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Probabilistic Approach to FSE and Fire Resistance of Structures

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History of structural fire design in Switzerland

- **Natural Fire Tests**
  Eduard Geilinger,Winterthur 1947

- **SIA Dokumentation 81**

Contents

- Fire regulation concepts (prescriptive vs. performance based)
- Fire safety concepts (structural, technical, organizational)
- Fire - some general aspects
- Fire action (thermal-mechanical, modelling)
- Fire safety objectives and fire safety concepts
- Structural fire design (structural modelling, variables)
  - Conceptual design for fire safety
  - Robustness of fire safety measures
- Structural fire design verification
  - Probabilistic - deterministic
  - Eurocodes

Fire Safety Regulations - Concepts

Fire safety of buildings is a strongly regulated sector:

- Performance based vs. prescriptive regulations
- Enforcement of regulations: building permission, periodical controls

- **Prescriptive** (normative) **Regulations**:
  - Detailed requirements concerning time temperature curve, fire resistance period, size of compartments, length and with of escape ways, use of combustible materials, technical and organisational measures, ...

  ⇨ Easy to check, little flexibility, suitable for common type of construction, clear requirements for design and approval (deemed to satisfy)

Fire Safety Regulations – Concepts

- **Performance based regulations**:
  - Objectives, basic requirements, acceptance criteria ...
  - ⇨ Models and input to be agreed with authorities, huge freedom of design and flexibility, design risk. Variable input parameters, verifications difficult and time-consuming. Alternative: check by qualification.
- **“Concept based prescriptive”**:
  - Free choice of concept (e.g. traditional structural concept – sprinkler concept with reduced fire resistance) but then prescriptive:
  - ⇨ Design- und cost certainty, medium freedom of design and flexibility (deemed to satisfy)

Fire safety objectives

General objectives:

- Safety of occupants and fire brigade
- Safety of neighbors and their goods
- Limitation of financial loss (buildings and contents)
- Protection of the environment in case of fire

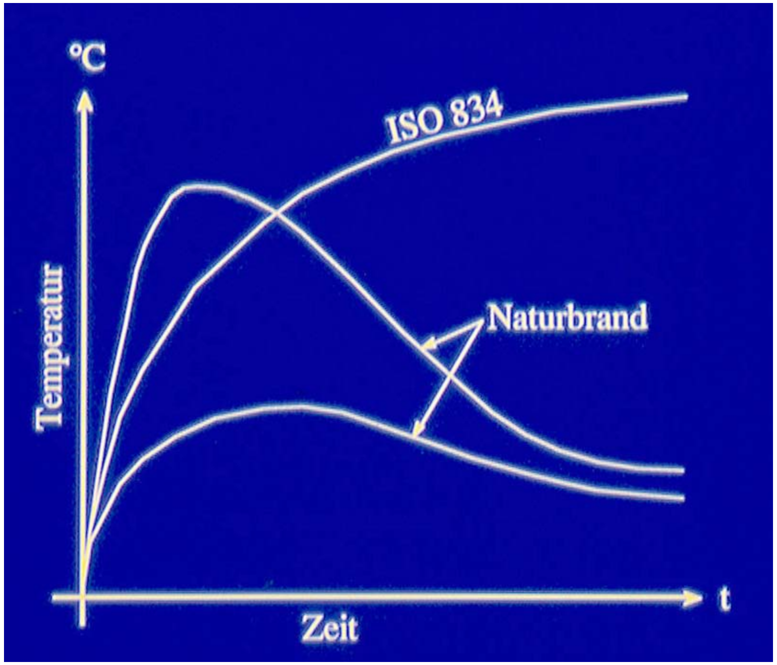
Fire an accidental action for structural design

- Fire is an accidental action that rarely or never occurs during the life time of a structure (EN factor $\psi_{2,i}$)
- For the structure the leading action is the temperature (thermal action)
- The effect of the thermal action is loss of strength and stiffness of the building materials and thermal elongations (strains) and thermal stresses
- The fire action can be modelled by:
  - Nominal fire actions ISO 834, ASTM 113, …
  - Natural fire curves
    - Parametrical fire curves (EN 1991-1-2 Annex A…)
    - Numerical Fire simulation (Zone, CFD computer models)

Modelling of time - temperature development

- Fire is a accidental, uncertain event governed by the parameters at the out-break of fire

- Time-temperature develop-ment is often simplified and modeled by time-temperature curves:
  - Nominal time-temperature curves
  - Parametrical time-temperature curves
  - Design–fire curves (Natural fire curves – fire simulation)

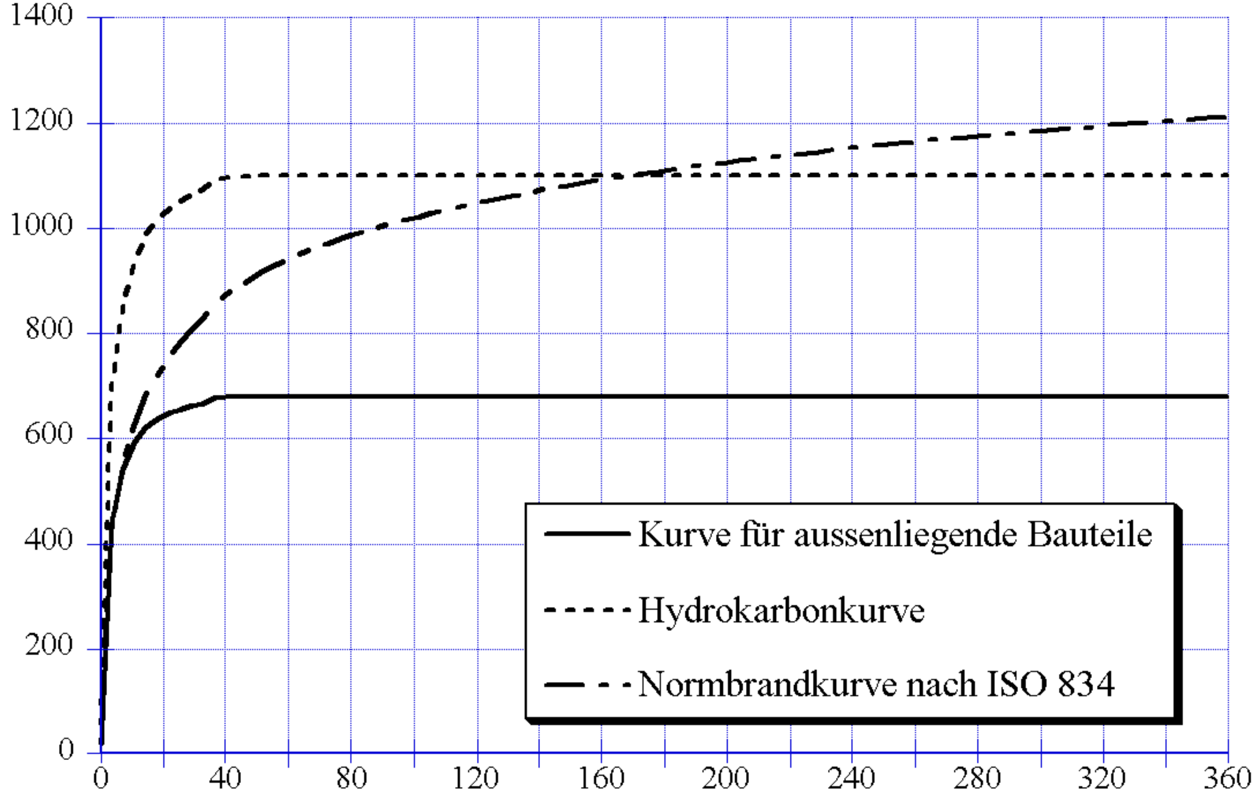


Time - temperature Modeling for structures

- Nominal time-temperature curves:
  - Characteristic: Nominal time-temperature curves – only time as input no physical parameters
  - Main application: Fire tests, regulations
- Natural Fire Curves:
  - Characteristic: Realistic time-temperature curves - main physical parameters are taken into account
    - Type and amount of combustible material
    - Ventilation conditions in the room
    - Thermal properties of the enclosures
    - Fire fighting action
  - Input variables uncertain, discussion with regulators

Time Temperature development

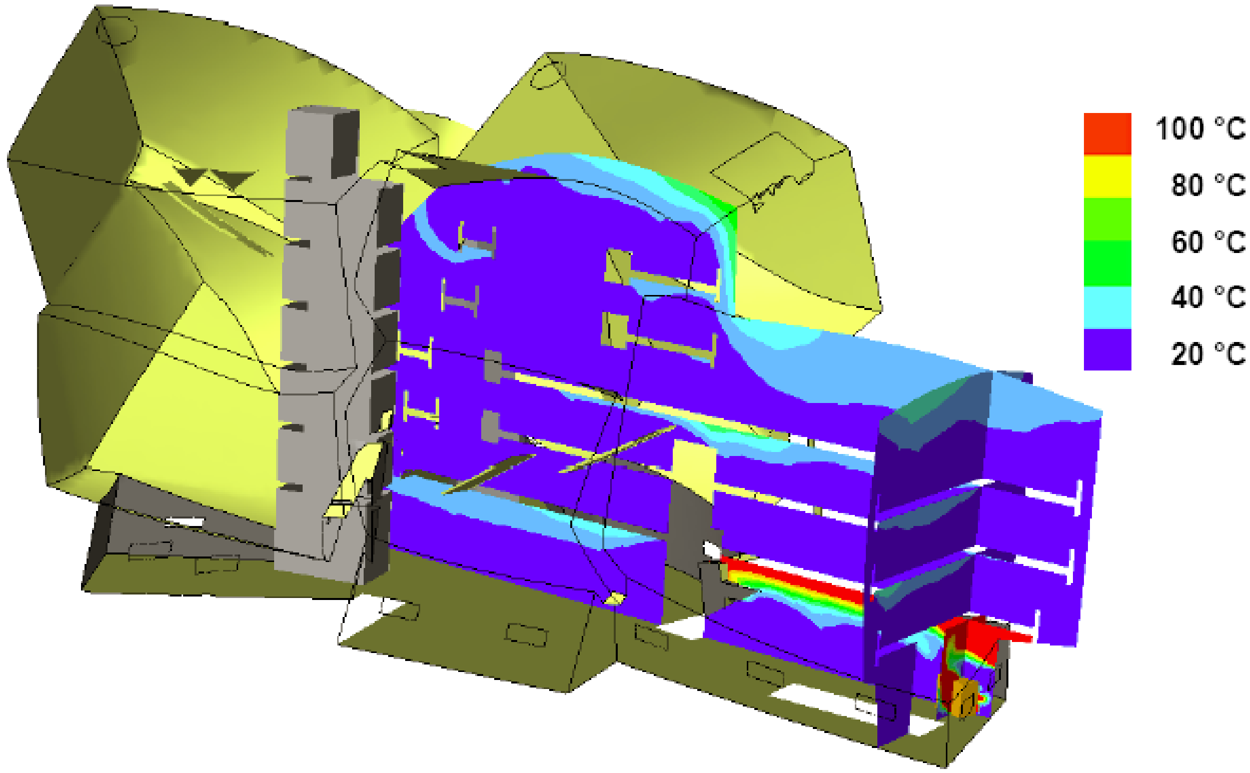
Nominal time-temperature curves



Time Temperature development

Numerical Fire Simulation

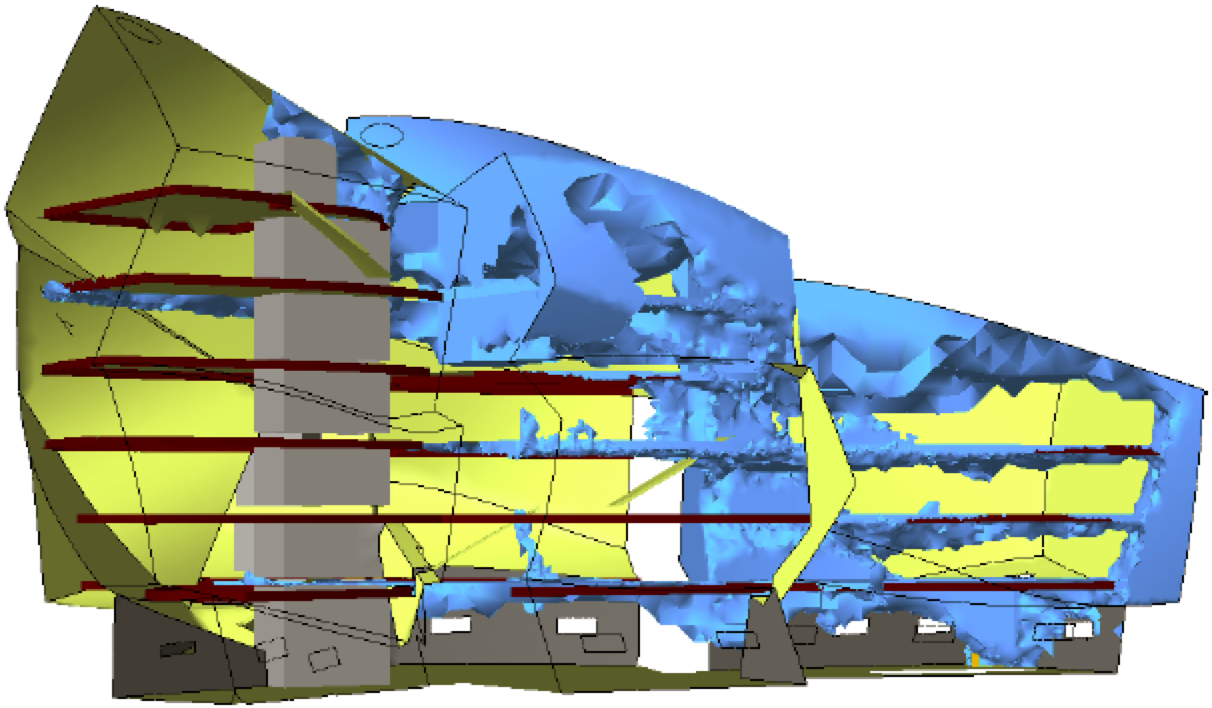
Example: CFD-Simulation in open space office building



Smoke propagation

Numerical Fire Simulation

Example: CFD-Simulation in open space office building



Fire safety design concepts – strategies

- Structural concept
  - Main focus on compartmentation and fire resistance
- Surveillance concept
  - Main focus on automatic early detection of fire while small
- Suppression concept
  - Main focus on automatic suppression of fire while small
- Organizational concept
  - Main focus on human behavior, fire prevention and fire fighting

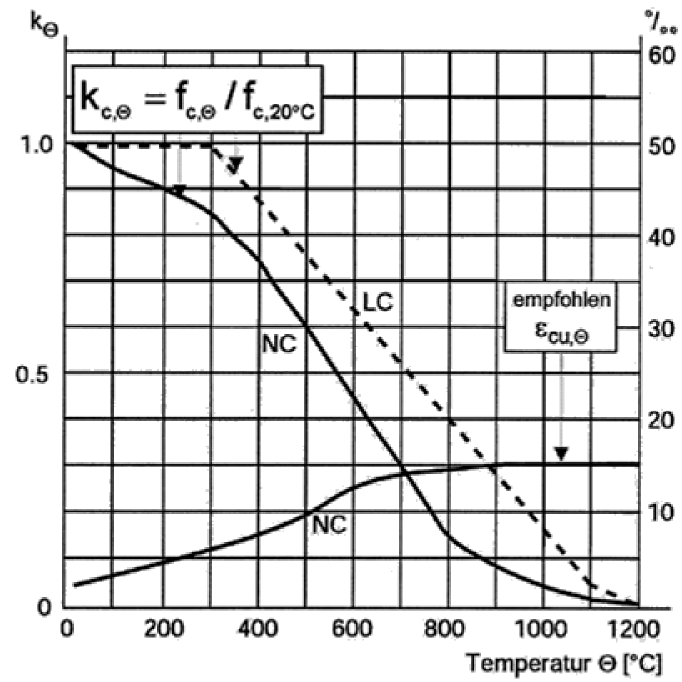
Structural fire design – objectives and properties

Objective

- Limit the spread of fire to room of origin or parts of the structure – no collapse

Properties

- combustibility of building materials
- Strength and stiffness of materials in fire
- Specific material behaviour



Concrete

Structural fire design – Properties

Specific behavior of materials in fire

- **Wood:**

  Combustible, compact sections beneficial, very slow heating. Pyrolysis.

- **Steel:**

  non combustible, fast heating, regaining strength

Structural fire design

- **Concrete:**

  Non combustible, slow heating, spalling

- **Masonry:**

  non combustible, slow heating

- **Glass:**

  complex behavior, low melting temperature

Structural fire design – models for fire action and structure

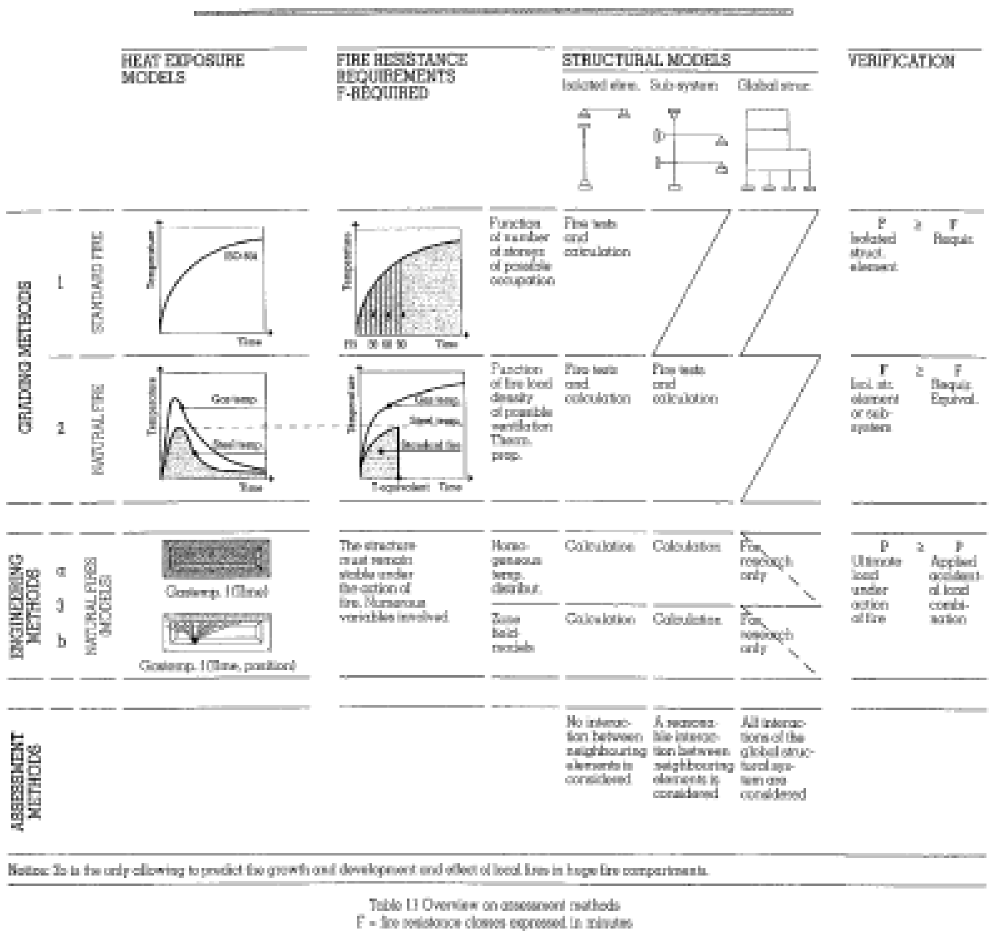
"Fire safety of steel structures – a global approach"[1]:

- Structural Model:

  Isolated member (test, regulation)

  global structure (fire engineering – conceptual design)
- Heat Exposure Model:

  nominal, fire simulation
- Complex interaction

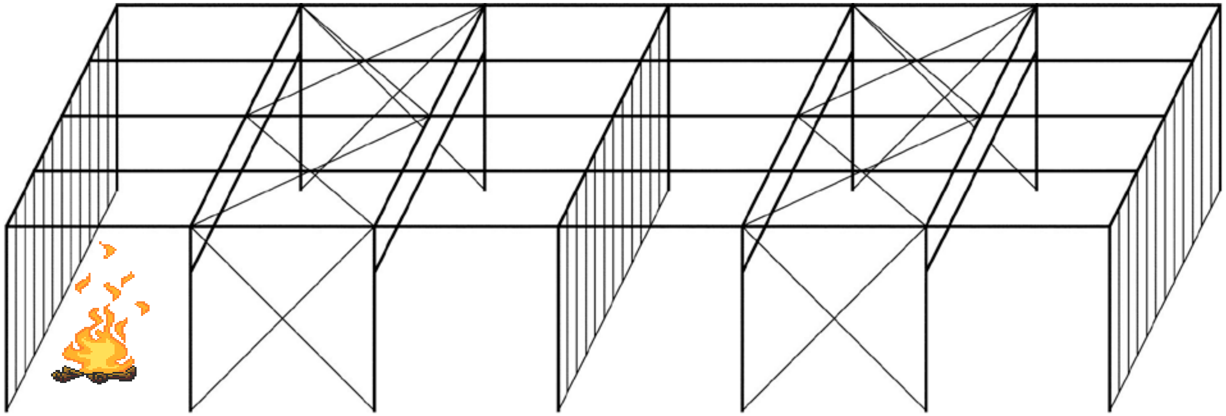


Graphic: Eurofer, Brussels

[1]) Eurofer, Brussels 1993

Global Stuctural Design for Fire safety

- By providing alternative load path or activating alternative structural systems like membrane action unprotected structures may survive severe fires
- Satisfactory behavior depends on good construction practice

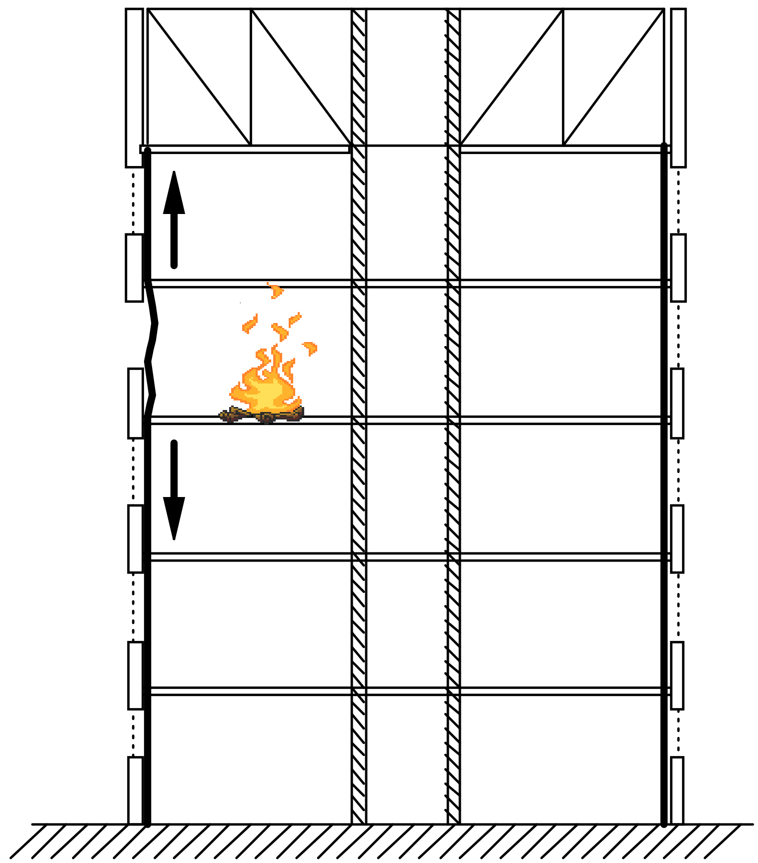


- Fire resistance time against standard fires must not be confused with the time for safe escape or until collapse

Membrane action of an unprotected slab

Cardington tests show excellent behavior of unprotected slabs

Alternative load path



Robustness of fire safety measures

- Design practice does only consider two extreme events at the same time or following each other if they are dependent e.g. :
  - Earthquake followed by a fire (but not fire followed by an Earthquake!)
  - Impact followed by a fire
- Must a fire protection measures be fully effective after mechanical impact?
- Partial damage of fire protection has a marked influence on the fire resistance. However this is not considered in testing nor in design.

Robustness of fire protection

Fire safety of structures – design approaches

- Choice of input variables and design approches:
  - Deterministic approach
    (Characteristic values and design fires given in Codes)
  - Probabilistic approach (Parameters as variables – Variable model e.g. Standard, Poisson… mean values, standard deviation or statistical data) quality of assumption???
  - Semi probabilistic approach (characteristic values, safety factors) concentrating on main variables…

Main variables for structural fire design

- Fire action
  - The fire load (density, characteristics, heat release rate)
  - The ventilation conditions in the room
  - The thermal characteristics of the enclosures
  - Suppression measures (fire brigade, sprinklers…)
  - and the fire suppression measures
  - →RHR
- Fire resistance
  - Choice of model: (element, global, fire,…)
  - Level of fire protection and robustness
  - Sprinklers (design and maintenance)
    - Cooling effect (correct design to keep fire low)
    - Availability of sprinkler (correct installation, maintenance, water resource…)

Fire load survey – Example

- Survey in 95 industrial plants in Switzerland by VKF and ETH
- Period August – December 2005. (ca. 90 work days)

  -> approx. ½ day per industrial plant
- Several compartments surveyed per industrial plant (e.g. Offices, production and storage)
- Assed were the amount and heat of combustions of the combustible material and the area or volume of compartment
- Survey of further data on ventilation und room envelope.

(Data was used for rapid risk assessment method in ch fire regulation: http://www.praever.ch/de/bs/vs/erlaeuterungen/seiten/115-03.pdf)

Design approaches for structural elements in fire

- Deterministic (semi probabilistic) approach:

$$E_{d,fi} < R_{d,fi}$$

$E_{d,fi}$: design value of action during fire

$R_{d,fi:}$ design value of resistance during fire

- Probabilistic approach

$$p_f < p_{f,accepted}$$

p_f: Structural failure probability given fire free status (unconditional failure probability)

Failure probability of a structure

$$p_{\mathrm{f}} = p_{\mathrm{fi}} \cdot p_{\mathrm{f,fi}}$$

p_{f}: Structural failure probability given fire free status (unconditional failure probability)

p_{fi}: probability of a severe (≥design) fire including event. sprinkler suppressing fire

$p_{\mathrm{f,fi}}$: Structural failure probability given a severe fire (conditional failure probability)

Fire safety functional requirements

EU Council Directive 89/106/EEC of 21 December 1988:

- **Safety in case of fire:**
  The construction works must be designed and built in such a way that in the event of an outbreak of fire:
  - the load-bearing capacity of the construction can be assumed for a specific period of time,
  - the generation and spread of fire and smoke within the works are limited.
  - the spread of the fire to neighboring construction works is limited,
  - occupants can leave the works or be rescued by other means.
  - the safety of rescue teams is taken into consideration.

Quality control and checking of fire design

- Models for Quality control:

  Problem: Checking authority v.s. designer, contractor

  (Analogy: from statics: Prüfingenieur–entwerfender Ingenieur Gemany vs. no checking authority in CH)

  - Trust vs. detailed checking
  - Appeal
- Prescriptive Design:
  - Compliance with detailed requirements.
  - Degree of details in regulations
  - Margin of discretion
  - System as most common today
- Performance based Design:
  - Codes, Regulation
  - Input parameter - expert judgement, statistical data
  - Plausibility check
  - Check by external expert
  - Plausibility check vs. check by qualification

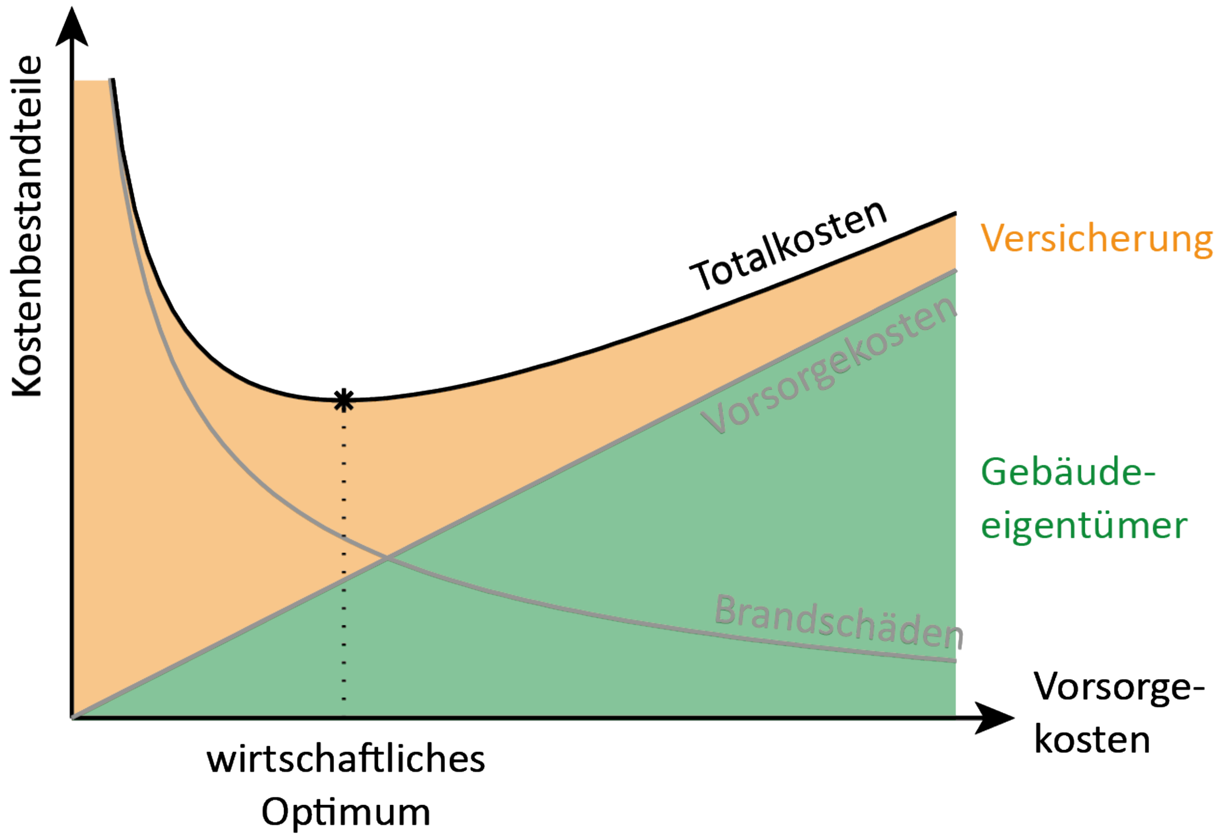
Economic optimization in FSE - cost

Economic optimization is where the sum of all cost is minimal

Elements of cost:

- Prevention cost
- Fire damage
- Cost of Fire brigade
- Administrative cost

A societal view point must consider all cost



Grah: K. Fisxher

Economic Optimization in FSE

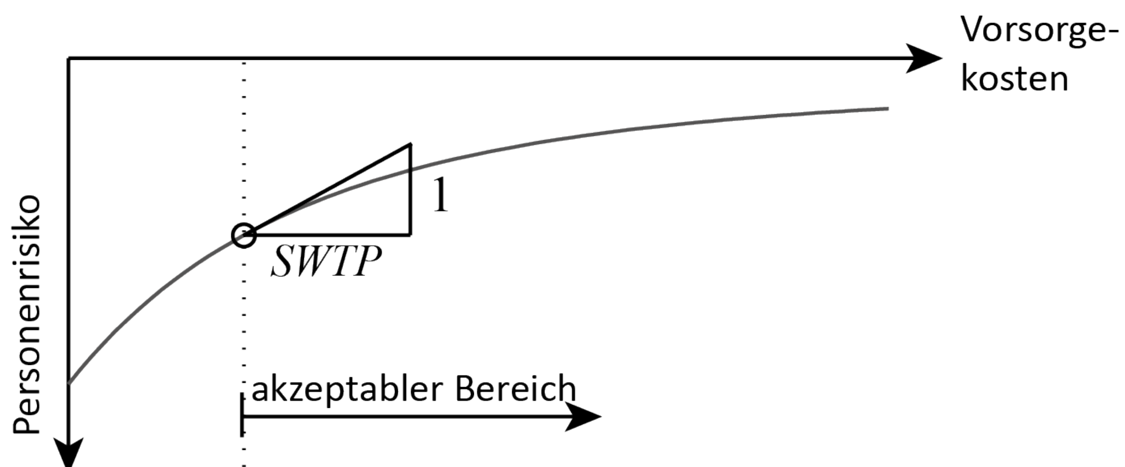
Is there an ethical limit to cost?

The societal resources for life safety are limited !!

- **Efficiency considerations** also for life safety required.
  (N.B. : Too much spending (e.g. for inefficient fire safety) kill, because resources will be mission to safe lives for more efficient measures or in other areas)
- Comparison between limits of cost to safe an additional life and the societal willingness to pay (SWTP)[2] or Societal capacity to commit resources.
- A quantitative acceptance criteria: **Life Quality Index**[1)] (LQI)

1) Nathwani, Lind & Pandey «Affordable Safety by Choice: The Life Quality Method» University of Waterloo 1997

[2] SWTP: Societal willingness to pay bzw. Societal capacity to commit resources.



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Economic Optimization in FSE

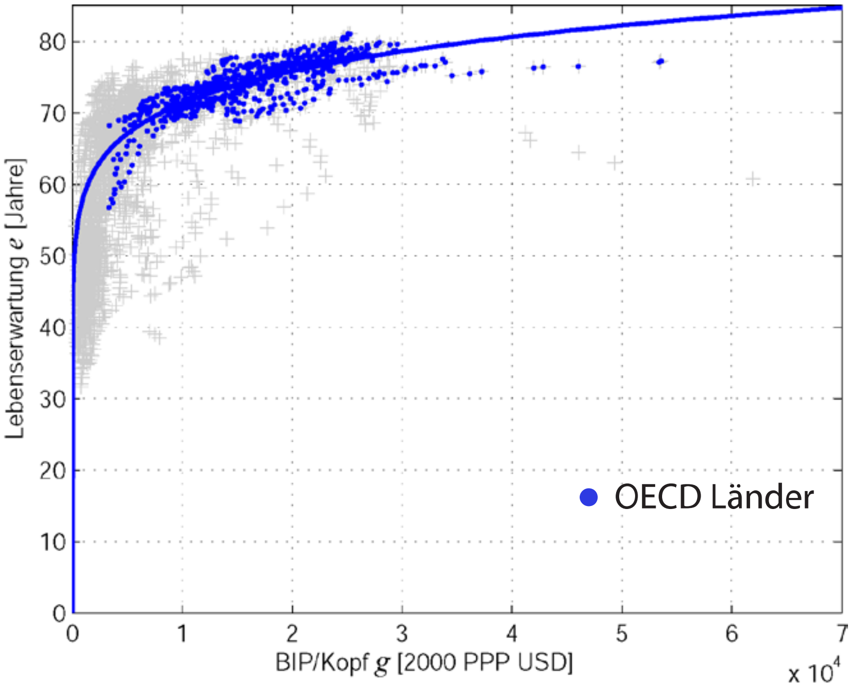
Life Quality Index (LQI):

$$L(g,l) = g^q l(1-w)$$

LQI is a societal indicator considering:

- Gross domestic product g
- Expectancy of life l
- Share of working time of total lifetime, w
- Exponent q, to model societal preferences.

O. Kübler (2006)



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Economic Optimization in FSE

Life Quality Index (LQI):

$$L(g,l) = g^q l(1-w)$$

Advantages of Life Quality Index to assess the SWTP:

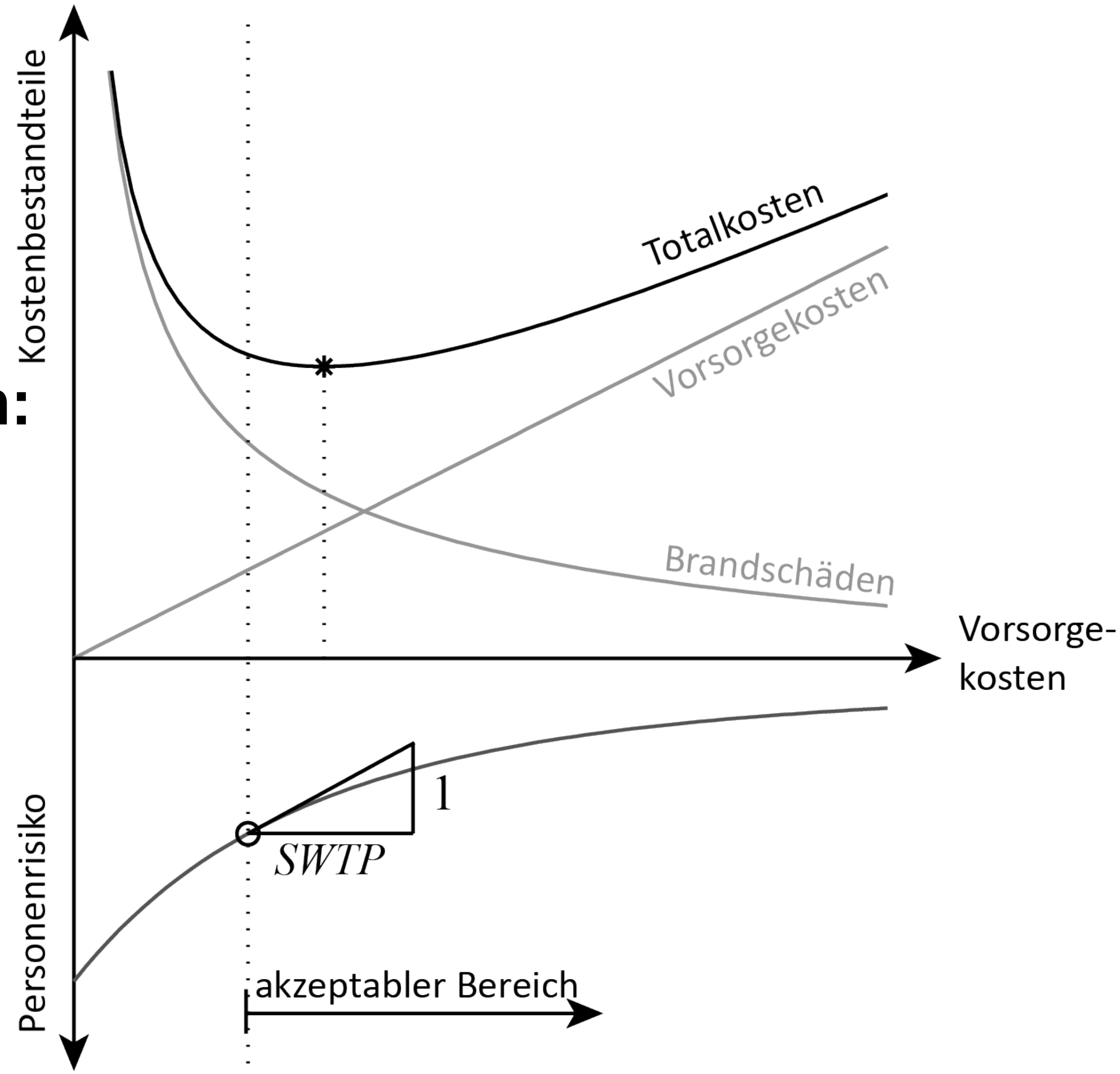
- Basis given by GDP and Expectancy of life.
- Based on observed Preferences (Working hours/Lifetime ration..)
- GDP represents wealth of a society.

Calculated from easily available data, easy to evaluate.

Economic Optimization in FSE

Life safety condition:

Economic optimization only permissible in area acceptable with respect to life safety.



Grah: K. Fisxher

Economic Optimization in FSE

Societal Willingness to Pay (SWTP):

$$SWTP = \frac{g}{q} C_x \Delta\mu \, [CHF / Jahr]$$

«Societal Willingness to Pay» or
«Societal Capacity to Commit Resources»

Switzerland, 2010

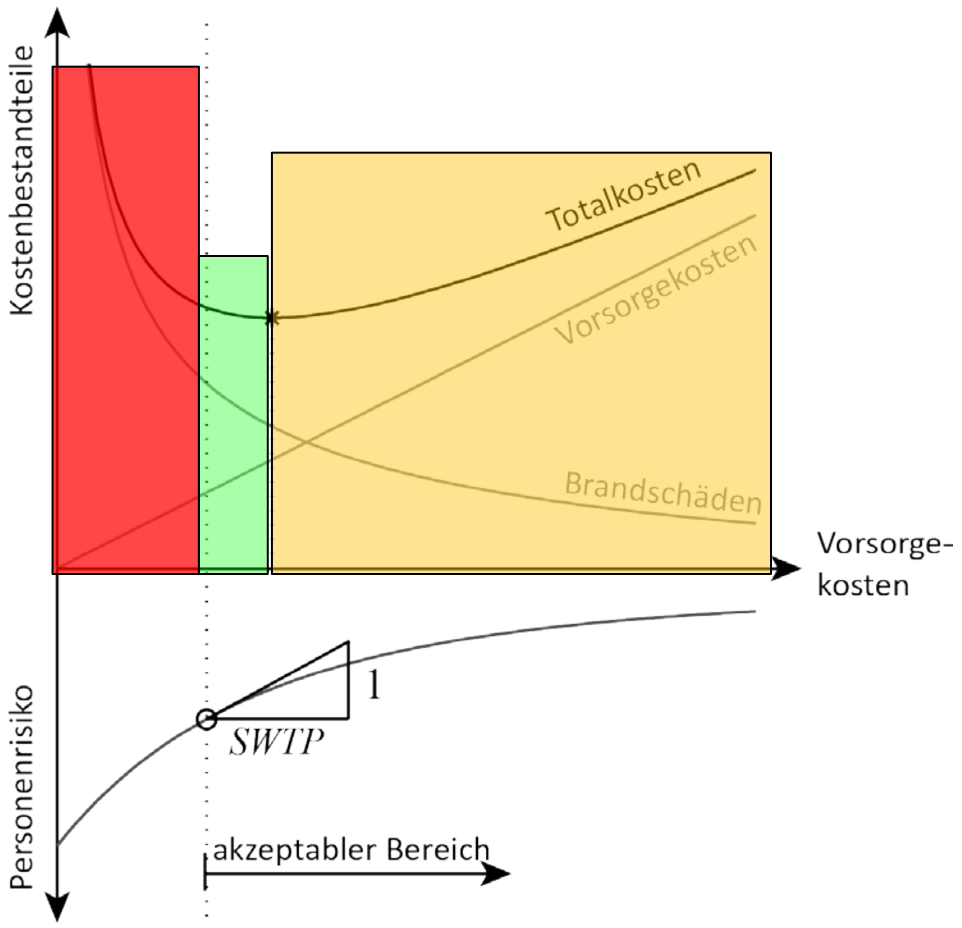
g	69’887 CHF	Income per capita (DSP/resident)
q	0.1905	Exponent for Trade-off between Work and Leisure
C_x	13.85	Demographic constant
$\Delta\mu$	(=1)	(1 Persons saved / Year)

Calculation of Societal Willingness to Pay (SWTP):

$$SWTP = \frac{69'887}{0.1905} \cdot 13.85 \cdot 1 = 5.1 Mio. CHF / Jahr / Person$$

Economic Optimization in FSE

- No economic optimization not allowed because of societal life safety requirement
- Economically reasonable area up to cost optimum
- Higher cost economically not reasonable but acceptable for individual preferences



The Eurocode-Programm of CEN (Committé Européen de Normalisation) Brussels

The structural Eurocode consist of the following parts:

Basic Codes for Design and Actions

EN 1990: 2002 **Basis of Design**

EN 1991: 2002 **Actions on structures** – General actions - Densities, self-weight and imposed loads

The Eurocode programme of CEN

Each Code is structured into different parts e.g.:

EN 19xx-1-1	General rules – Common rules and rules for **buildings**
EN 19xx-**1-2**	Structural **fire** design
EN 19xx-1-x	other parts (e.g. Fatigue strength)
EN 19xx-**2**	Bridges
EN 19xx-x	other (e.g. Chimneys)

For earthquake full series of codes exists:

EN 199**8**:	Design provisions for **earthquake** resistance of Structures
-1	General rules, seismic actions and rules for buildings

Conclusions

- Characteristics of FSE for structures:
  - Fires can be modelled much more realistically with **natural fires** (physical Models) than with standard fires
  - The structural model must take into account **behaviour of the global structure** including load-transfer and large deformation (load-transfer, membrane action)
  - **Uncertainties** can be assessed with probabilistic approaches. Limit sate function depends on the **SWTP**.

Conclusions – FSE for FR of structures

- **Preconditions for the application of FSE:**
- **Fire Regulations** must be **performance based** to efficiently apply fire safety engineering
- **Checking procedures** need to be adequate to allow efficient FSE (Role of fire authorities?)
- **Results :**
- Fire safety engineering and performance based regulations allow **efficient objective based** and safe **fire safety design** (if trustfully applied)
- Limited societal **resources** are used efficiently (SCCR)