NTNU
Norwegian University of
Science and Technology

# Bridges and Structural Safety

## A brief introduction to principles and challenges

Jochen Köhler

9.04.2021

Norwegian University of Science and Technology, Trondheim, Norway



# Structural Safety
# - a principle demand

## Structural Safety...

...a principle demand (by law):

- Plan - og bygningsloven: § 29-5
  *(Konstruksjonen) skal prosjekteres og utføres slik at det ferdige tiltaket oppfyller* ***krav til sikkerhet****, helse, miljø, energi og bærekraftighet, og slik at vern av liv og materielle verdier ivaretas.*
- Forskrift om krav til byggverk (TEK): § 7-33
  *Byggverk skal utformes og dimensjoneres slik at de har tilfredsstillende* ***sikkerhet mot brudd*** *for de laster som kan oppstå under den forutsatte bruk. (...) Dersom forutsetningene for bruk endres, skal byggverkets sikkerhet vurderes på nytt.*

## Structural Safety for New Structures

## Attaining Structural Safety

...by following a combination of:

- **Design/Dimensioning for safety**
  - Structural capacity is controlled such that it is (most probably) larger than the demand.
  - The comparison is done by a so called limit state $G$, i.e. $G = \text{Capacity} - \text{Demand}$, such that $G < 0$ is defined as *failure* and the *failure probability* is correspondingly $P(G < 0)$.
  - Safety requirement might be formulated in terms of a target failure probability.
- **Quality Control**
  - Assuring that planning, design, execution and use is according to specifications and no errors are present.

## Requirements on Safety

How safe is safe enough?

In the Eurocodes *appropriate* level of reliability is dependent on:

- the possible cause and /or **mode** of attaining a limit state;
- the possible **consequences** of failure in terms of risk to life, injury, potential economical losses;
- public **aversion** to failure;
- the **expense** and procedures necessary to **reduce** the risk of failure.

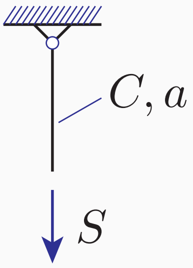


## Safety requirement

| Reliability Class | Minimum values for $\beta$ | |
|---|---|---|
| | 1 year reference period | 50 years reference period |
| RC3 | 5,2 | 4,3 |
| RC2 | 4,7 | 3,8 |
| RC1 | 4,2 | 3,3 |

Figure 1: Reliability requirements as stated in EN 1990:2002

## Reliability based design - a simple example

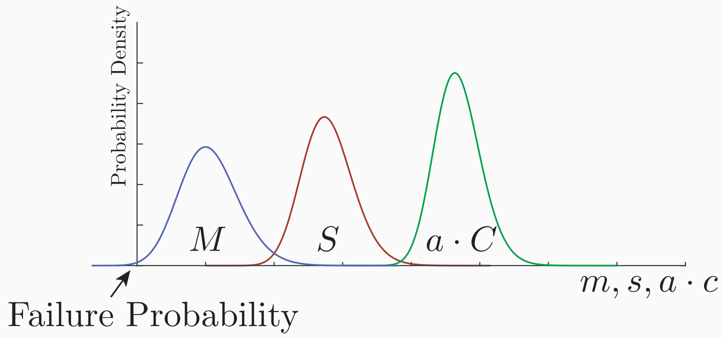



| | $\mu$ | $\sigma$ |
|---|---|---|
| Capacity $C\ [kN/mm^2]$ | 1 | 0.10 |
| Load $S\ [kN]$ | 1 | 0.34 |

C,S Normal distributed.

Failure $= \{a \cdot C - S < 0\}$

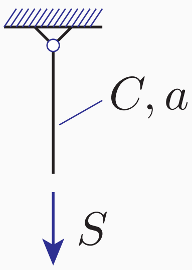
Failure Probability:
$P(\text{Failure}) = P(a \cdot C - S < 0) = P(M < 0)$




$$P(M < 0) = \Phi\left(\frac{0-\mu_M}{\sigma_M}\right) = \Phi\left(\frac{-a\cdot\mu_C+\mu_S}{\sqrt{a^2\sigma_C^2+\sigma_S^2}}\right) = \Phi(-\beta)$$



## Reliability based design - a simple example




| | $\mu$ | $\sigma$ |
|---|---|---|
| Capacity $C\ [kN/mm^2]$ | 1 | 0.10 |
| Load $S\ [kN]$ | 1 | 0.34 |

C,S Normal distributed.

Reliability based design with target reliability $\beta_t = 3.8$:

$$a \text{ such that } \beta_{req} = 3.8 \leq \beta = \frac{a\cdot\mu_C - \mu_S}{\sqrt{a^2\sigma_C^2 + \sigma_S^2}}$$

In this example equality is obtained for $a = 2.615\ mm^2$.

## Reliability based design - discussion

- A design can be identified that **corresponds** to a specified reliability requirement.
- The most simple form of reliability problem was considered here, but in practice it is often much **more complex**.
- The achieved reliability is **conditional on utilised knowledge** - the reliability based design solution is also conditional on knowledge!
- Reliability is always dependent on specified **reference time**.



## Practical Design

## Practical Design

Recapturing the Example from above, Safety/Reliability is evaluated based on a limit state function:

$$a \cdot C - S < 0$$

which required (cumbersome) reliability analysis.

In practical design, Safety/Reliability is evaluated based on *Design Equations* that are related to the limit state:

$$a \cdot \frac{c_k}{\gamma_C} - \gamma_S \cdot s_k < 0$$

Here, the random variables are replaced by a combination of so-called characteristic values ($c_k$, $s_k$) and safety factors ($\gamma_C$, $\gamma_S$). No reliability analysis is necessary.



## Practical Design

According to the Eurocode Design Equations are generally used. Corresponding information is provided by the standard, i.e.:

- safety factors for different structural materials and loads,
- characteristic values for material strength, load intensity,
- modification factors to account for temporal, spatial and/or combination effects.

**The information is generalised and valid for the design of new structures!**

## Practical Design

In particular, the following simplifications should be observed:

- spatial variability of material strength is assumed to be small and neglected,
- load process ergodic, resistance constant (once it is realised),
- safety evaluated at single cross sections individually.



## Intermediate Conclusion

- practical design based on generalized information and subject to simplifications,
- reliability requirement not to be seen as absolute by relative to the generalized and simplified representation.
- **However**, the approach works: Structures are perceived safe and (sufficiently) efficient.

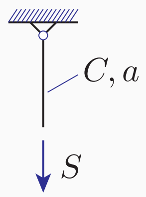
# Structural Safety
# of Existing Structures

## Reassessing Structural Safety

- As part of maintenance
  - The safe use of the structure has to be guarantied during the service life.
  - No reassessment necessary if (1) resistance can be assumed to be constant and (2) load ergodic.
  - Reassessment necessary when doubts about (1) and (2).
- Service life extension
  - The safe use of the structure has to be confirmed after the projected service life has passed.
- Change in use
  - Change in use implies different loading than projected and requires reassessment.



## Reliability reassessment - a simple example (cont.)



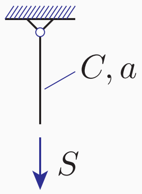

| | Type | $\mu$ | $\sigma$ |
|---|---|---|---|
| Capacity $C\ [kN/mm^2]$ | Logn | 1 | 0.10 |
| Load $S\ [kN]$ | Gumbel | 1 | 0.34 |
| Corrosion loss $R\ [mm/a]$ | Logn | 0.1 | 0.05 |

$$a = 2.6\ mm$$

$$\text{Failure} = \{(a - R \cdot t) \cdot C - S < 0\}$$

- The limit state has to be extended in order to represent the deterioration mechanism.
- The reliability becomes time dependent (and the decay of reliability can be predicted based on the model assumptions).
- All variables can be updated based on new information. E.g. for $R$ direct or indirect information might be utilized.
- The consideration of information has a direct effect on the computed reliability!

## Reliability reassessment - a simple example (cont.)




| | Type | $\mu$ | $\sigma$ |
|---|---|---|---|
| Capacity $C\left[kN/mm^2\right]$ | Logn | 1 | 0.10 |
| Load $S\,[kN]$ | Gumbel | 1 | 0.34 |
| Corrosion loss $R\,[mm/a]$ | Logn | 0.1 | 0.05 |

$$a = 2.6\ mm$$

$$\text{Failure} = \{(a - R \cdot t) \cdot C - S < 0\}$$

### Challenges

- The a-priory model for deterioration is difficult to formulate due to large uncertainties.
- Deterioration processes often add a spatial dimension to the problem.
- Measurements/observations provide often only indirect information, updating requires likelihoods and these are difficult to specify.



## Reliability reassessment - Bridge Challenges

### Bridge Challenges

- The mechanical system is far **more complex** and many simplifications taken during the design are not longer valid.
- Deterioration affects the strength **locally** - global measurements are not very informative; local measurements are likely misplaced.
- The computed **reliability** (as relative to the model representation) is **difficult to compare** with absolute reliability requirements.
- Mitigation measures are costly and often hard to implement.

# Conclusion

## Conclusion

- The principles of safety assessment of new and existing structures was briefly addressed.
- The level of detail was correspondingly low but sufficient to highlight the main challenges of safety assessment.
- In practical assessment situations aspects that are not directly related to safety are often addressed as a proxy for the overall “health” of the structure.
- The presentations at the workshop will deepen the discussion to a much more informative level of detail from the perspective of research, infrastructure owner and technical consultant.

Questions?