Risk and Safety

in

Engineering

Prof. Dr. Michael Havbro Faber

Swiss Federal Institute of Technology

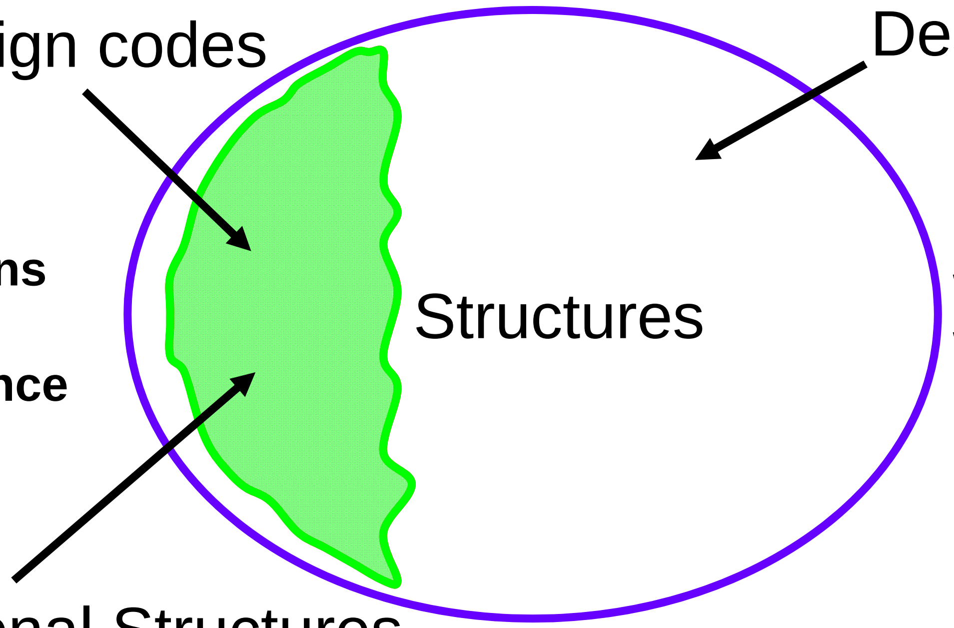
ETH Zurich, Switzerland

Contents of Presentation

- Codes and design of structures
- Structural reliability and safety formats
- Code calibration as a decision problem
- Target reliabilities for the design of structures
- The JCSS approach to code calibration
- The software CodeCal – for calibration of design codes

Codes and design of structures

- “Normal structures” are designed according to structural design codes

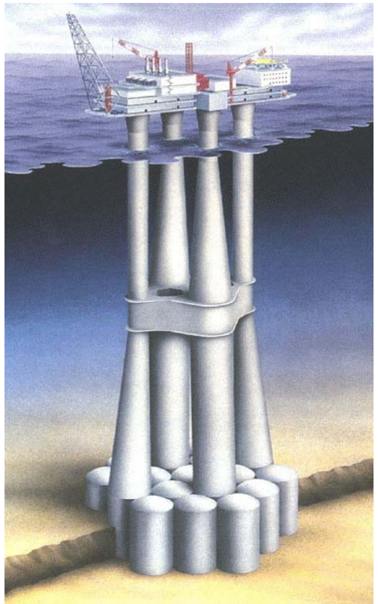


Codes and design of structures

- Exceptional structures are often associated with structures of

"Extreme Dimensions"

Great Belt Bridge under Construction

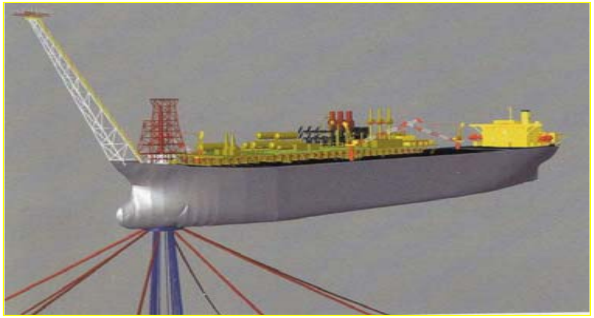


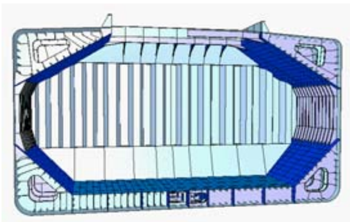
Concept drawing of the Troll platform

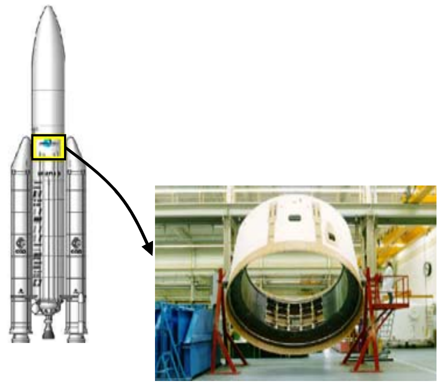
Codes and design of structures

- or associated with structures fulfilling

“New and Innovative Purposes”







Concept drawing of Floating Production, Storage and Offloading unit

Illustrations of the ARIANE 5 rocket

Structural reliability and safety formats

Structural performance is subject to uncertainty due to:

- Natural variability in material properties and loads or load effects
- Statistical uncertainties due to lack of or insufficient data
- Model uncertainties due to idealisations and lack of understanding in the physical modelling of the structural performance

Structural reliability and safety formats

- Structural performance may be treated in probabilistic terms by means of

  limit state functions

  i.e. defining the events of special concern (large consequences) – failure events such as

  - Collapse
  - Loss of serviceability
  - Deterioration

  } Failure Events

  as functions of the most important uncertainties – the basic random variables

$$F = \{g(\mathbf{x}) \leq 0\}$$

F: Failure Events

g: Limit state functions

$\mathbf{x}$: Outcome of basic random variables

Structural reliability and safety formats

- The fundamental case

$$P_F = P(R \leq S) = P(R - S \leq 0) =$$

$$\int_{-\infty}^{\infty} F_R(x) f_S(x) dx$$

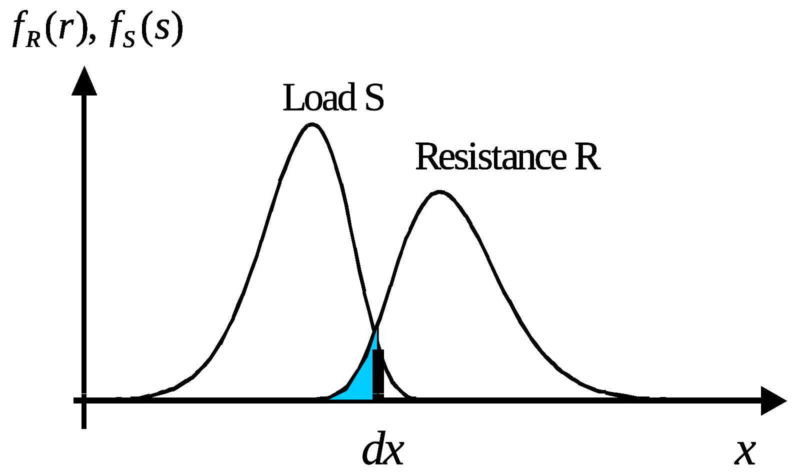
- Normal distributed safety margin

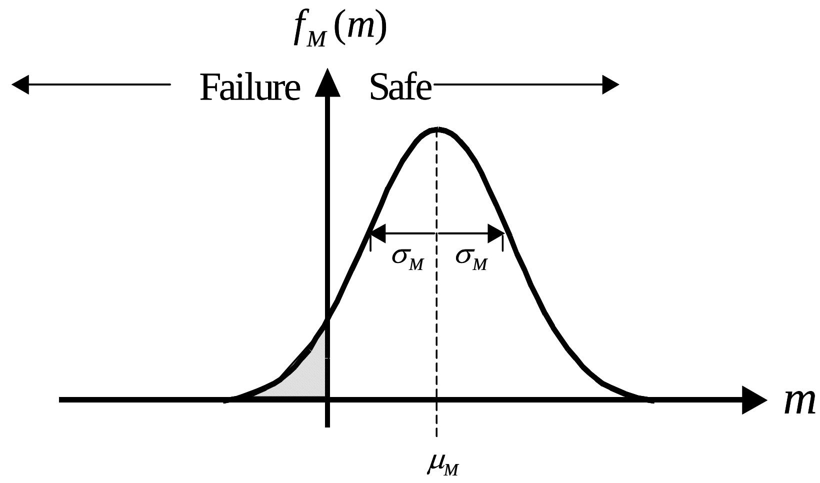
$$P_F = P(R - S \leq 0) = P(M \leq 0)$$

$$\mu_M = \mu_R - \mu_S$$

$$\sigma_M = \sqrt{\sigma_R^2 + \sigma_S^2} \qquad \mu_M / \sigma_M = \beta$$

$$P_F = \Phi\left(\frac{0 - \mu_M}{\sigma_M}\right) = \Phi(-\beta)$$





Structural reliability and safety formats

- The probability of failure
  with regard to:

  - Ultimate collapse

  - Loss of serviceability

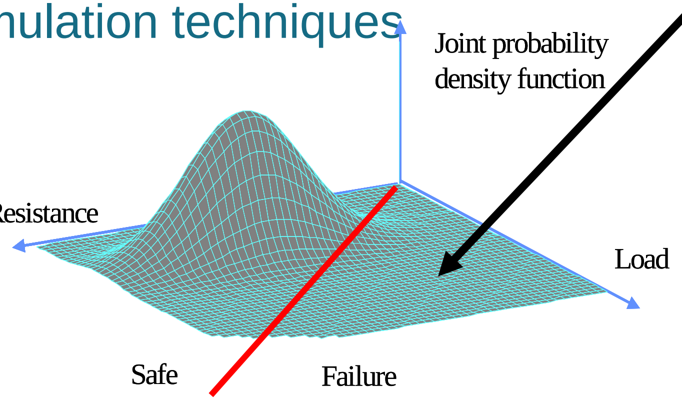
  - Excessive deterioration

  may then be assessed by evaluation of probability integrals using e.g. FORM/SORM or simulation techniques

$$P_f = \int_{g(\mathbf{x})\leq 0} f_{\mathbf{X}}(\mathbf{x})d\mathbf{x}$$

Failure event

Joint density function for the basic random variables



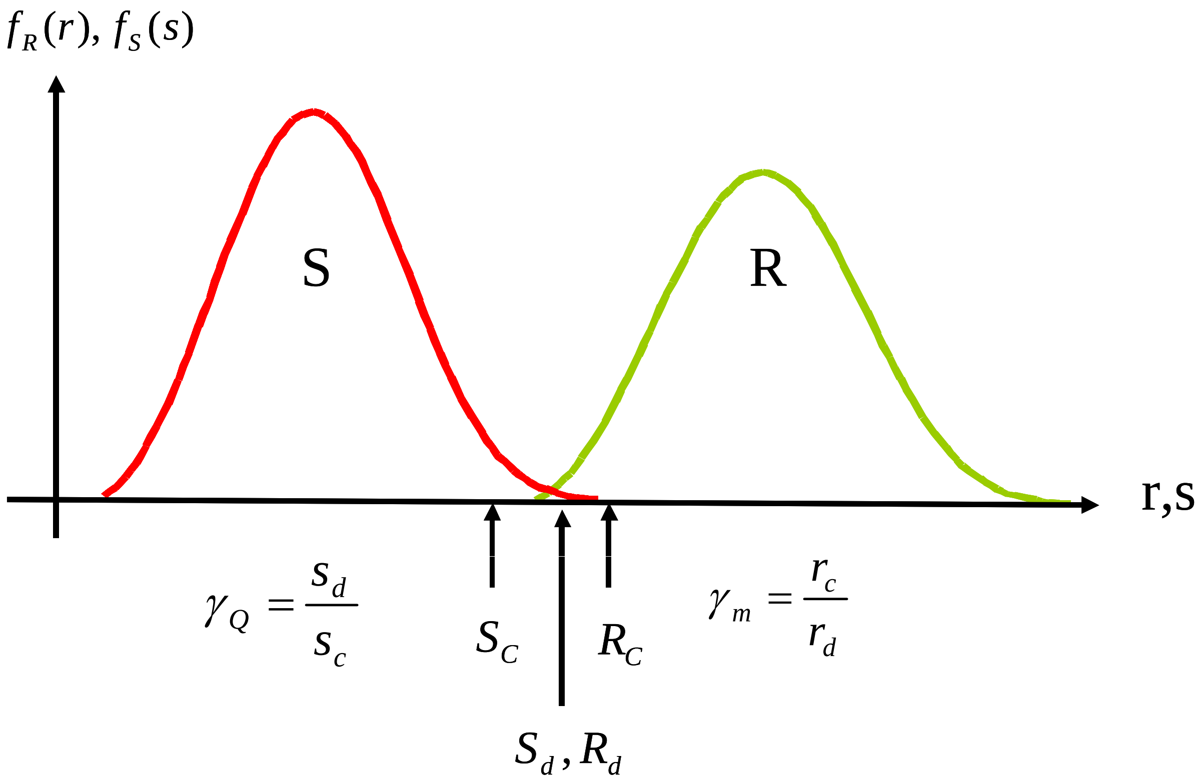
Structural reliability and safety formats

- The Load and Resistance Factor Design safety format is built up by the following components

Design situations	Ultimate, serviceability, accidental
Design equations	$g = \mathbf{z}R_c/\gamma_m - \left(\gamma_{G_a}G_c + \gamma_Q Q_C\right) = 0$
Design variables	$\mathbf{z}$
Characteristic values	$G_C \quad Q_C$
Partial safety factors	$\gamma_m \quad \gamma_G \quad \gamma_Q$
Design values	$\gamma_m = \dfrac{x_c}{x_d} \qquad \gamma_Q = \dfrac{x_d}{x_c}$

Structural reliability and safety formats

- The results of a FORM/SORM reliability analysis can be related to the parameters of a LRFD safety format



Code calibration as a decision problem

- The code calibration problem can be seen as a decision problem with the objective to maximize the life-cycle benefit obtained from the structures by "calibrating" (adjusting) the partial safety factors

$$\max_{\gamma} \quad W(\gamma) = \sum_{j=1}^{L} w_j \left[B_j - C_{Ij}(\gamma) - C_{Rj}(\gamma) - C_{Fj} P_{Fj}(\gamma) \right]$$

$$s.t. \quad \gamma_i^l \leq \gamma_i \leq \gamma_i^u \quad , i = 1, \ldots, m$$

- The "optimal" design is determined from the design equations

$$\min_{\gamma} \quad C_{Ij}(\mathbf{z})$$

$$s.t. \quad G_j\left(\mathbf{x}_c, \mathbf{p}_j, \mathbf{z}, \gamma\right) \geq 0$$

$$z_i^l \leq z_i \leq z_i^u \quad , i = 1, \ldots, N$$

$$G_j(\mathbf{x}_c, \mathbf{p}_j, \mathbf{z}, \gamma) \geq 0$$

Target reliabilities for the design of structures

- **Target reliabilities for Ultimate Limit State verification**

Relative cost of safety measure	Minor consequences of failure	Moderate consequences of failure	Large consequences of failure
High	β=3.1 ($P_F \approx 10^{-3}$)	β=3.3 ($P_F \approx 5\ 10^{-4}$)	β=3.7 ($P_F \approx 10^{-4}$)
Normal	β=3.7 ($P_F \approx 10^{-4}$)	β=4.2 ($P_F \approx 10^{-5}$)	β=4.4 ($P_F \approx 5\ 10^{-5}$)
Low	β=4.2 ($P_F \approx 10^{-5}$)	β=4.4 ($P_F \approx 10^{-5}$)	β=4.7 ($P_F \approx 10^{-6}$)

- **Target reliabilities for Serviceability Limit State Verification**

Relative cost of safety measure	Target index (irreversible SLS)
High	β=1.3 ($P_F \approx 10^{-1}$)
Normal	β=1.7 ($P_F \approx 5\ 10^{-2}$)
Low	β=2.3 ($P_F \approx 10^{-2}$)

The JCSS approach to code calibration

- A seven step approach

1. Definition of the scope of the code
   - Class of structures and type of failure modes

2. Definition of the code objective
   - Achieve target reliability/probability

3. Definition of code format
   - how many partial safety factors and load combination factors to be used
   - should load partial safety factors be material independent
   - should material partial safety factors be load type independent
   - how to use the partial safety factors in the design equations
   - rules for load combinations

The JCSS approach to code calibration

- A seven step approach

4. Identification of typical failure modes and of stochastic model
   - relevant failure modes are identified and formulated as limit state functions/design equations
   - appropriate probabilistic models are formulated for uncertain variables

5. Definition of a measure of closeness
   - the objective function for the calibration procedure is formulated e.g.

$$\min_{\gamma} W(\gamma) = \sum_{j=1}^{L} w_j \left(\beta_j(\gamma) - \beta_t\right)^2 \qquad \min_{\gamma} W'(\gamma) = \sum_{j=1}^{L} w_j \left(P_{Fj}(\gamma) - P_F^t\right)^2$$

The JCSS approach to code calibration

- A seven step approach

6. Determination of the optimal partial safety factors for the chosen code format

$$
\begin{aligned}
&\min && C(\mathbf{z}) \\
&s.t. && c_i(\mathbf{x}_c,\mathbf{p}_j,\mathbf{z},\gamma)=0 \quad ,i=1,\ldots,m_e \\
& && c_i(\mathbf{x}_c,\mathbf{p}_j,\mathbf{z},\gamma)\geq 0 \quad ,i=m_e+1,\ldots,m \\
& && \mathrm{z}_\mathrm{i}^\mathrm{l} \leq \mathrm{z}_\mathrm{i} \leq \mathrm{z}_\mathrm{i}^\mathrm{u} \quad ,i=1,\ldots,N
\end{aligned}
$$

7. Verification
   - incorporating experience of previous codes and practical aspects

The code calibration software CodeCal

- CodeCal