Design criteria for wind-loaded structures beyond Eurocode

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with contributions from

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Challenges

When Eurocode is not (directly) applicable: How to find equivalent design criteria?

- Illustration 1: Equivalent design loads for retractable structures
- Illustration 2: Translating results from advanced numerical models into design values

How to open up the path to more optimal (economical) designs with advanced analysis methods?

- How to deal with hidden safety in Eurocode?

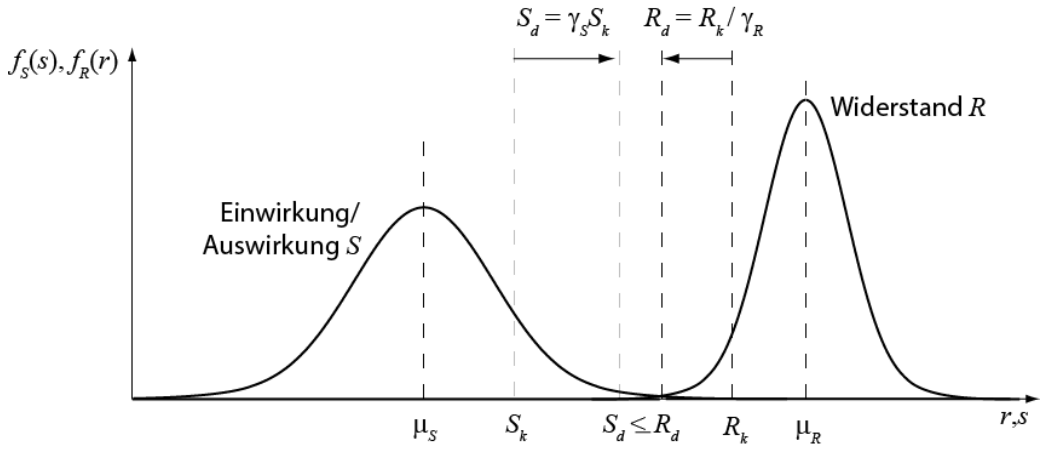
Background: Eurocode design criteria

Design of structures following Eurocode

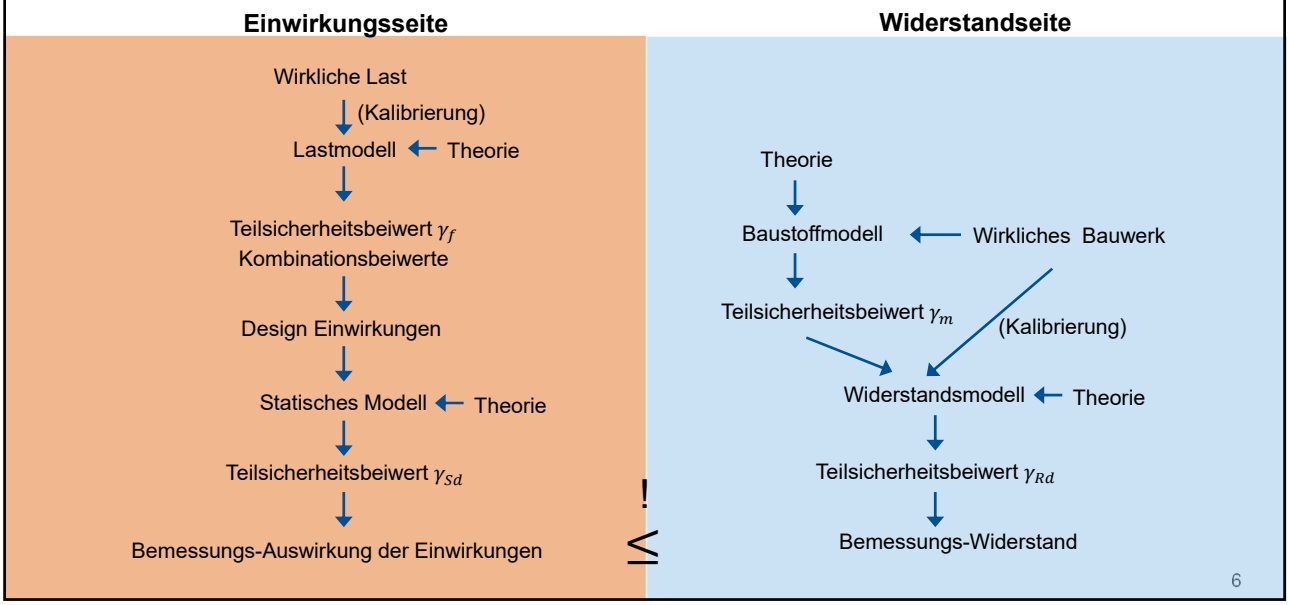
Eurocode 0 (EN 1990) prescribes basis of design:

- Partial safety factor concept (LRFD)
- Balance between safe and economic
- Developed for and applicable to standard design situations

Background to partial safety factor design (Eurocode)



Nachweisverfahren nach Eurocode



Design of a retractable roof

Retractable roof

- Roof area: 30‘000m^2
- Under strong winds, the roof is automatically retracted
- Based on wind measurements

➢ Availability of the retraction process in case of strong winds: 99%

Concept for design criteria

- Reliability of the roof must correspond to the reliability implied by Eurocode design
- During a strong wind event, the roof is not retracted with probability 1%

It follows:

➢ P_F of the roof in its deployed state under strong winds $\leq \frac{p_F}{0.01} = 100\, p_F$ of a code-based design

➢ Probabilistic model must enable a relative comparison of reliability

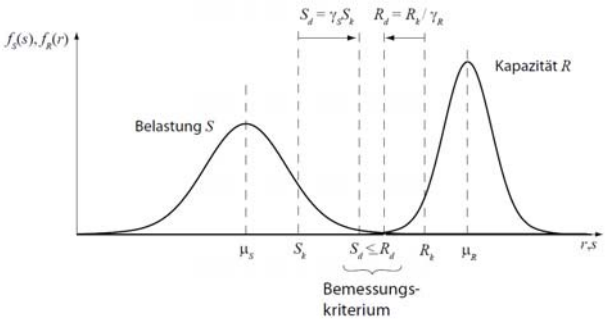
Design criteria

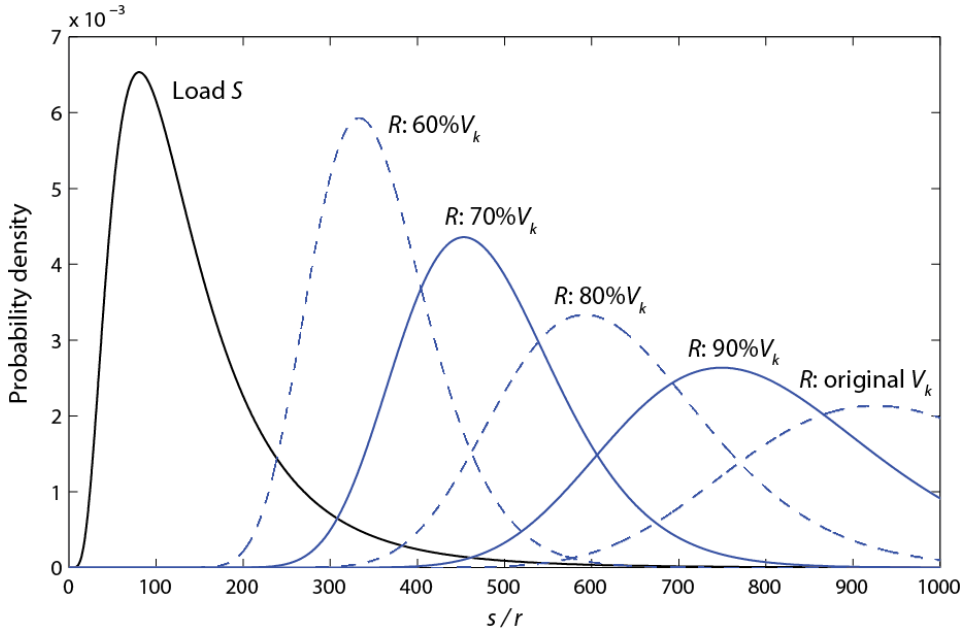
- Simplest reference model: Failure at $S \geq R$
- Load effects:

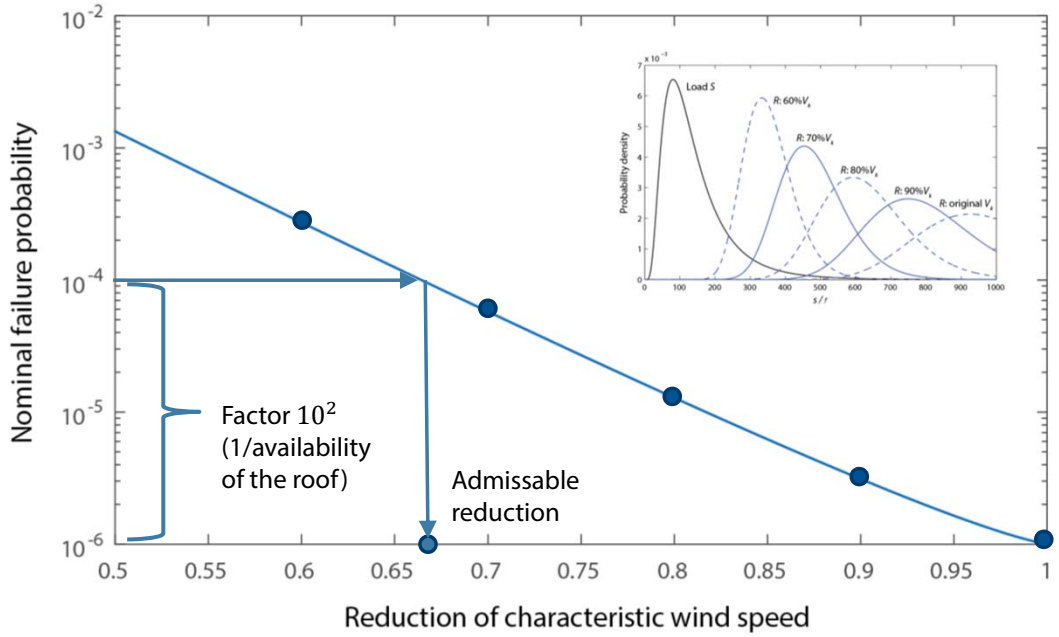
$$S = \alpha\, V_a^2\, X_m$$

- α: constant (linear, thus irrelevant)
- V_a: wind speed: Gumbel distributed
- X_m: model uncertainty: lognormal distributed
- Resistance R: lognormal distributed

➢ The mean value of R can be determined from the partial safety factor (EC) design check



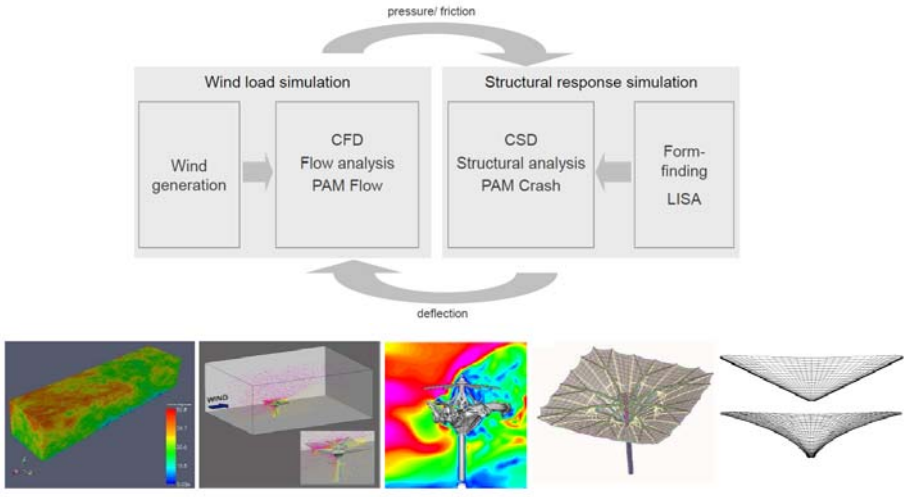

x 10 −3
Load S
R: 60%V k
R: 70%V k
R: 80%V k
R: 90%V k
R: original V k
Probability density
s / r


Nominal failure probability
Factor 10 2
(1/availability
of the roof)
Admissable
reduction
Reduction of characteristic wind speed

Translating results from advanced numerical models into design values

ERACONS. Engineering Reliability

Computational Wind Simulation & Structural Analysis



Michalski, A., P. D. Kermel, et al. (2011). Validation of the computational fluid-structure interaction simulation at real-scale tests of a flexible 29 m umbrella in natural wind flow. *Journal of Wind Engineering and Industrial Aerodynamics* **99**(4): 400-413.

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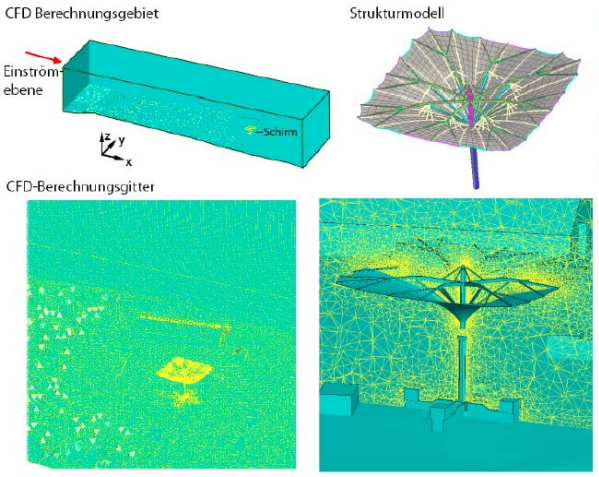
Computational efforts are significant
Thus length of the simulation is limited



Details:

Fully coupled FSI simulation

7 Mio elements

Simulated real time 600s

8 Cores ("Nehalem")
Linux SMP computer
7 CPU for CFD simulation
1 CPU for CSD simulation

Total elapsed CPU time
approx 32 d

CFD > 147 644 timesteps
CSD > 101 159 000 timesteps
average subcycling ratio 1/685

Michalski, A., P. D. Kermel, et al. (2011). Validation of the computational fluid-structure interaction simulation at real-scale tests of a flexible 29 m umbrella in natural wind flow. *Journal of Wind Engineering and Industrial Aerodynamics* **99**(4): 400-413.

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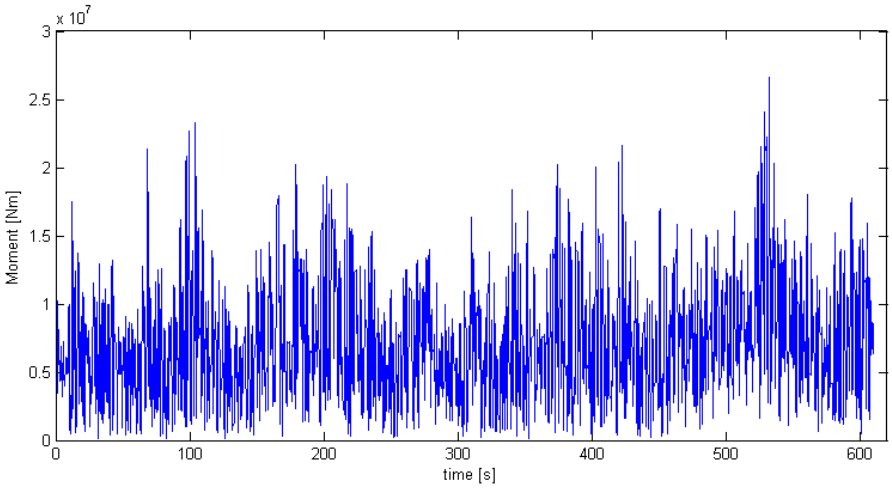
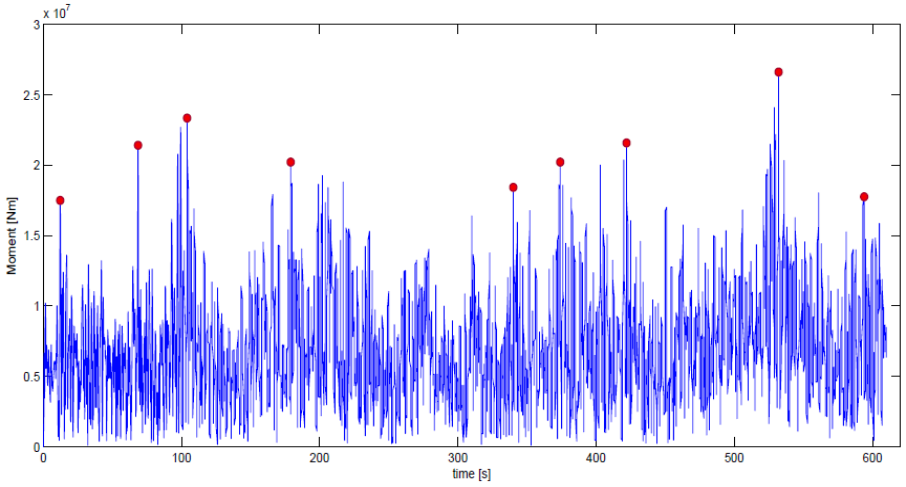
How to determine the design values?

Time series of a load effect resulting from characteristic (50 yr) wind:



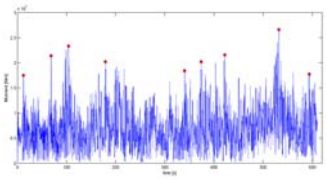
Step 1: Extreme value analysis

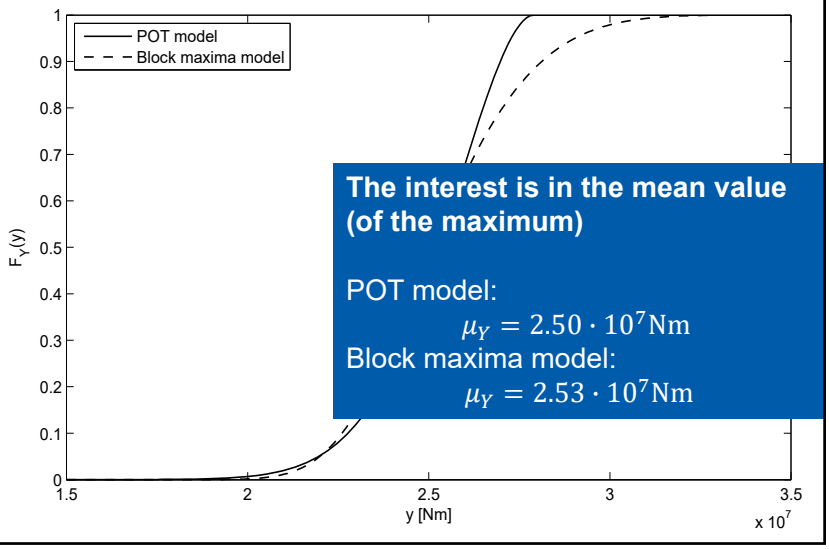
Peak-over-threshold:



Step 1: Extreme value analysis

Peak-over-threshold to assess maximum in a 10min time window





The interest is in the mean value (of the maximum)

POT model:

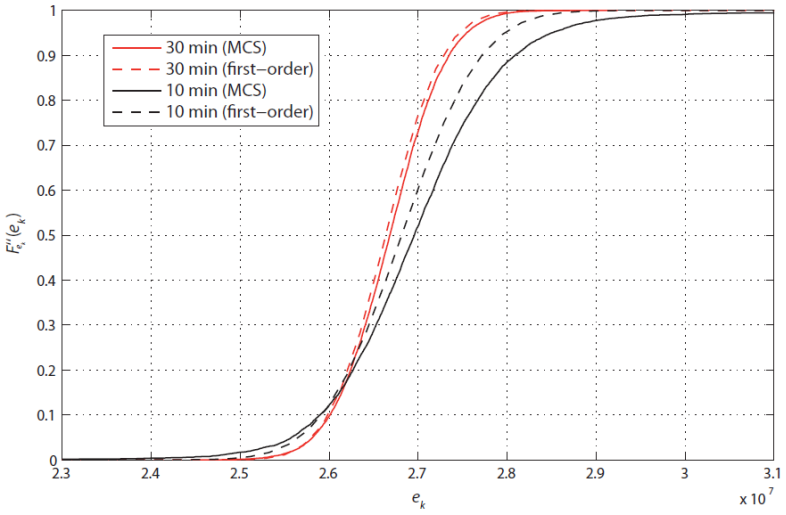
$$\mu_Y = 2.50 \cdot 10^7 \text{Nm}$$

Block maxima model:

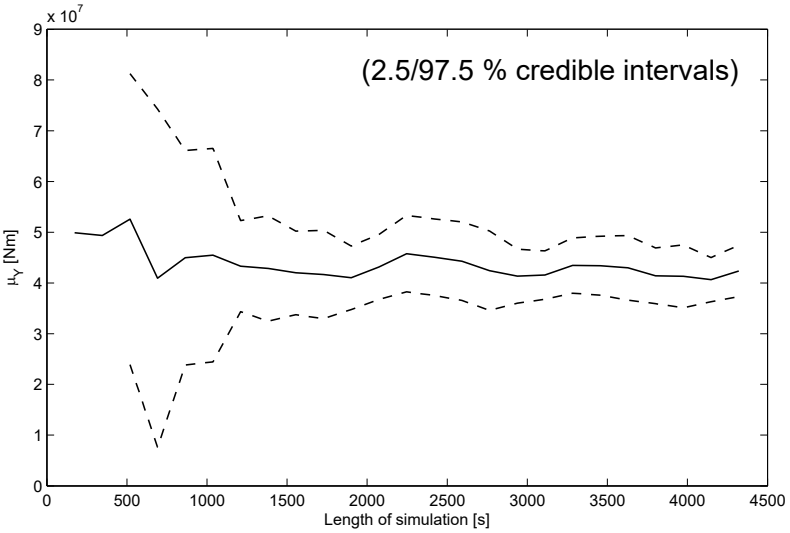
$$\mu_Y = 2.53 \cdot 10^7 \text{Nm}$$

Step 2: Quantify statistical uncertainty

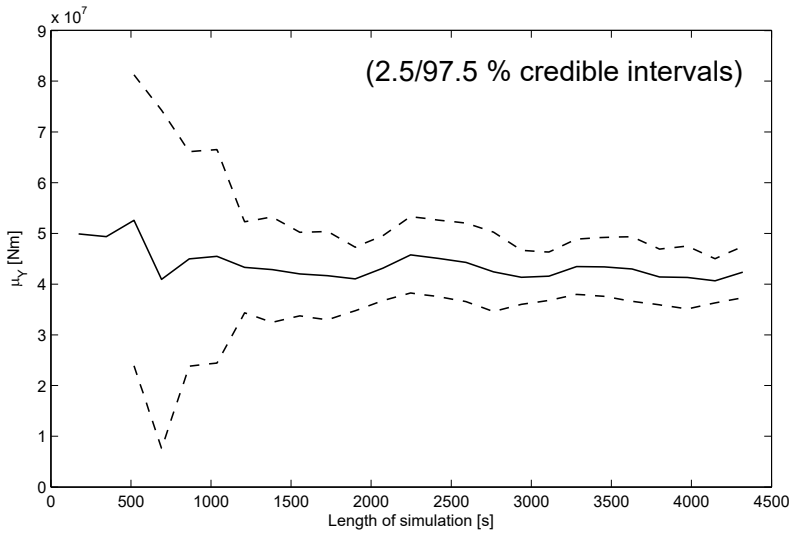
- Parameters θ of EV models determined by a Bayesian approach
- Resulting statistical uncertainty in the load effect by propagating uncertainty in $\boldsymbol{\theta}$ to $E_k(\boldsymbol{\theta})$



Statistical uncertainty varies with length of simulation



Step 3: Compensate the statistical uncertainty



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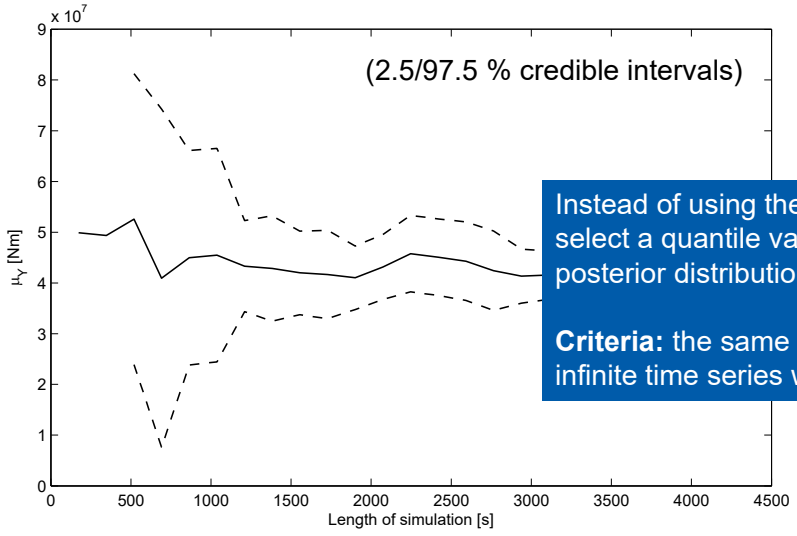


Instead of using the mean value, select a quantile value in the posterior distribution of the mean

Criteria: the same reliability as if an infinite time series was available

Step 3: Compensate statistical uncertainty

Criteria: Reliability achieved with limited data should be equal to reliability with unlimited data

$$\beta_k^{(T,q)} = \beta_k^{(\infty)}$$

where:
β_k: conditional reliability index (conditional on characteristic 50yr wind load scenario)
T: duration of simulation

Conditional reliability evaluation

Maximum load effect S: $$S = Y \cdot Z_m$$

Z_m : model error of the structural (FSI) analysis (LN distribution based on validation experiments)

Y : maximum load, predictive distribution as obtained from data:

$$F_Y(y) = \int_{\boldsymbol{\theta}} F_Y(y;\boldsymbol{\theta}) f_{\boldsymbol{\theta}}''(\boldsymbol{\theta}) \mathrm{d}\boldsymbol{\theta}.$$

Limit state function:

$$g(R, Y, Z_m) = R - Y \cdot Z_m$$

Conditional reliability evaluation

Distribution of R from:

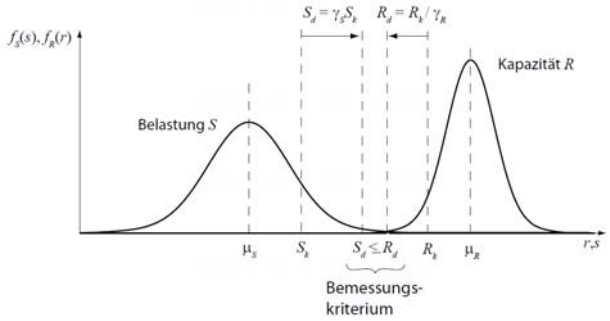
$$\frac{R_k}{\gamma_R} \geq E_{kq}\gamma_Q$$

thus:

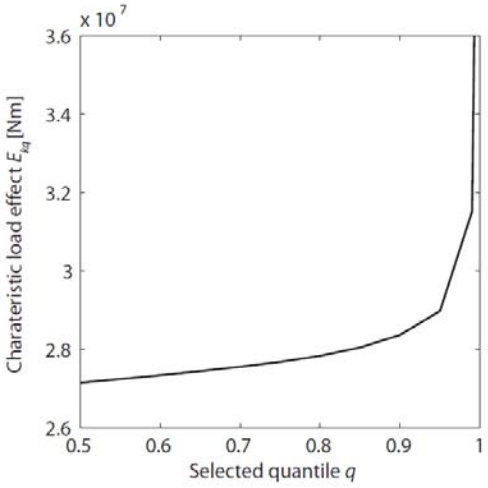
$$R_k = E_{kq}\gamma_Q\gamma_R$$

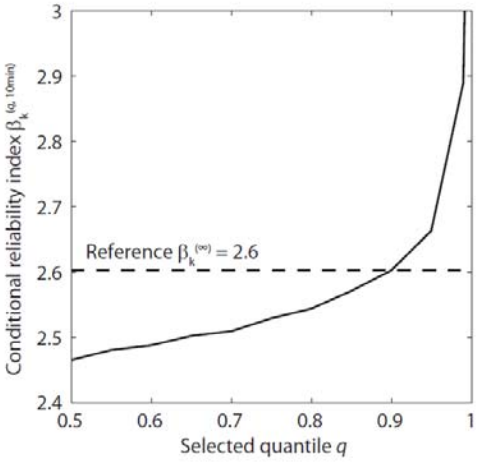
and

$$F_R^{-1}(0.05) = E_{kq}\gamma_Q\gamma_R$$

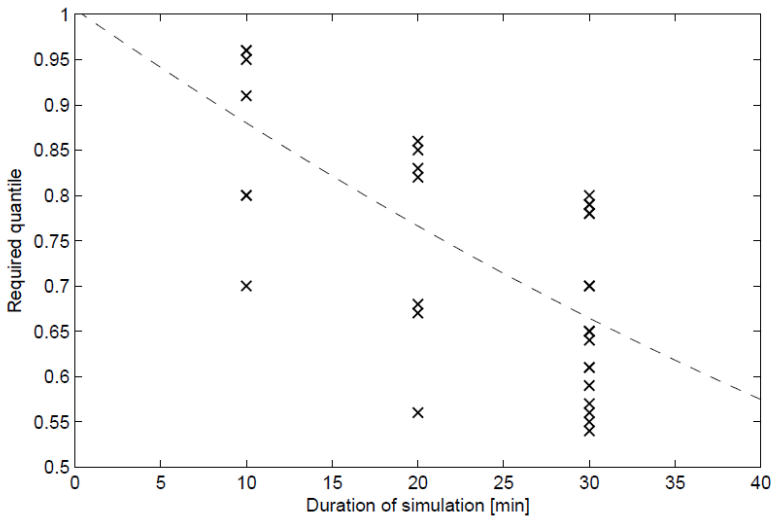


Effect of quantile selection on characteristic load effect and on reliability





Final result: required quantiles in function of time series length



Trade-off between computational cost (duration of simulation) and construction cost can be made

Use of advanced design methods: The *hidden safety* challenge

Eurocode: wind load model

Based on Davenport's wind loading chain (1987):

Wind climate → Influence of terrain → Aerodynamic effects → Dynamic effects → Criteria

Wind load determined from

- Reference wind speed (98 [%] quantil of 10 min mean wind speeds at 10m)
- Gust-, Pressure-, Roughness-coefficient

More precise predictions of wind loads are possible

This might be desirable from an economic point-of-view

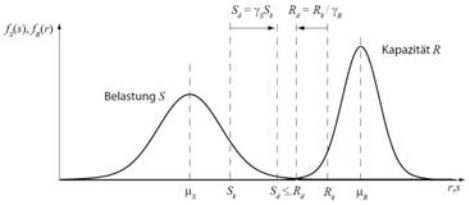
E.g. replace code coefficients by a virtual wind tunnel

E,g, replace wind generic wind speed map by a site-specific, direction dependent wind speed prediction

What is the effect of using advanced design methodologies?

Formal partial safety factor concept is based on:

- Characteristic values
- Partial safety factors



In reality, an additional safety element are conservative (parameter) choices in simplified models

This safety element can disappear if advanced models are utilized. What is the effect on the reliability?

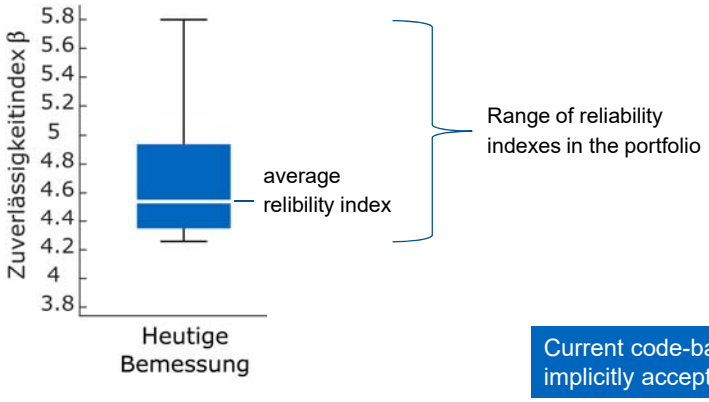
Numerical investigation

- Based on a representative portfolio of relevant structures (limit states) (as used inTC250 SC10 WG 1 for calibration of safety factors in Eurocode 0)
- Hidden safety is modeled through model uncertainties with biases
- Probabilistic model for hidden safeties follows Davenport (1987)

Confirmed with data from German weather service (DWD)

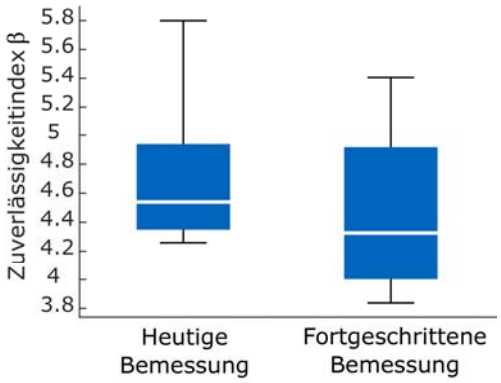
Quantity	Ratio: Expected / Specified	Coefficient of Variation
q (once-in-50 years)	0.8	0.2 - 0.3
C_{exp}	0.8	0.1 - 0.2
C_{shp}	0.9	0.1 - 0.2
C_{dyn}	1.0	0.1 - 0.2
ζ_{str} (damping)	1.0	0.4 - 0.5

Numerical investigation



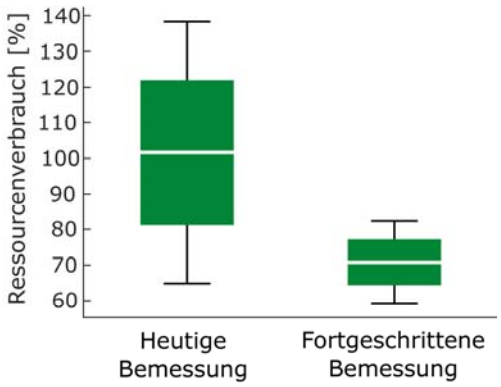
Current code-based design: implicitly accepted reliability level

Numerical investigation



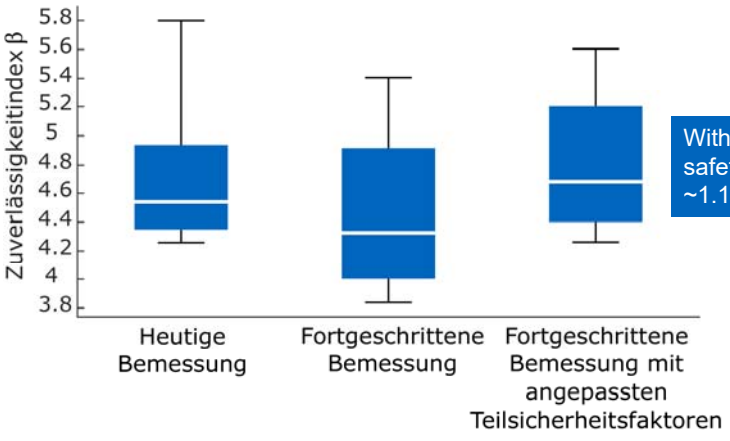
Design according to advanced methods with Eurocode safety factors and characteristic value. Is more precise, but can still lead to lower safety in the portfolio

Numerical investigation: economic aspects



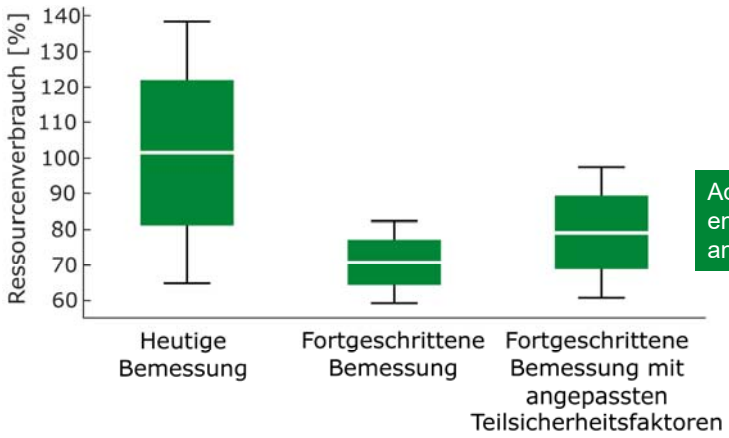
Advanced design methods leads to more economic structures

Additional safety factor to compensate for lost hidden safety



With additional safety factor ~1.15

Additional safety factor to compensate for lost hidden safety



Adjusted safety factor ensures an economic and safe design

What is the effect of using advanced design methodologies?

Formal partial safety factor concept is based on:

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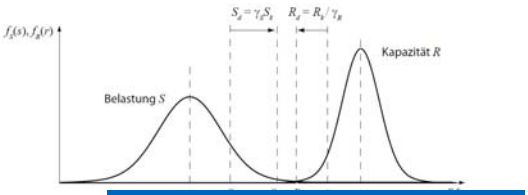
- Partial safety factors

In reality, an additional safety element are conservative (parameter) choices in simplified models



We do not really know how conservative they are (but often reflect legacy experience)

This safety element can disappear if advanced models are utilized. What is the effect on the reliability?

Conclusions

- Considerations based on simple probabilistic models enable a rational approach to identifying characteristic values and safety factors consistent with code requirements
- They can also address the uncertainty associated with limited knowledge and data
- When replacing Eurocode wind load design equations with advanced models, hidden safety should be addressed (possibly with additional safety factores) to maintain the reliability level

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