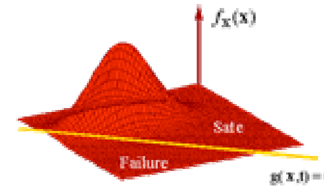
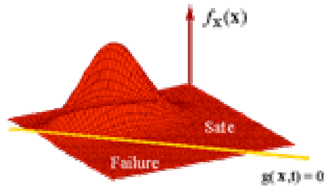


Reliability Based Code Calibration

M. H. Faber, ETH Zurich, Switzerland
J.D. Sorensen, AAU, Aalborg, Denmark.

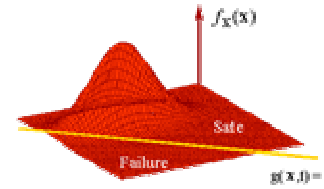
JCSS Workshop on *Reliability Based Code Calibration*, March 21-22, 2002, Zurich, Switzerland.



Overview of Presentation

- Design Codes and Code Calibration in the Past
- Principles of Structural Reliability
- Reliability and Partial Safety Factors
- The Code Calibration Decision Problem
- Optimality and Target Reliabilities
- A Practical Code Calibration Procedure
- Conclusions and Future Challenges

Design Codes and Code Calibration in the Past



Structural safety is a matter to be considered throughout all phases of the life of a structure

- **Uncertainties**
- **Traffic volume**
- **Loads**
- **Resistances (material, soil,..)**
- **Degradation processes**
- **Service life**
- **Manufacturing costs**
- **Execution costs**
- **Decommissioning costs**

Idea & Concept

Planning and feasibility study

Investigations and tests

Design

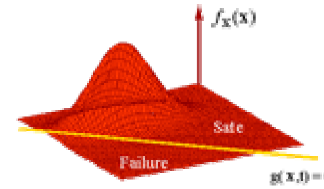
Manufacturing

Execution

Operation & maintenance

Decommissioning

Design Codes and Code Calibration in the Past

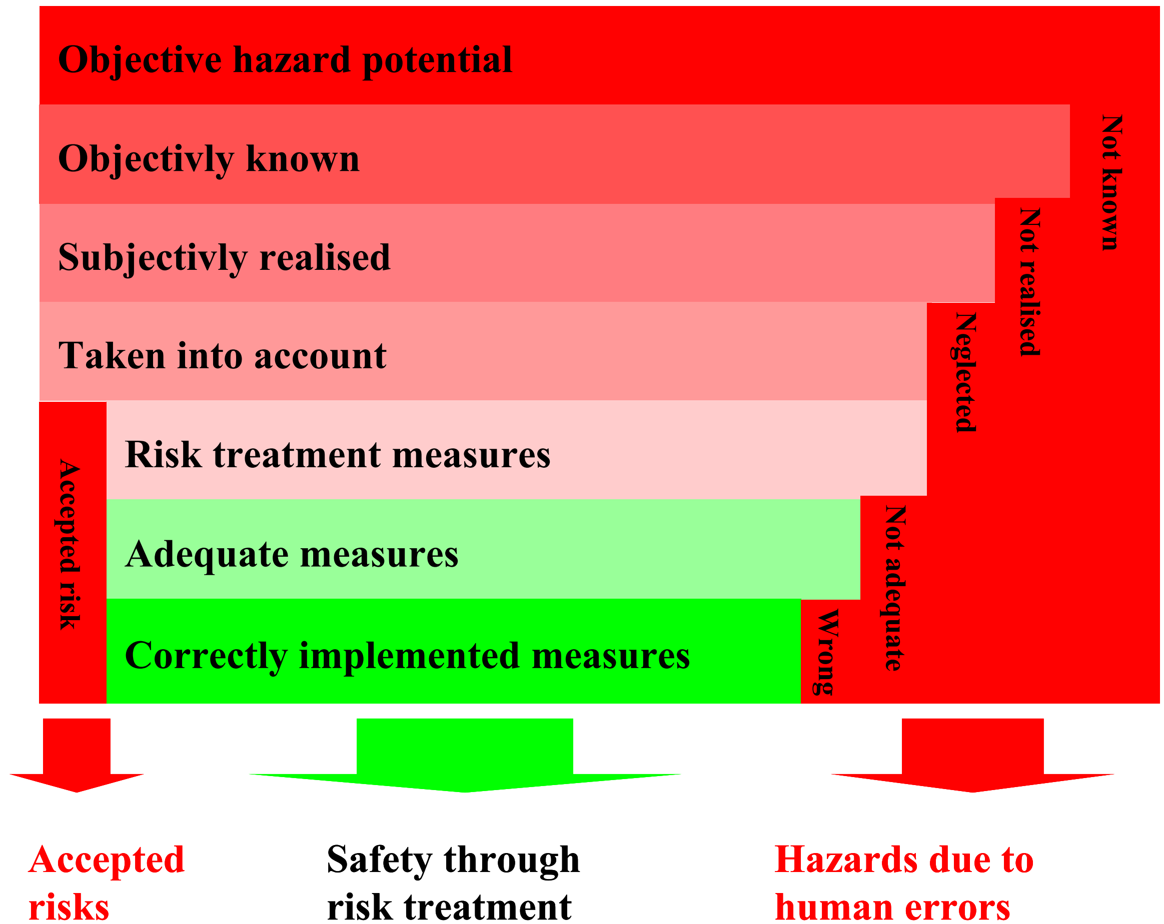


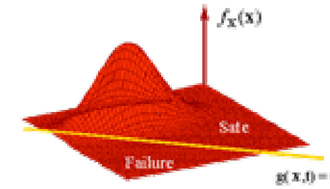
The risk potential associated with a given structure may be subdivided as

Structural reliability is ensured by means of selecting

- appropriate dimensions
- appropriate control

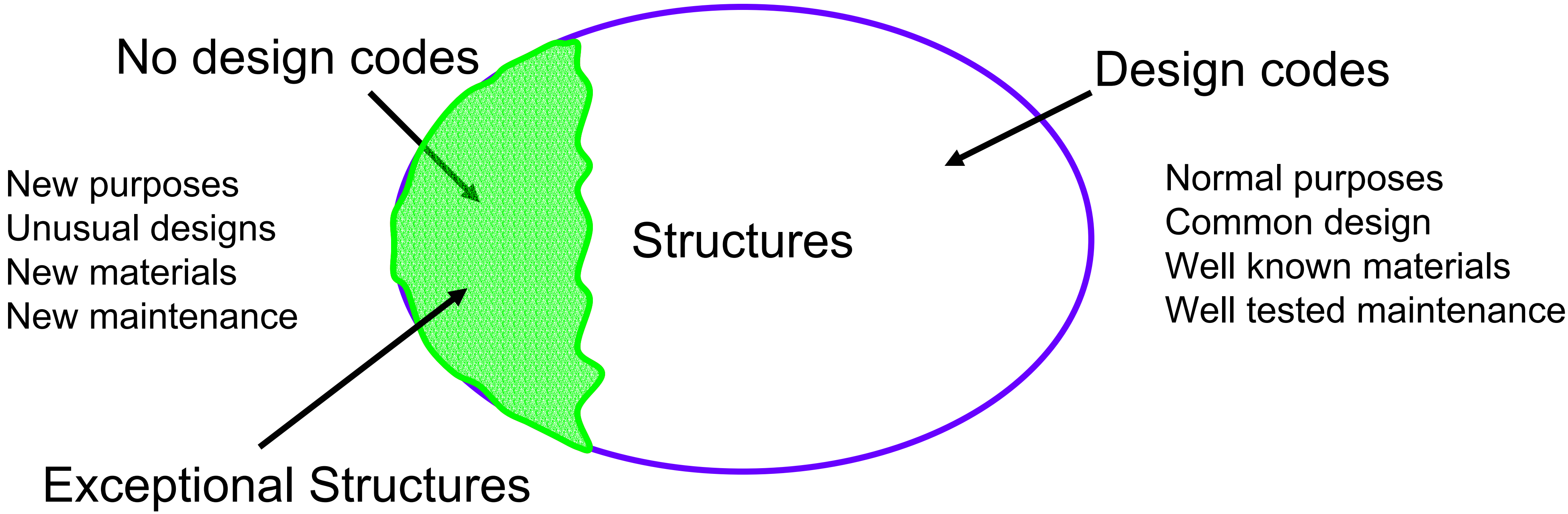
Accepted risks is a matter of choise – based on cost benefit considerations



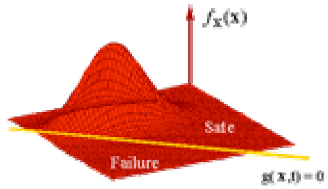


Design Codes and Code Calibration in the Past

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



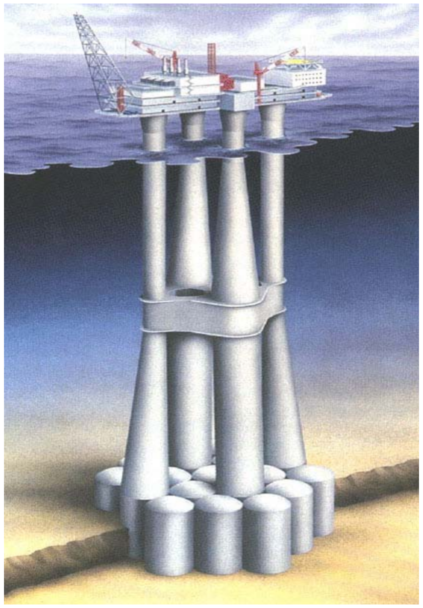
Design Codes and Code Calibration in the Past



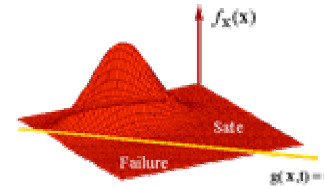
- **Exceptional structures is often associated with structures of**

„Extreme Dimensions“

Great Belt Bridge under Construction



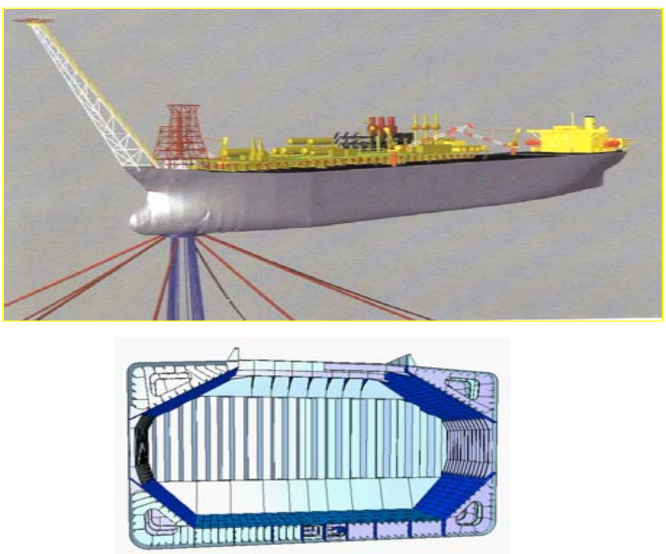
Concept drawing of the Troll platform

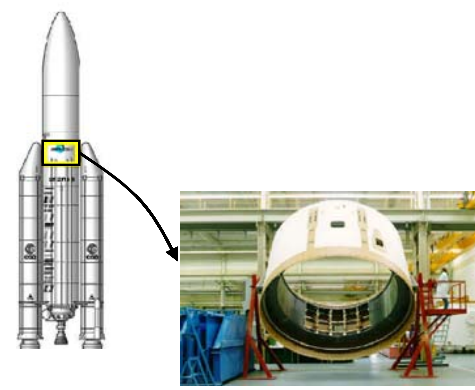


Design Codes and Code Calibration in the Past

- or associated with structures filfilling

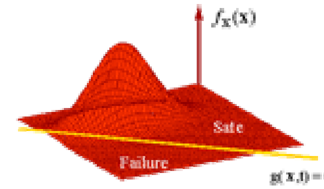
„New and Innovative Purposes“





Concept drawing of
Floating Production, Storage and Offloading unit

Illustrations of the ARIANE 5 rocket



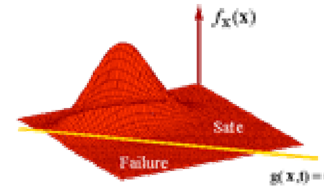
Principles of Structural Reliability

- 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



Principles of Structural Reliability

- 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 e.g.

  - **Collapse**
  - **Inserviceability**
  - **Deterioration**

  $\Big\}$ Failure Events

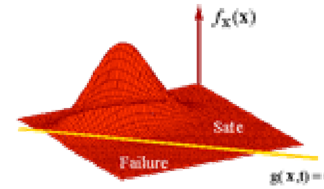
  as function of the most important uncertainties – the **basic random variables**

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

Failure Events

Limit state functions

Outcome of basic random variables

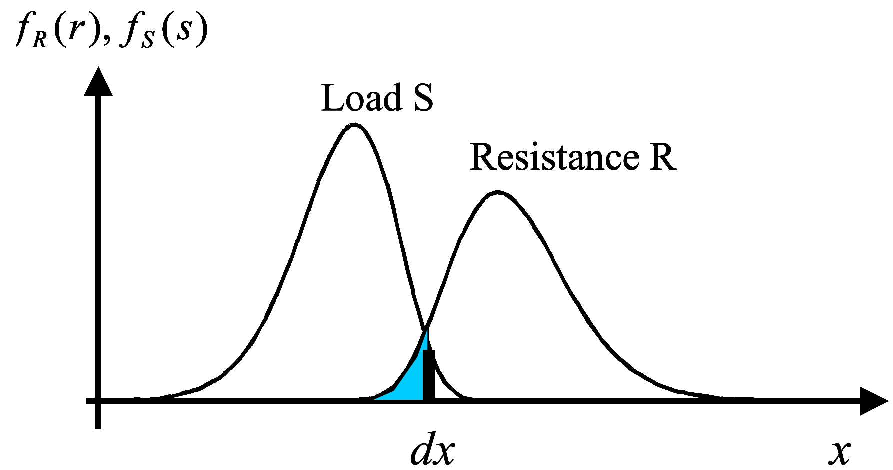


Principles of Structural Reliability

- ***The fundamental case***

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

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



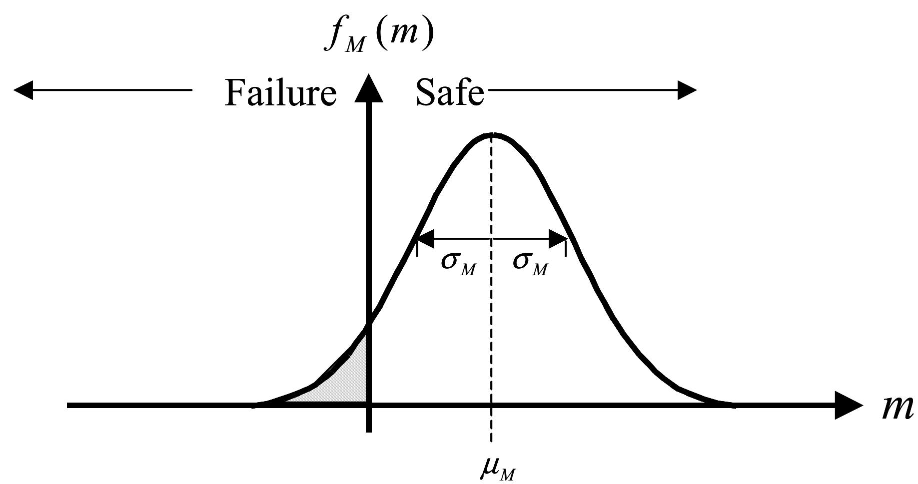
- ***Normal distributed safety margin***

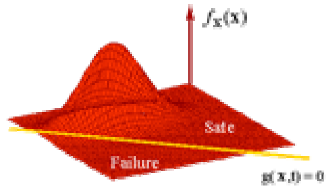
$$P_F = P(R - S \le 0) = P(M \le 0)$$

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

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

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





Principles of Structural Reliability

- The probability of failure in regard to

  - Ultimate collapse

  - Loss of serviceability

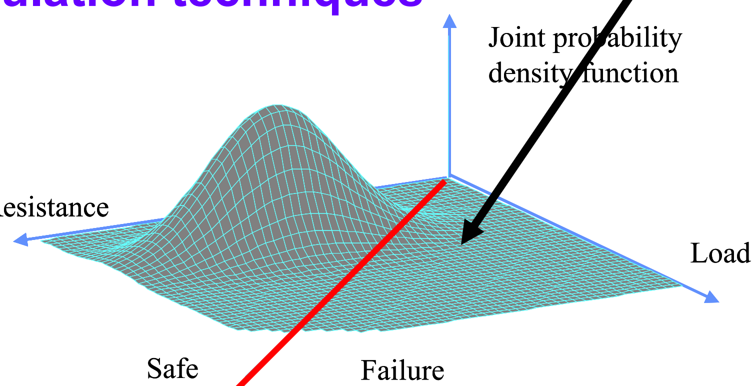
  - Excessive deterioration

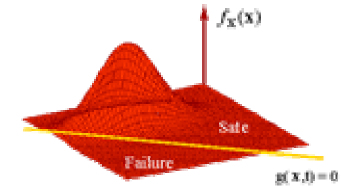
  may then be assessed by evaluation of probability integrals using e.g. FORM/SORM or simulation techniques

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

Failure event

Joint density function for the basic random variables





The Code Calibration 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

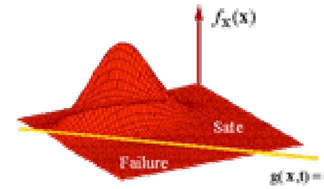
$$\min_{\gamma} \quad C_{Ij}(\mathbf{z})$$

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

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

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

Optimality and Target Reliabilities



- Acceptance criteria may be established on the basis of cost benefit considerations

$$E[B] = I \cdot (1 - P_F(C_D)) - C_D - C_F \cdot P_F(C_D) = I - C_D - (I + C_F)P_F(C_D)$$

Cost of failure

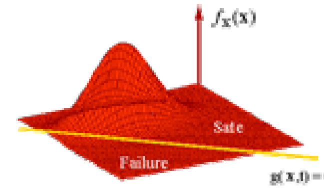
Income

Cost of risk treatment / design

Probability of failure

- Optimality may be determined from

$$\frac{\partial E[B]}{\partial C_D} = -1 - (I + C_F) \cdot \frac{\partial P_F(C_D)}{\partial C_D} = 0$$



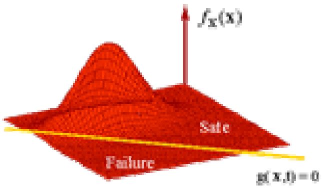
Optimality and Target Reliabilities

- **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 ($P_F \approx 10^{-2}$)



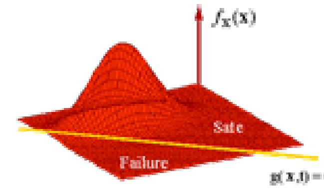
A Practical Code Calibration Procedure

- 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



A Practical Code Calibration Procedure

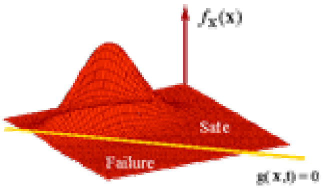
- A seven step approach

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.

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

A Practical Code Calibration Procedure

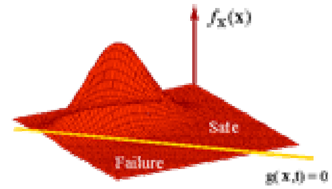


- **A seven step approach**

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

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

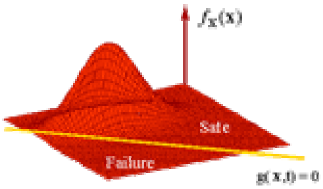
7. Verification
- incorporating experience of previous codes and practical aspects



Conclusions and remarks

- Simplified and straight forward formulations exist for the calibration of deterministic LRFD safety formats
- Traditionally the safety formats have only allowed for a rather limited differentiation in regard to failure consequences

  - the codes have origin in „one man – one structure" situations
- In the modern society the failure of one structure may be associated with consequences reaching far beyond the „interest" of the individual
- More work is needed to include more realistically the consequences of failure from a societal point of view – including the situations
  - one extreme event affecting one structure (of extreme importance)
  - one extreme event affecting many structures (of moderate importance)



Thanks for your attention !