Risk and Safety

in

Engineering

Prof. Dr. Michael Havbro Faber

Swiss Federal Institute of Technology

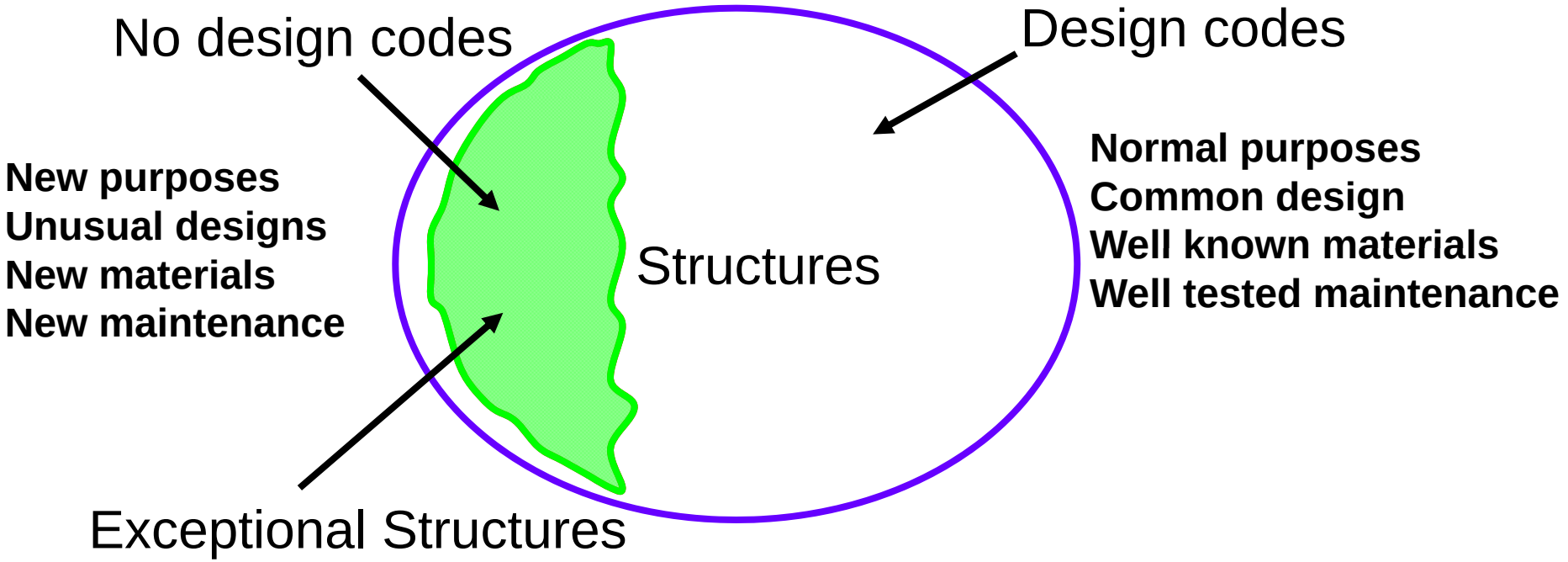
ETH Zurich, Switzerland

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
- CodeCal – a software 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 associated with

"Extreme Dimensions"

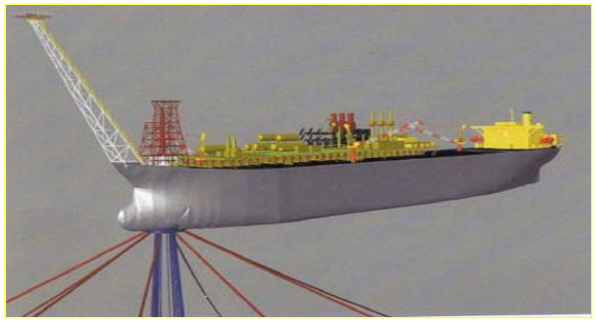
Great Belt Bridge under construction

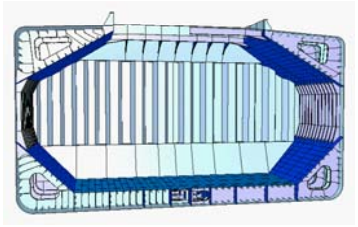
Concept drawing of the Troll platform

Codes and design of structures

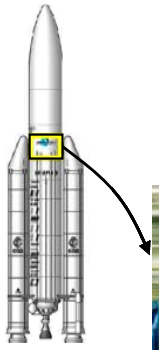
- Exceptional structures are associated with fulfilling

“New and Innovative Purposes”





Concept drawing of Floating Production, Storage and Offloading (FPSO) 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 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 (having large consequences) or failure events such as

  - Collapse
  - Loss of serviceability
  - Deterioration

  } Failure Events

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

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

Limit state functions

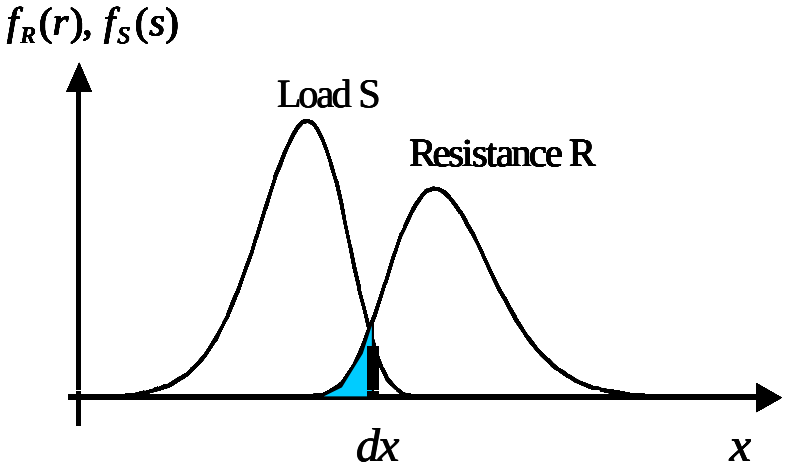
Outcome of basic random variables

Structural reliability and safety formats

- The fundamental case

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

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



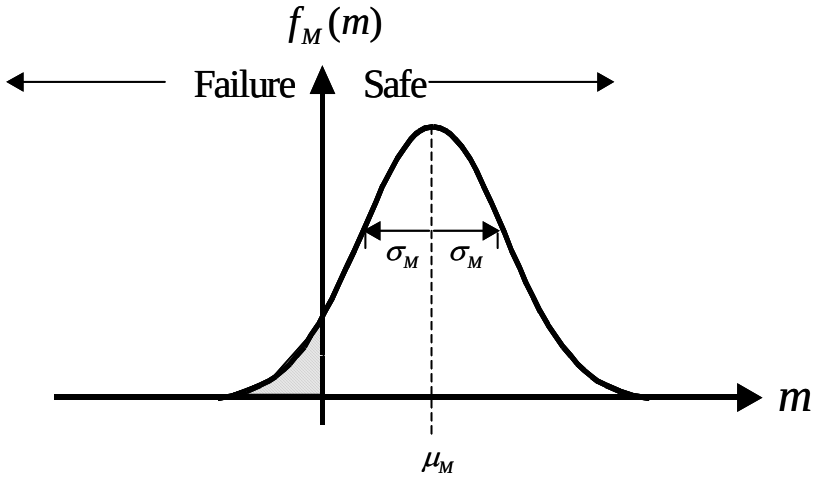
- Normal distributed safety margin

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

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

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

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



Structural reliability and safety formats

- The probability of failure with regard to:

  - Ultimate collapse

  - Loss of serviceability

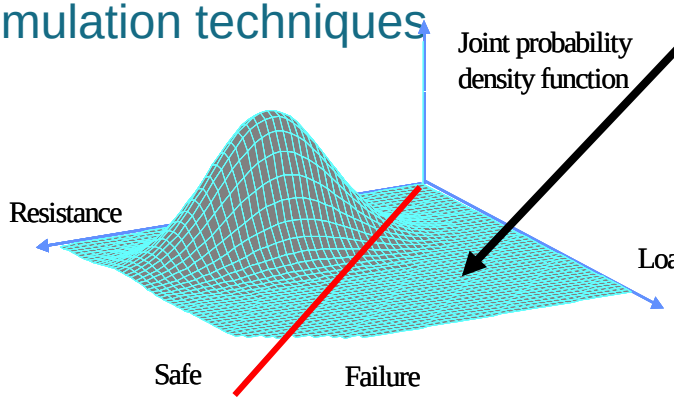
  - Excessive deterioration

  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



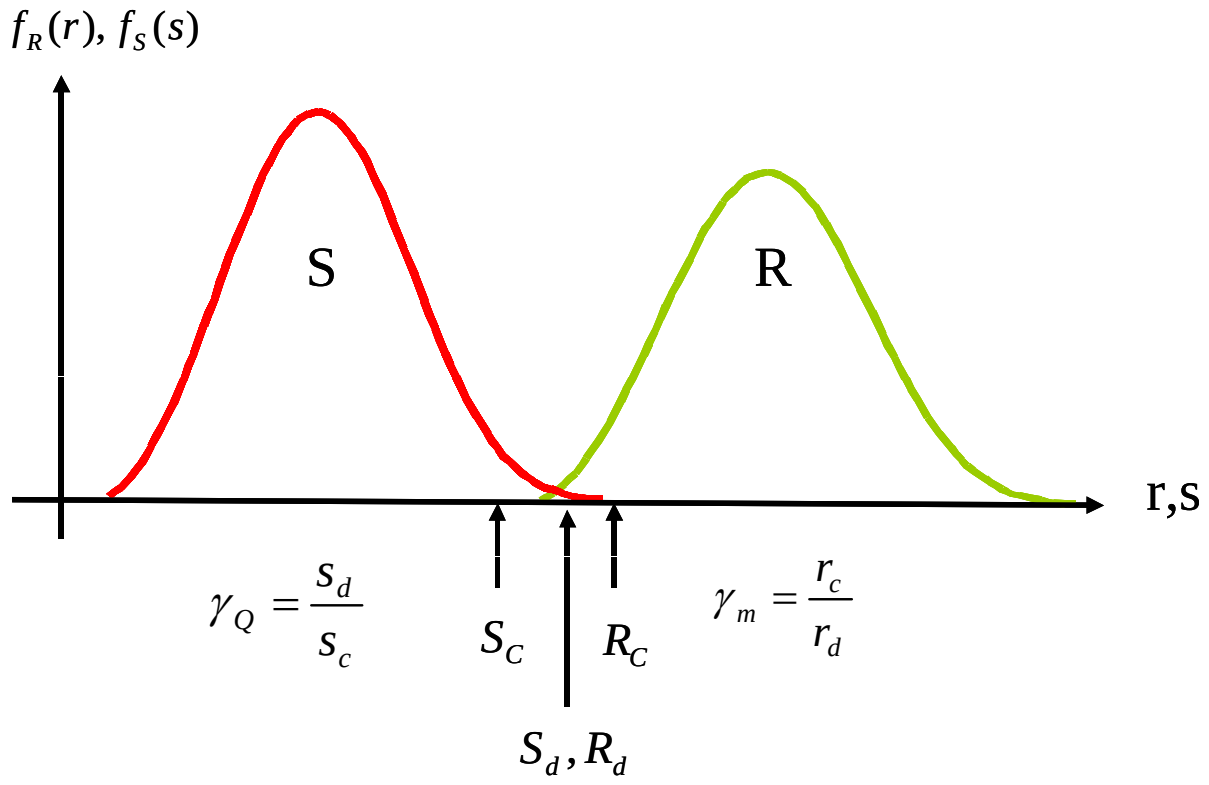
Structural reliability and safety formats

- The Load and Resistance Factor Design (LRFD) 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	$\gamma_m = \frac{x_c}{x_d} \qquad \gamma_Q = \frac{x_d}{x_c}$

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

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

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

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

$$\min_{\gamma} \quad C_{Ij}(\mathbf{z}) \qquad\qquad G_j(\mathbf{x}_c, \mathbf{p}_j, \mathbf{z}, \gamma) \ge 0$$

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

$$\mathbf{z}_i^l \le z_i \le \mathbf{z}_i^u \quad , i = 1,\ldots,N$$

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	$\beta=3.1$ ($P_F \approx 10^{-3}$)	$\beta=3.3$ ($P_F \approx 5\ 10^{-4}$)	$\beta=3.7$ ($P_F \approx 10^{-4}$)
Normal	$\beta=3.7$ ($P_F \approx 10^{-4}$)	$\beta=4.2$ ($P_F \approx 10^{-5}$)	$\beta=4.4$ ($P_F \approx 5\ 10^{-5}$)
Low	$\beta=4.2$ ($P_F \approx 10^{-5}$)	$\beta=4.4$ ($P_F \approx 10^{-5}$)	$\beta=4.7$ ($P_F \approx 10^{-6}$)

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

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

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

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

7. Verification

   - incorporating experience of previous codes and practical aspects

The code calibration software CodeCal

- CodeCal