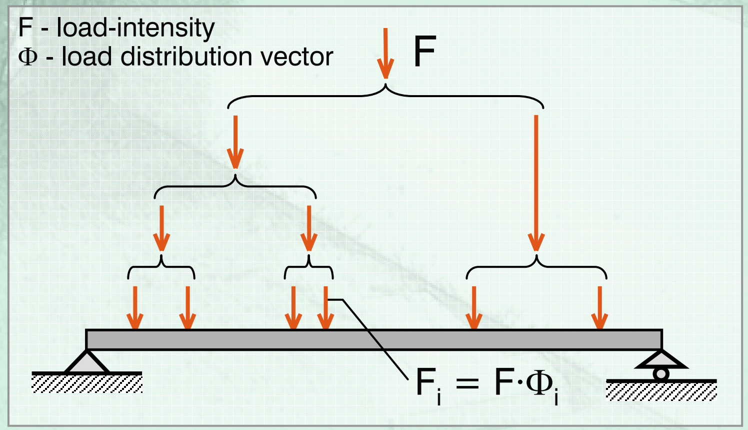
Mean value of structural resistance ($F_{u,m}$) was calculated by Finite Element Method (FEM).



Beam elements (compression and bending)

- Mean values of structural dimensions and material properties were used for the calculation
- Non-linear material model was used to describe the post-cracking behavior of concrete
- The applied load was single-parameter load.
- The value of the load-intensity (Φ) was increased in steps until structural failure (crushing of concrete or splitting of steel bars) occurred.





Applied calculation method

Standard deviation of structural resistance (s_{Fu}, ν_{Fu}) was calculated by Stochastic Finite Element Method (SFEM).

The variation of stiffness matrix ($\delta \underline{K}$) was approximately expressed by first order partial derivative of $\underline{K}$ with respect to an "x" random input variable:

$$\delta \underline{K} = \frac{\partial \underline{K}}{\partial x} s_x$$

where s_x is the standard deviation of x.

The standard deviation of structural resistance was evaluated from:

$$\underline{C}_q = \delta \underline{\tilde{q}} \delta \underline{\tilde{q}}^T = \underline{\tilde{K}}^{-1} \frac{\partial \underline{K}}{\partial \alpha} \underline{u} \delta \underline{x} \, \underline{C}_r \delta \underline{x}^T \underline{u}^T \frac{\partial \underline{K}^T}{\partial \alpha} \underline{\tilde{K}}^{-T}$$

$\underline{\tilde{q}}$ – load vector including load intensity (F)

$\underline{K}$ – stiffness matrix

$\underline{\tilde{K}}$ – stiffness matrix including F

$\delta \underline{x}$ – matrix including standard deviations of random input variables

$\underline{u}$ – nodal displacements

$\underline{C}_r$ – correlation matrix

$\underline{C}_q$ – covariance of load vector

Previous studies on the field of probabilistic design

Author	Applied method	Effects considered						
		Random structural geometry	Random material properties	Random load effect	Non-linear material behavior	Change of geometry and material properties in time	Change of load effect in time	Carbonation induced corrosion of steel bars
Handa & Andersson (1975)	SFEM[1]	■	■	■				
Almási (1978)	FEM + MCS	■	■		■			
Liu, Besterfield & Belytschko (1988)	SFEM[1]	■	■	■	■			
Dasgupta & Yip (1989)	SFEM[1]		■					
Besterfield, Liu & Lawrence (1990)	SFEM[1]	■	■	■				
Deodatis (1990)	SFEM[1]	■	■					
Teigen, Frangopol, Sture, Felippa (1991)	SFEM[1]		■	■	■			
Ruiz & Aguilar (1994)	MCS	■	■	■	■			
Eibl &Schmidt-Hurtienne (1995)	SFEM[1]	■	■	■	■			
Bergmeister, Novák & Pukl (2004)	FEM + MCS	■	■	■	■			
Krätzig & Petryna (2004)	SFEM[1]	■	■	■	■	■	■	
Koris (2008)	SFEM[1]	■	■	■	■	■	■	■

[1] Different authors used different mathematical approach and formulation.

FEM – Finite Element Method, SFEM – Stochastic Finite Element Method, MCS – Monte-Carlo Simulation

Initial values of process parameters

Products of 7 different Hungarian companies were considered during the determination of material properties.

Concrete strength:

- Compression tests on 150x150x150 mm cubes
- Altogether 732 specimens tested at age of 28 days
- 5 different concrete classes

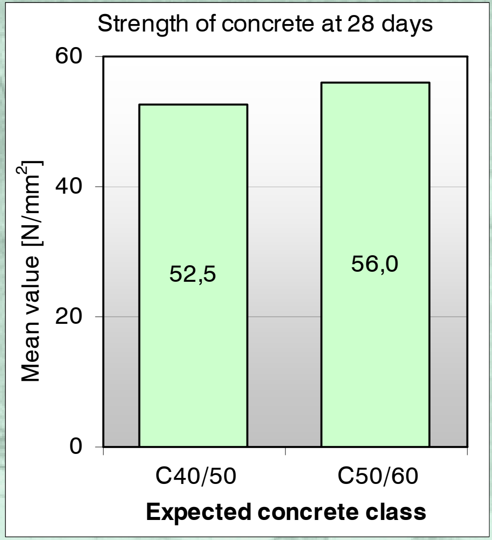
Steel bar strength:

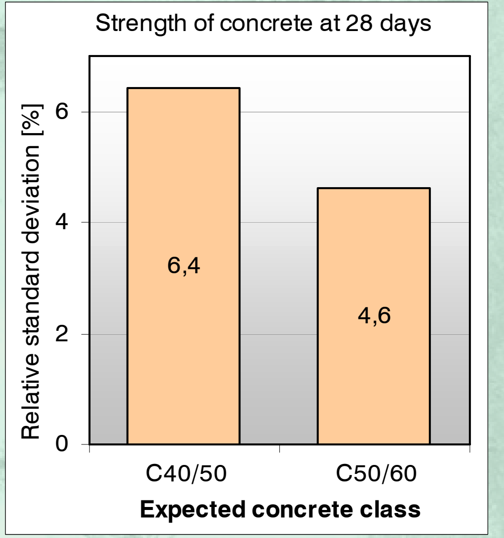
- Tensile tests on altogether 291 specimens
- 3 different classes, 9 different diameters

Prestressing tendon strength:

- Tensile tests on 20 specimens
- 2 different types

Geometry of the cross-sections was measured on manufactured beams.





Evaluation of process parameters as a function of time

Effects considered:

- Loss of initial prestress σ_{p0} (Eurocode 2: EN 1992-1-1)
- Increase of standard deviation of geometrical sizes (Mistéth, 2001)
- Decrease of mean value of material strength (concrete, steel bars, prestressing tendons) (Mistéth, 2001)
- Increase of standard deviation of material strength (Mistéth, 2001)
- Carbonation of concrete (***fib*** bulletin 34. “Model Code for Service Life Design”, 2006)
- Carbonation induced corrosion of steel bars and tendons (D. Zao & L. Fan, 2007)
- Change of mean value and standard deviation of loads (Mistéth, 2001)

New result #1.

I developed a method based on probabilistic approach for the durability-design of prefabricated concrete structural members. This method can predict the probability of failure of the members at any given point of time. The deterioration of material strengths and geometrical sizes, the effect of carbonation induced corrosion as well as the change of load effect in time can be taken into account during the analysis. Random input parameters that are considered by the developed method are the strength of concrete, steel bars and prestressing tendons, the height and width of cross section, effective height of steel bars and tendons and the load effect.

Results of analyses / Verification

Bending tests on prestressed EE beams:

- 4 different beam types (different size and reinforcement)
- Altogether 26 beams were tested

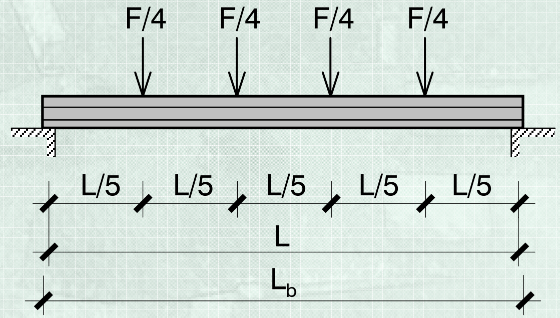
Average of measured values:

Type of beam	L [m]	Number of wires	L_{bm} [m]	h_m [mm]	$b_{f,m}$ [mm]	$b_{a,m}$ [mm]	$a_{p,m}$ [mm]	$d_{p,m}$ [mm]	$F_{u,m}$ [kN]
EE-42	4,27	1+4	4,40	189,8	80,8	144,1	37,8	168,5	49,28
EE-48	4,87	1+6	5,01	195,2	80,6	145,4	30,8	175,4	53,93
EE-54	5,47	1+6	5,64	196,1	81,7	144,4	39,5	176,5	51,60
EE-66	6,67	1+6	6,85	197,1	79,8	142,3	45,7	175,3	47,50

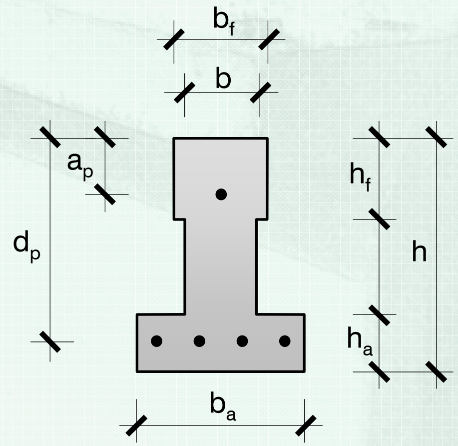
Relative standard deviation of measured values:

Type of beam	L [m]	Number of wires	ν_{Lb} [%]	ν_h [%]	ν_{bf} [%]	ν_{ba} [%]	ν_{ap} [%]	ν_{dp} [%]	ν_{Fu} [%]
EE-42	4,27	1+4	0,171	1,60	3,13	1,59	18,21	1,73	6,92
EE-48	4,87	1+6	0,224	1,86	1,30	1,49	19,48	0,86	3,86
EE-54	5,47	1+6	0,119	2,72	1,96	1,98	11,32	2,07	6,32
EE-66	6,67	1+6	0,084	2,27	0,48	0,23	4,42	0,92	6,93

Test arrangement



Cross-section (EE-42)

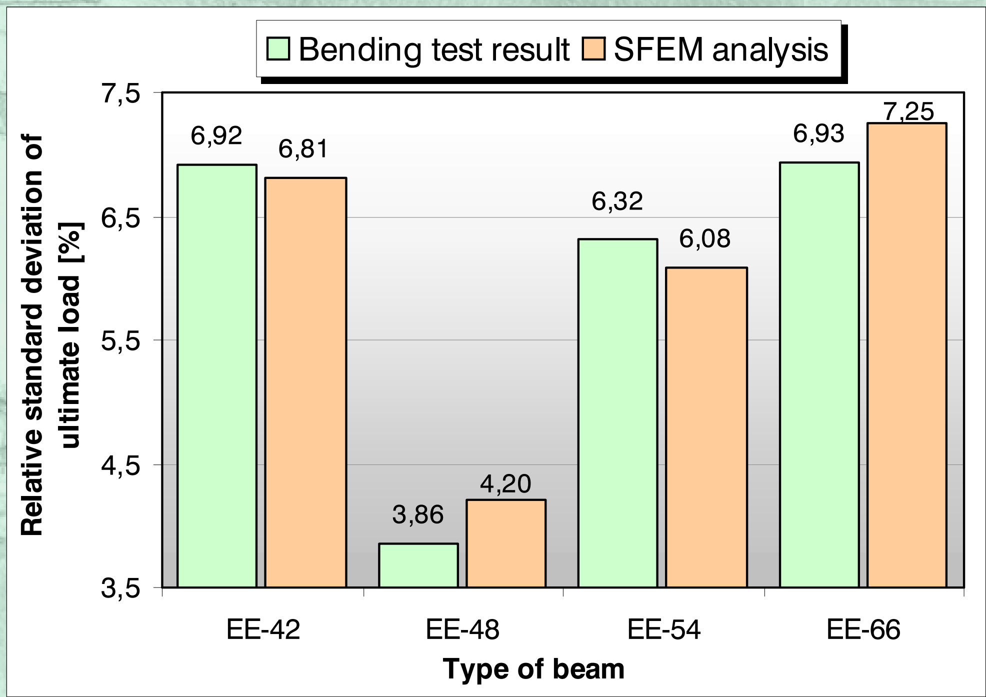


Concrete: C40/50
Prestressing wires: d = 5mm 1770/1540

Results of analyses / Verification II.

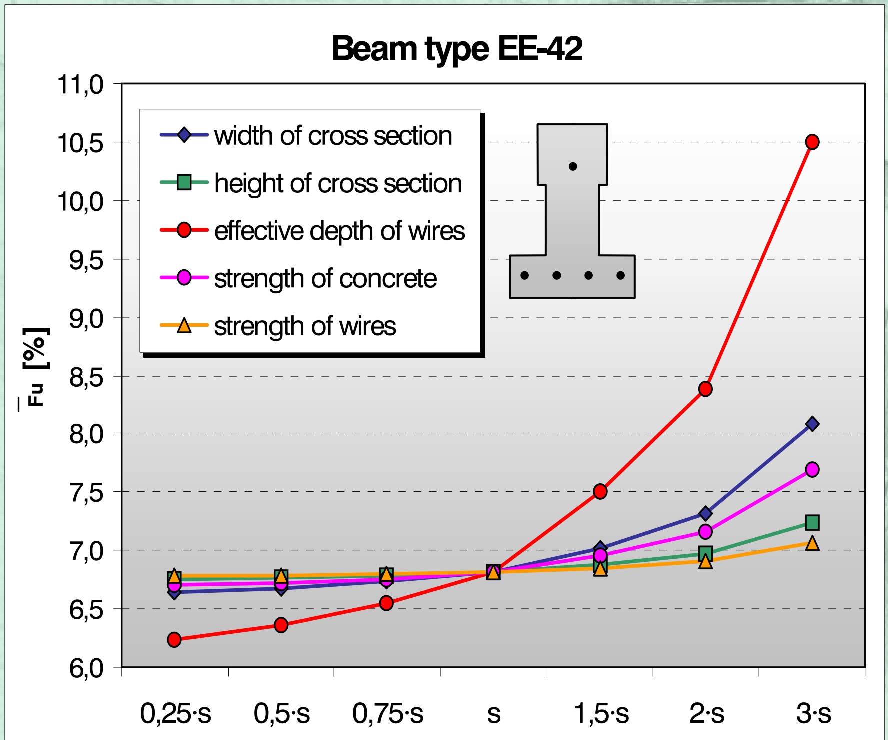
Comparing the relative standard deviation of ultimate load (ν_{Fu}) derived from bending tests and from numerical analysis:

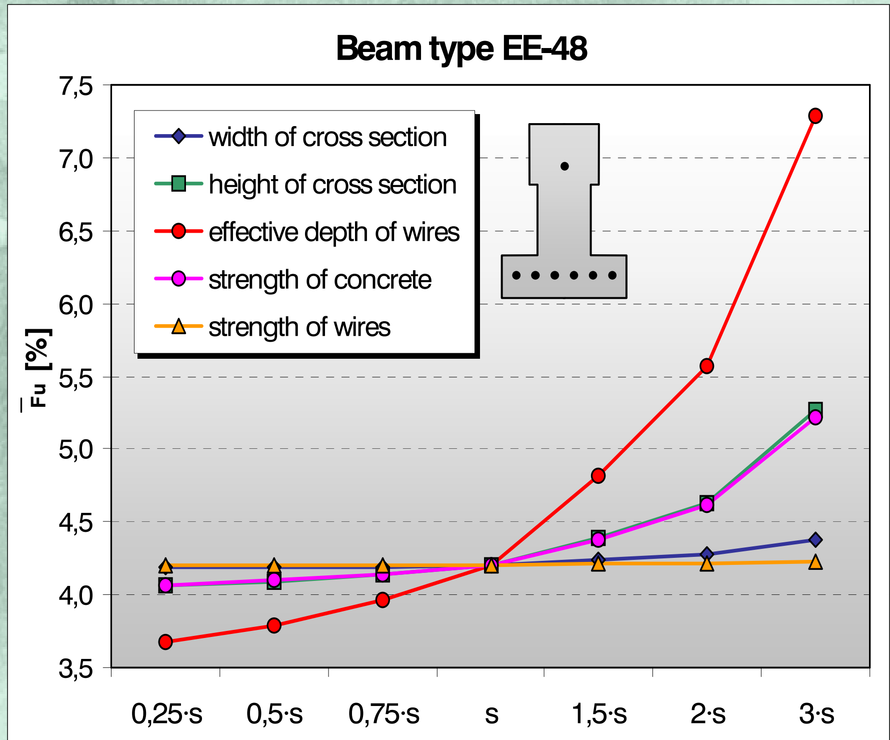
Type of beam	ν_{Fu}		
	Bending test result [%]	SFEM analysis [%]	Difference between test and calculation [%]
EE-42	6,92	6,81	-1,6
EE-48	3,86	4,20	8,8
EE-54	6,32	6,08	-3,8
EE-66	6,93	7,25	4,6



Results of analyses / Verification III.

The effect of the standard deviation of different input parameters on the standard deviation of ultimate load (ν_{Fu}).





New result #2.

I compared the standard deviation of load carrying capacity of prestressed concrete beams derived from bending test results to the results of numerical analyses. I proved by this comparison that the developed method is appropriate for the analysis of the standard deviation of load carrying capacity in case of pre-cast concrete structural members. I demonstrated that results of the numerical analysis can be used for practical purposes if the values of input parameters are derived from material test results and geometry measurements on the corresponding members.

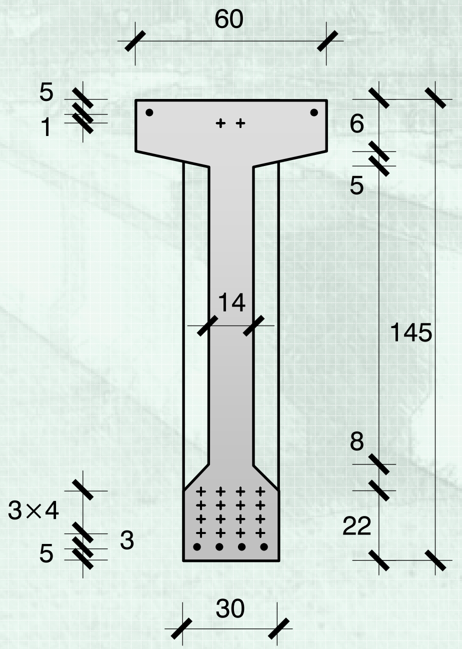
New result #3.

I performed parametric numerical analyses on pre-cast, prestressed concrete beams with the following results:

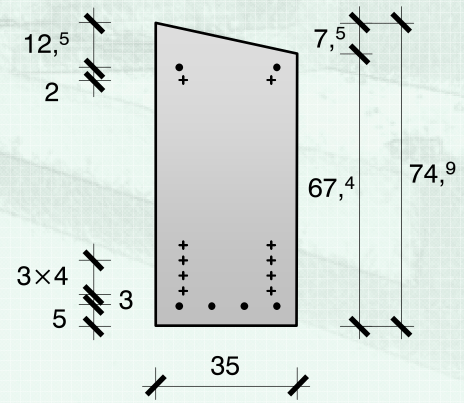
a.) I determined the effect of standard deviations of different input parameters (height and width of cross-section, effective depth of tendons, strength of concrete and tendons) on the standard deviation of load carrying capacity of examined beams. The influence of the standard deviations of effective depth and concrete strength is the most significant, while change of the standard deviation of tendon strength has the least influence. (parts **b**,**c** and **d** will follow on page 21)

Results of analyses / Durability of long-span girders

The durability of two pre-cast members was analyzed by the implemented method.



Reinforcement of beam "4000"



<u>ID. Nr. "4000"</u>

Length: 28,782 m
Height: 1,45 m
Function: main girder

<u>ID. Nr. "4700"</u>

Length: 6,06 m
Height: 0,749 m
Function: supporting main girders

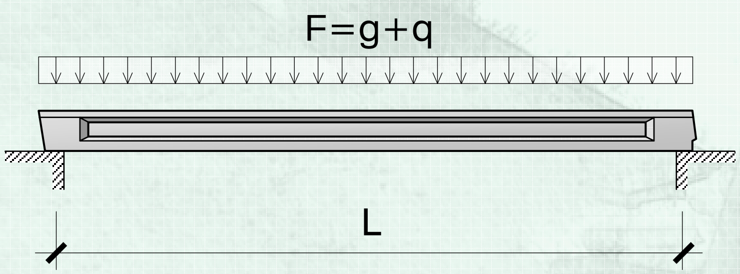
Results of analyses / Durability of long-span girders II.

Initial values of input parameters:

Beam “4000”

Values measured on 11 beams:

	Number of strands	L	h_m	$b_{f,m}$
Mean value[mm]	2+16	27691	1442	604
Standard deviation [%]		0,028	0,533	1,177

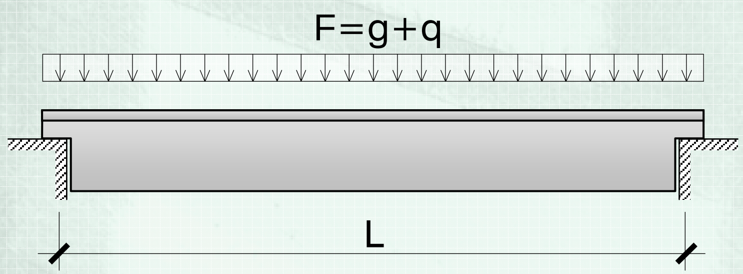


Concrete: C40/50
Steel bars: 4Ø20+2Ø20 B60.50
Prestressing strands: 16+2 Fp-100/1770-R2

Beam “4700”

Values measured on 10 beams:

	Number of strands	L	h_m	b_m
Mean value[mm]	2+12	6060	752	351
Standard deviation [%]		0,070	0,435	0,451



Concrete: C40/50
Steel bars: 4Ø16+2Ø16 B60.50
Prestressing strands: 8+2 Fp-100/1770-R2

Results of analyses / Durability of long-span girders III.

To perform the calculations, I developed a computer software (PFEM2008) using the Matlab® mathematical software package.

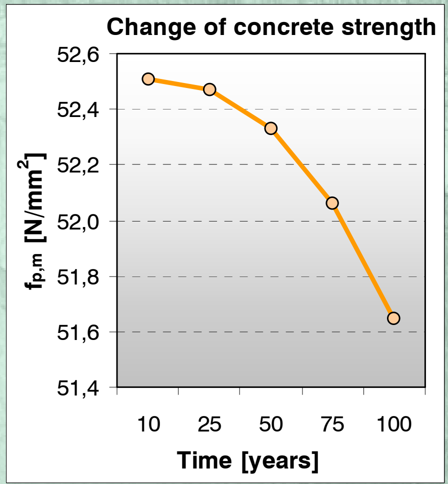
Conditions that were changed during the analysis:

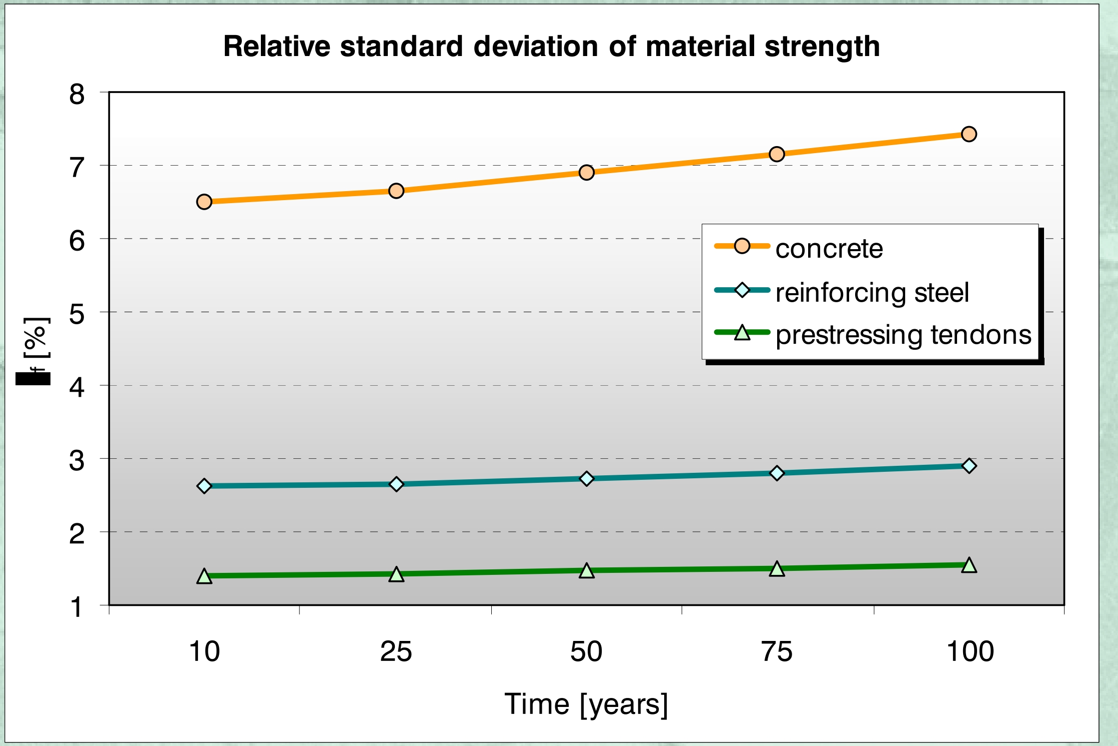
- Time: t = 10, 25, 50, 75 and 100 years
- Relative ambient humidity:
  - RH = 50%, 65% and 80%
- Initial value of imposed load (t=0):
  - q_0 = 16, 18, 20, 22 and 24 kN/m (beam “4000”)
  - q_0 = 115, 120, 125, 130 and 135 kN/m (beam “4700”)

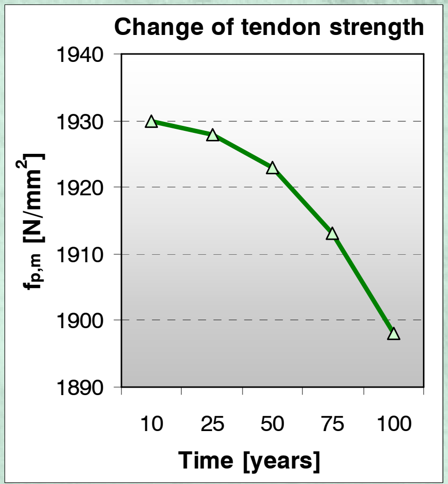
Number of runs was 5×3×5 = 75 for each beam.

Results of analyses / Durability of long-span girders IV.

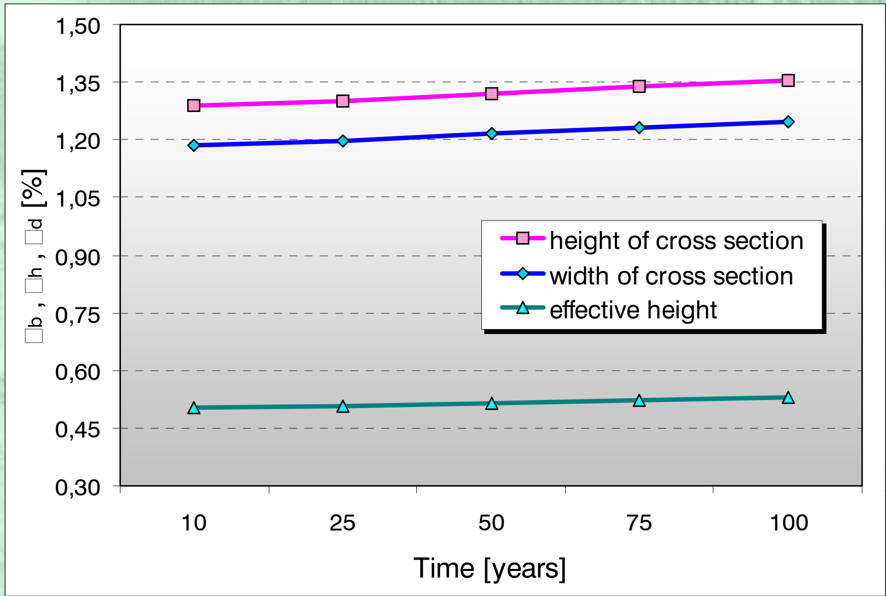
Change of mean value and relative standard deviation of material strength in case of beam "4000":



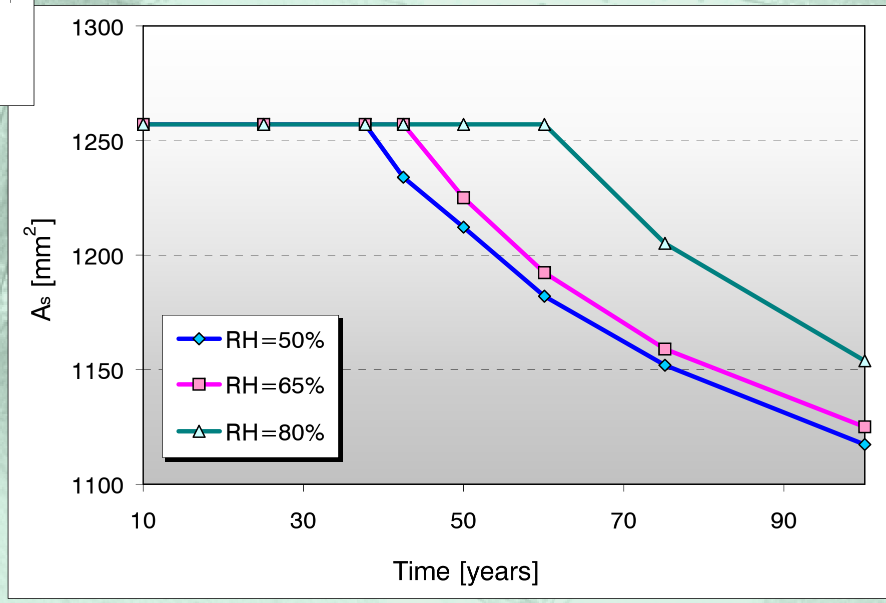




Results of analyses / Durability of long-span girders V.

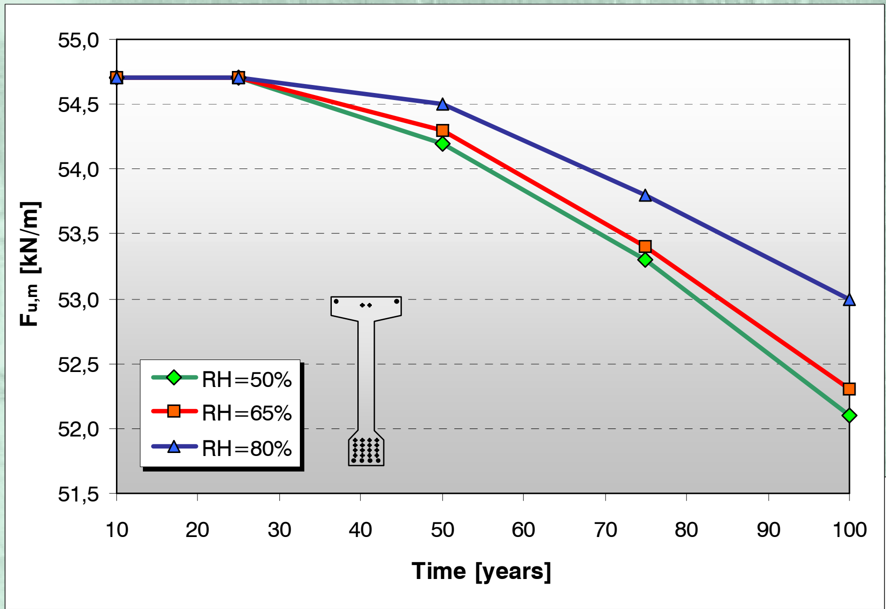


Change of relative standard deviation of structural sizes (height, width, effective height) in case of beam “4000”

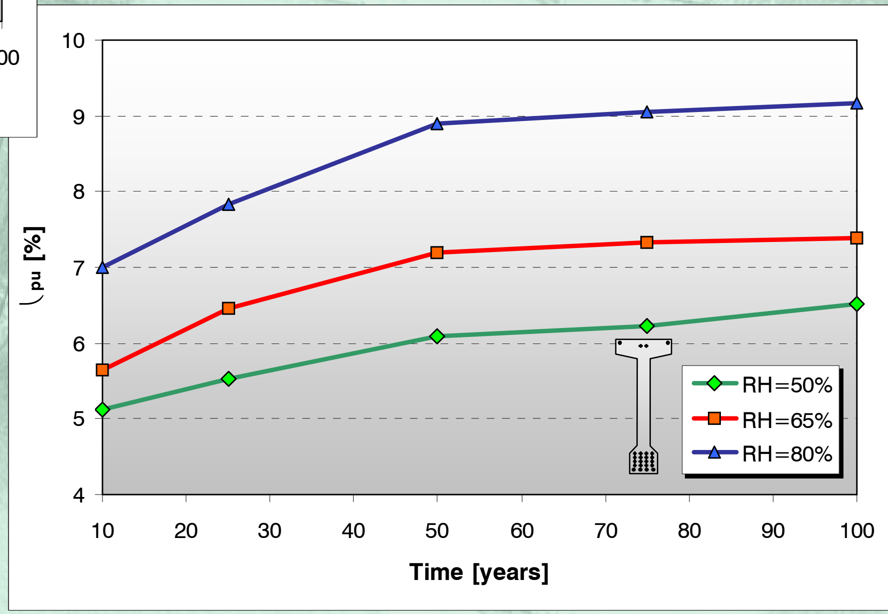


Change of cross-sectional area of steel bars due to corrosion in time at different relative humidity levels in case of beam “4000”

Results of analyses / Durability of long-span girders VI.

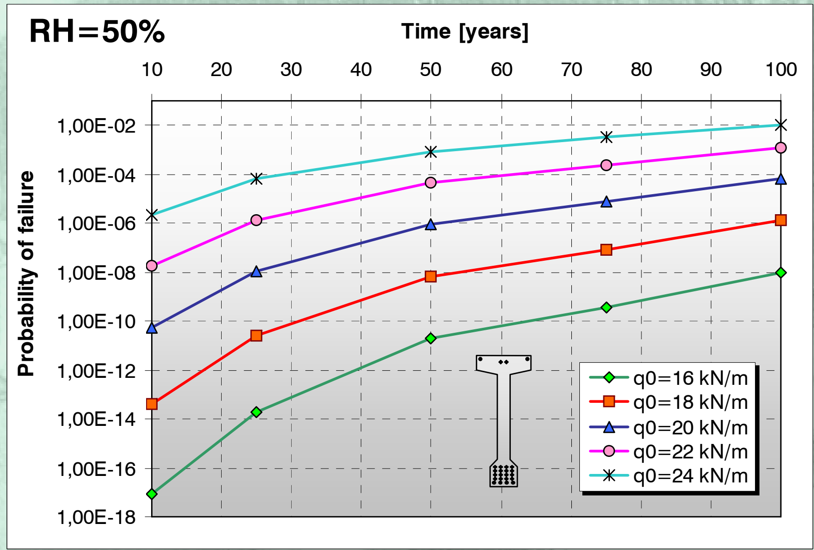


Change of mean value of structural resistance in time at different relative humidity (RH) levels in case of beam “4000”



Change of relative standard deviation of structural resistance in time at different RH levels in case of beam “4000”

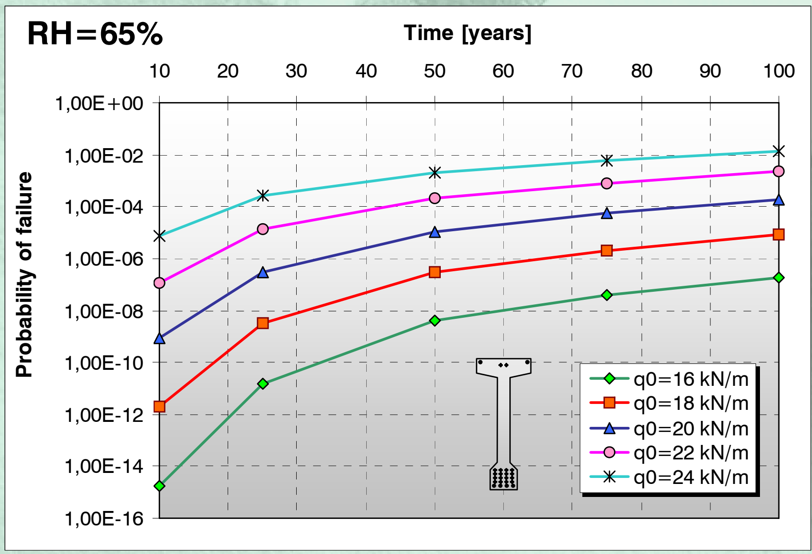
Results of analyses / Durability of long-span girders VII.

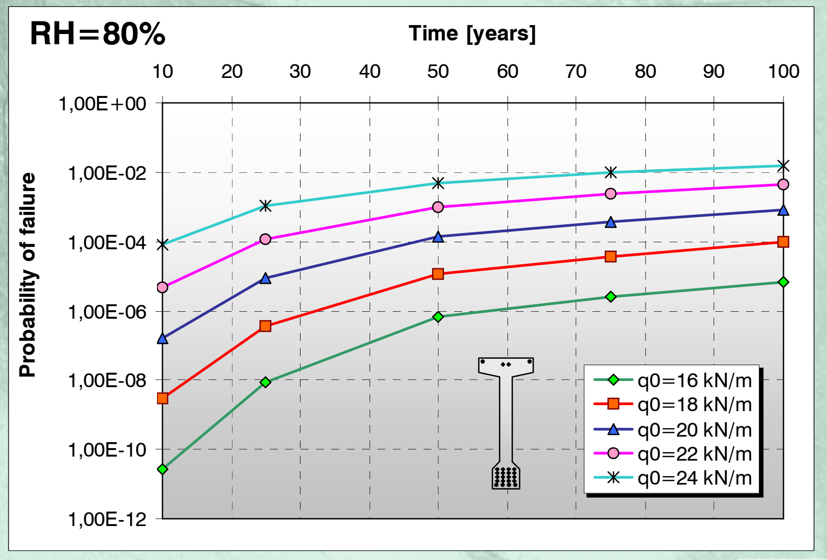


Change of the probability of failure of beam type "4000" in case of different initial imposed loads (q_0) and relative humidity (RH) levels.

The probability of failure is:

- increasing as time is passing by,
- increasing as the level of relative humidity (RH) is increasing,
- increasing as the initial value of imposed load (q_0) is increasing.





New result #3. (continued)

b.) I proved that the failure probability of pre-cast, prestressed concrete beams is increasing as time is passing by; it is increasing as the level of relative humidity is increasing and it is increasing as the initial value of imposed load is increasing. I demonstrated the increase rate of failure probability as a function of different parameters graphically. Durability-design of examined girders can be performed by the presented charts.

c.) I proved that the application of the presented method results in a more economic design (higher load carrying capacity or smaller member sizes) of the examined pre-cast, prestressed concrete beams than the use of the relevant Eurocode 2 standard.

d.) I proved that the presented method can be efficiently applied for the durability analysis of existing pre-cast, prestressed concrete members using geometry measurements and material tests on the examined members.

Acknowledgements

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Thank you for your attention!