Fire Engineering of Buildings –
A probabilistic Approach for FSE

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- Verification concepts for structural design
- Structural Fire design the Eurocode approach
  - Target reliabilities and design factors for fire design
  - Natural Fire Safety Concept
- Bayesian Probabilistic Nets
- General probabilistic approach to structural fire design
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  - Robustness of fire safety measures
- Statistical Data
Verification for structural design

- Verifications concepts for structural design
  - Allowable stress concept
  - Partial safety factor design (factors on load and resistance)
  - Probabilistic approach

- Probabilistic approach to structural design
  - Reliability index $\beta$: $[p_f = \Phi(-\beta)]$  
    $\Phi$ cum. standardized normal distribution func.

<table>
<thead>
<tr>
<th>$p_f$</th>
<th>$10^{-1}$</th>
<th>$10^{-2}$</th>
<th>$10^{-3}$</th>
<th>$10^{-4}$</th>
<th>$10^{-5}$</th>
<th>$10^{-6}$</th>
<th>$10^{-7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>1.3</td>
<td>2.3</td>
<td>3.1</td>
<td>3.7</td>
<td>4.2</td>
<td>4.7</td>
<td>5.2</td>
</tr>
</tbody>
</table>

- Eurocode target reliability index $\beta_0$:
  - Per building life 3.8 $(7.2 \cdot 10^{-5})$
  - Per year 4.7 $(10^{-6})$
Verification for structural design

- Probabilistic approach to structural design

  - Verification format (semi probabilistic approach):
    - \( E_d < R_d \)
    - \( P(E > E_d) = \Phi(\alpha_E\beta) = \Phi(-0.7\beta) \) for secondary action \( \Phi(-0.28\beta) \)
    - \( P(R > R_d) = \Phi(-\alpha_R\beta) = \Phi(-0.8\beta) \) for secondary action \( \Phi(-0.32\beta) \)
    - Limit state function \( g = R - E \)
    - \( \beta = \mu_g / \sigma_g \) for \( g \) normal distr.
    - \( P_f = p(g < 0) = p(\mu_g - \beta \sigma_g) \)
Verification in structural design

- \(\gamma\)-Factor approach

Fixed \(\alpha\)-values allow to establish partial design \(\gamma\) factors:

Example: resistance factor for steel variable lognormal with weighting factor \(\alpha_R=0.8\),
\[f_{y,d} = m \exp(-0.8\beta V_R) \quad \text{and} \quad f_{y,k} = m \exp(-1.645V_f) \quad \text{(5\% fractile)}\]
\(V_f\): variation coefficient for steel = 0.03
\(V_R\): variation coefficient for design value = \((V_{geom}^2 + V_{model}^2 + V_f^2)^{0.5} = 0.052\)

\[\gamma_a = \frac{f_{y,d}}{f_{y,k}}\]

With \(f_{y,k}\) as 5\% fractile and lognormal distribution \(\gamma_a\) can be calculated as a function of \(\beta\)
\[\gamma_a = \frac{f_{y,d}}{f_{y,k}} = \exp(0.7\beta V_R - kV_f)\]
\[= \exp(0.7 \times 3.8 \times 0.052 - 1.645 \times 0.03) = 1.1 \quad \text{for} \quad \beta = 3.8 \quad \text{(life time)}\]
NFSC (Natural Fire Safety Concept - Eurocode)

- Probabilistic approach to structural fire design

\[ \rho_f = \rho_{fi} \cdot \rho_{f,fi} \]

- \(\rho_f\): Structural failure probability given fire free status (unconditional failure probability)
- \(\rho_{fi}\): probability of a fire
- \(\rho_{f,fi}\): Structural failure probability given such a fire (conditional failure probability)

\[ \rho_f < \rho_t \]

- \(\rho_t\): accepted structural failure probability given fire free status (unconditional failure probability)
- \(\rho_t\) as for cold design 1.13 \(10^{-6}\) per year or reduced if evacuation possible 10\(^{-5}\) to 10\(^{-4}\) depending of number of people evacuated.
NFSC

- Semi probabilistic NFSC approach:

$$\beta_{fi,t} = \Phi^{-1} \left( \frac{p_t}{p_{fi}} \right) = \Phi^{-1} \left( 1.13 \times 10^{-6} / p_{fi} \right)$$

- $p_t$: accepted structural failure probability given fire free status (unconditional failure probability)
- $\beta_{fi,t}$: safety index
- $p_{fi}$: probability of a severe fire

<table>
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<th>$10^{-4}$</th>
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<td>3.7</td>
<td>4.2</td>
<td>4.7</td>
<td>5.2</td>
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NFSC

- $\delta_{qi}$ -Factor approach

Fire load is main variable with weighting factor -0.9.

$$q_{f,d} = \delta_{q1} \cdot \delta_{q2} \cdot \delta_{n1} \cdot \delta_{ni} \cdot q_{f,k}$$

With $q_{f,k}$ e.g. as 80% fractile and Gumbel distribution (with $V_d=0.3$) $\delta_{qi}$ can be calculated as a function of $\beta$ (or $p_t/p_f$)

Examples of $\delta$-factors from NSFC-Project (Annex E of EC 1-1.2):

- Compartment Area: 25 m$^2$ $\delta_{q1} = 1.10$; 250 m$^2$ $\delta_{q1} = 1.50$; 2500 m$^2$ $\delta_{q1} = 1.90$;
- Occupancy: offices $\delta_{q2} = 1.00$; machinery $\delta_{q2} = 1.22$; museum $\delta_{q1} = 0.78$
- Sprinkler: $\delta_{n1} = 0.61$; Smoke detection $\delta_{n4} = 0.73$
Swiss Fire Risk Evaluation Method (Empirical)

- SIA Documentation 81
- Hazards as well as safety measures are weighted by factors

Fire safety index $\gamma = \frac{R}{Ru}$

Risk $R = B \cdot A = \frac{q \cdot c \cdot r \cdot k \cdot i \cdot e \cdot g}{N \cdot S \cdot F}$

Hazard from content:
- q fire load mobile
- c combustibility
- r smoke production
- k corrosion

Hazard from building:
- i fire load mobile
- e Storey / -building height
- g Area of compartment

Safety factors:
- N Normal measures
- S Technical measures
- F structural measures

Akzepted Risk:
- p: occupancyclass
- H: Number of persons
- E: Storey
Fire risk evaluation SIA Dok 81 hazard factors

- Hazard factors are listed for different occupancies based on survey from the 1960ties.
- Examples:

<table>
<thead>
<tr>
<th>Nutzungen</th>
<th>Produktion / Verkauf</th>
<th>Lagerung</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qm (M/J/m²)</td>
<td>q</td>
<td>c</td>
</tr>
<tr>
<td>Flugzeughallen</td>
<td>200</td>
<td>1.0</td>
</tr>
<tr>
<td>Folien, Metall-</td>
<td>40</td>
<td>0.6</td>
</tr>
<tr>
<td>Fotoapparate</td>
<td>300</td>
<td>1.1</td>
</tr>
<tr>
<td>Fotocatellerr</td>
<td>300</td>
<td>1.1</td>
</tr>
<tr>
<td>Fotolabor</td>
<td>100</td>
<td>0.8</td>
</tr>
<tr>
<td>Fotofilme und -platten</td>
<td>1,000</td>
<td>1.5</td>
</tr>
<tr>
<td>Photobuch</td>
<td>300</td>
<td>1.1</td>
</tr>
<tr>
<td>Fruchtsafte</td>
<td>200</td>
<td>1.0</td>
</tr>
<tr>
<td>Punkstationen</td>
<td>80</td>
<td>0.8</td>
</tr>
<tr>
<td>Pariere</td>
<td>800</td>
<td>1.4</td>
</tr>
<tr>
<td>Futtermittel</td>
<td>2,000</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Risk assessment methods for fire

- **Bayesian Probabilistic Nets (BPN)**
  - Consider frequentistic information (statistical data) as well as subjective probabilities (experience, expert knowledge)
  - Conditional probabilities – respecting calculation rules for frequentistic probabilites
  - Relations between interacting nodes (events)
  - Deterministic models may be used to process in-put data
  - Commercial software (e.g. Hugin…)
Conditional Probability – Calculation rules according to Bayes

<table>
<thead>
<tr>
<th>PROBABILITY</th>
<th>Rule due to Bayes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequentistic definition</td>
<td>$P(X_j</td>
</tr>
<tr>
<td>Bayesian definition</td>
<td></td>
</tr>
</tbody>
</table>

| $P(X_j|Y)$              | [–]   | posterior probability of the event $X_j$                                      |
| $P(X_j)$               | [–]   | prior probability of the event $X_j$                                          |
| $P(Y|X_j)$             | [–]   | likelihood, i.e. the probability of observing a certain state given the true state |
| $P(Y)$                 | [–]   | total probability                                                              |

posterior = prior \cdot likelihood \cdot normalizing factor$^{-1}$
Bayesian Networks: Node Probabilities

Which is the probability of occurrence for state $X$, $Y$, or $Z$ (node probabilities)?

$P(Y) = \sum P(X_i) \cdot P(Y|X_i)$

→ theorem of total probability

How involve observed evidence?
Bayesian Networks: Observed evidence

**Basic elements**

- Evidence: definition of the exact state of a node based on observed evidence $e$.
- Which is the probability of a node considering evidence $e$?
- Bayes theorem

$$P(X | Y) = \frac{P(X | Y) \cdot P(Y | X)}{P(Y)}$$
BAYESIAN NETWORKS

Fire safety problems modeled

- Suppression
- Detection
- Member (R)El
- Combustibility
- Living space
- Fire load
- Means of escape
- Access firefighters
- Age of building
- Number of residents

Development of fire in fire cell
Spread of fire in building
Fire fighting by building users, firefighters and technical measures
Available means of escape

Maag/Fontana 2004

introduction  risk model  bayesian network  application  conclusions
Example: Structure of a Bayesian Network for Building fires
Example: Safety level in Swiss Fire Regulations 2005

- BPN to check reliability level for different code requirements e.g. timber buildings with different number of storeys.
- Code allows free choice between structural and sprinkler concept without further verification by the designer.
- Aim: discussion and harmonization of safety levels (values are conservatively chosen, first calculations with Bayesian networks show, that life safety of sprinkler concepts is superior).
# Required fire resistance for structural - and sprinkler concept (no further verification required)

<table>
<thead>
<tr>
<th>Occupancy No of storey</th>
<th>Offices and Industry &lt; 1000 MJ/m²</th>
<th>Industry &gt; 1000 MJ/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>No SPS</td>
<td>with SPS</td>
<td>no SPS</td>
</tr>
<tr>
<td>1</td>
<td>No req.</td>
<td>no req.</td>
</tr>
<tr>
<td>2 ≤ 1200 m²</td>
<td>Non combust</td>
<td>R30</td>
</tr>
<tr>
<td>2&gt; 1200 m²</td>
<td>R30</td>
<td>R60</td>
</tr>
<tr>
<td>3</td>
<td>R30</td>
<td>R60</td>
</tr>
<tr>
<td>4</td>
<td>R60</td>
<td>R90</td>
</tr>
<tr>
<td>6</td>
<td>R60</td>
<td>R90</td>
</tr>
<tr>
<td>8</td>
<td>R60</td>
<td>R90</td>
</tr>
</tbody>
</table>
Example: Bayesian network to compare safety level of basic concepts in regulations

**APPLICATION**

<table>
<thead>
<tr>
<th>Parametric studies</th>
<th>Risk assessments</th>
<th>Additions</th>
</tr>
</thead>
</table>

**FAR**  
Fatal Accident Rate  
Number of Fatalities per $10^8$ hours of exposure to building

**Review of fire safety designs**

Example Swiss regulations: fire safety measures according to
- number of storeys
- standard fire safety design
→ how safe are such buildings?

<table>
<thead>
<tr>
<th></th>
<th>standard structural design</th>
<th>standard sprinkler design</th>
</tr>
</thead>
<tbody>
<tr>
<td>requirements</td>
<td>FAR</td>
<td>requirements</td>
</tr>
<tr>
<td>6 storeys R 60 n.comb.</td>
<td>0.1276</td>
<td>0.0065 R 60</td>
</tr>
<tr>
<td>4 storeys R 60</td>
<td>0.1241</td>
<td>0.0064 R 30</td>
</tr>
<tr>
<td>3 storeys R 30</td>
<td>0.1367</td>
<td>0.0074 combustible</td>
</tr>
<tr>
<td>2 storeys combustible</td>
<td>0.1243</td>
<td>0.0063 combustible</td>
</tr>
</tbody>
</table>

→ uneconomical fire safety measures?
→ erroneous safety levels?
Fire risk for structures – design approaches

- **Safety objectives**: What are the aims (life, property, business interruption…) and what are the acceptability criterions? (e.g. no structural collapse during specific period of time)

- **Exposure**: What fire scenarios must be considered? (Fire action, standard fire or natural fire time/temperature, main parameter: fire load)

- **Vulnerability**: How do building elements behave given an specific exposure

- **Robustness**: How does the building behave (globally) given a specific damage/failure of an element or of parts of the structure

  - Deterministic approach (Characteristic -, design values; design fires)
  
  - Probabilistic approach (Parameters as “stochastic” variables)
Exposure - Fire action for structures

- **Nominal Fires**
  - Standard fire curves for testing (ISO, ASTM, …)

- **Natural Fire**
  - The fire safety objective can not be verified with nominal time temperature curves. Natural fire has to be consider as exposure
  - The main parameters for natural fire (fire load, heat release rate, ventilation, characteristics of enclosures, Suppression measures…) may change during the live time of a structure and are not known at the time of a eventual fire outbreak, therefore different approaches may be used to deal with the *uncertainties*:
    - Deterministic approach (Characteristic values; design fires, partial safety factors)
    - Probabilistic approach (Parameters as “stochastic” variables)
Vulnerability: Example: Behaviour of a steel element in fire

- Structural elements are designed with a safety margin against mechanical action (loads) e.g. steel 1.5 – 2.0
- When the steel temperature during a fire gets so high that the reduction of its strength due to temperature has consumed the safety margin - the structure will fail (critical temperature)

- Main parameters:
  - Heating of the section
  - Mechanical action on the hot section
    - The load level (stress level)
  - Integrity and behaviour of protection
Vulnerability of fire protection
Robustness of structures in fire
Conclusion

- Probabilistic approach allow realistic description of fire behaviour giving more information than deterministic approach
- Difficulty in setting and explaining targets
- Still statistical input data rare (existing data often incoherent or not existing)
- Verification more complicated than with deterministic methods
- A full probabilistic approach is still more successful applications for code writing than for building verification
Conclusion

- Probabilistic approach allow realistic description of fire behaviour giving more information than deterministic approach
- Difficulty in setting and explaining targets
- Still statistical input data rare (existing data often incoherent or not existing)
- Verification more complicated than with deterministic methods
- Still more successful applications for code writing than for building verification
Statistical data of building fires (>40,000 fires)

- Analysis for Canton of Berne
  - new buildings (1990 – 1999)
- Fire consequences
  - fire fatalities
  - fire damage
- Influence parameters
  - type of use of building
  - type of structure
  - age of building
- Fire load survey (110 factories)
- Fire fatalities Zurich 1990-1999

- Definition type of structure: combustible/non combustible (criterion: combustible if > 20% structure combustible)
### Fire damages on buildings Bern 1990 – 1999 (new buildings)

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Dwellings</th>
<th>All types of use</th>
<th>Structure type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value insured [CHF]</td>
<td>13,6 Mrd</td>
<td>21,2 Mrd</td>
<td>non combustible</td>
</tr>
<tr>
<td>Loss [CHF]</td>
<td>4,7 Mio</td>
<td>7,9 Mio</td>
<td>non combustible</td>
</tr>
<tr>
<td>Loss per value and year (loss burden) [%/a]</td>
<td>0.066</td>
<td>0.066</td>
<td>non combustible</td>
</tr>
<tr>
<td>Loss per value and year (all buildings, 1986-1995) [%/a]</td>
<td>0.106</td>
<td>0.124</td>
<td>non combustible</td>
</tr>
<tr>
<td></td>
<td>0.262</td>
<td>0.391</td>
<td>combustible</td>
</tr>
</tbody>
</table>
Investigation on fire fatalities in Zurich 1990-99

Influence of Human behavior:

- During that period of 10 yrs 35 fires with 37 fatalities occurred (not including suicide and murder)

- Review of accident reports
  - Only in two of the 35 fires double fire fatalities occurred; all other cases claimed only one victim
  - Only one case was related to fire spread and possibly unsatisfactory behavior of the structure
  - All other cases had causal relation to the behavior of the victims (1/3 smoking, 1/3 accidents, negligence, 1/3 other e.g. faint, heart failure …)
Fire load survey for industrial premises 2005

- Fire load survey in 95 industries; 136 production and 210 storage rooms
Results: Example paper storage

- survey data; cumulative distribution log-normal and normal
Design values

- What design value should be chosen?

- The design value is dependant on the target probability
- It is chosen in function of the design concept (e.g. safety factors, distribution function (e.g. Lognormal - Gumbel)...)
Ergebnisse der branchenbezogenen Brandlasten Papierlager

Log-Normalverteilung für Brandlasten "Papier" (Lagervolumen [MJ/m³])

Messwerte
- Log-Normalverteilung
- Normalverteilung
- SIA Wert Papier
- SIA Wert Papier, Alt-, lose

SIA 81 Altpapierlager
SIA 81 Papierlager
Example: Office building of the City Administration in Langenthal (CH)

(4-storey steel frame 80 m / 20 m)
Office Building Langenthal - Fire Safety Concepts

- **Structural concept** according to 1993 Swiss regulations:
  - Structure R 60 (insulated Steel)
  - Fire compartments REI 60 smaller 600 m²

- **Sprinkler concept:**
  - Structure R 30 (intumescent paint – composite floors)
  - Fire compartments REI 30 smaller 1600 m² (d.h. only one compartment per storey)
  - Sprinkler protection
Probability of fire start and fire development

\[ p_{fi} = p_1 \cdot A \cdot (A/A_0)^x \cdot n \cdot p_M \]

- \( p_1 \): frequency of fire start [per year and m²]
- \( A \): area of fire compartment [m²]
- \( A_0 \): reference area [m²]
- \( x \): exponent for fire compartment size
- \( n \): life time of structure [year]
- \( p_M \): influence of fire fighting measures
Example Langenthal: fire probabilities

- Structural concept R 60 / 600 m²:
  \[ p_{fi} = 0.4 \cdot 10^{-6} / (m^2 \cdot \text{year}) \cdot (600m^2) \cdot 1.0 \cdot 50 \text{ years} \]
  \[ = 0.012 / \text{lifetime} \]

- Sprinkler concept R 30 / 1600 m²:
  \[ p_{fi} = 0.4 \cdot 10^{-6} / (m^2 \cdot \text{year}) \cdot (1600m^2) \cdot 1.0 \cdot 50 \text{ years} \cdot 0.02 \]
  \[ = 0.00064 / \text{lifetime} \]
Structural behaviour under natural fire conditions

The probability of structural failure given a fire depends on:

- mechanical actions on beams
- thermal actions
- structural behaviour in case of fire
Mechanical Action

- Deterministic Models (Structural mechanics, Thermo dynamics)
- Probabilistic Models (stochastic distributions)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Distribution type</th>
<th>$V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self weight $N$</td>
<td>Normal</td>
<td>0.1</td>
</tr>
<tr>
<td>Variable load $P$</td>
<td>Gumbel</td>
<td>0.3</td>
</tr>
<tr>
<td>Structural steel $f_y$</td>
<td>Lognormal</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Thermal Action

- **Fire load**  \( q_{d,f} = 570 \text{ MJ/m}^2 \) (80 % fractile)
- **Rate of heat release**  \( q'_{d,f} = 320 \text{ kW/m}^2 \)
- **Fire compartment**  12 cm concrete; 600 / 1600 m\(^2\)
- **Ventilation**  \( h_f = 2.5 \text{ m}; A_v = 160 / 480 \text{ m}^2 \)
- **Fire fighting measures**

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<th>Variable</th>
<th>Distribution type</th>
<th>( V )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire load density ( q )</td>
<td>Gumbel</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Example Langenthal
gas temperature in room

Temperature $q$ [°C]

Time $t$ [min]
Structural behaviour in case of fire

- Maximum steel temperature
- Beam IPE 400 with two spans
- Fire resistance R 30 / R 60 ISO
- Development of the gas temperature according to the different room geometries
Example Langenthal steel temperature

Maximum steel temperatures $\theta$ [°C] in function of fire load $\theta$ [MJ/m$^2$]
Structural Reliability
2-Span Beam, Plastic Design

- Limit state function
  \[ G = R - S \geq 0 \]
  \[ G = R_{d,fi} - M_{d,fi} = (k_{y,q} \cdot f_y \cdot Z_y) - \frac{(N + P) \cdot \ell^2}{11.67} \]
- FORM-Analysis
- Monte-Carlo-Simulation
Example Langenthal Failure probability given a natural fire

- Room 600 m²; beam IPE 400 R 60:
  FORM: \( p_{f,fi} = 6.52 \cdot 10^{-4} \) \( \beta = 3.22 \)
  Monte Carlo: \( p_{f,fi} = 6.83 \cdot 10^{-4} \)

- Room 1600 m²; beam IPE 400 R 30:
  FORM: \( p_{f,fi} = 7.97 \cdot 10^{-4} \) \( \beta = 3.16 \)
  Monte Carlo: \( p_{f,fi} = 8.74 \cdot 10^{-4} \)
Failure probability of a structure

\[ p_f = p_{fi} \cdot p_{f,fi} \]

- \( p_f \): Structural failure probability given fire free status (unconditional failure probability)
- \( p_{fi} \): probability of a severe (\( \geq \)design) fire
- \( p_{f,fi} \): Structural failure probability given a severe fire (conditional failure probability)
Example Langenthal – Failure probability starting from fire free status

- Room 600 m²; beam IPE 400 R 60:
  \[ p_f = p_{fi} \cdot p_{f,fi} = 0.012 \cdot 6.52 \cdot 10^{-4} = 7.82 \cdot 10^{-6} \]

- Room 1600 m²; beam IPE 400 R 30:
  \[ p_f = p_{fi} \cdot p_{f,fi} = 0.00064 \cdot 7.97 \cdot 10^{-4} = 5.10 \cdot 10^{-7} \]

⇒ Sprinkler concept has a smaller failure probability