Computational Mechanics
Enhanced Civil Engineering Applications
Fire and Blast

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The numerical challenge

Numerics

- Classified as „Fire resistant“
- Sectional Hot Design
  - Temperature distribution
  - Temperature dependant strength
- Structural Hot Design
  - Non uniform temperature elongation
  - Redistribution of forces (main topic)
- Natural Fires
  - Limited fire load / CFD - Analysis
- Complete Fire Analysis
  - Combustion / Smoke and CO-distribution

Generality

Econmy ? o

An example project

- Problem:
  - Architectural design competition for an open air swimming pool owned by the State.

- Answer:
  - should contain solutions such that the client is convinced of the economic sustainability of the design concept.

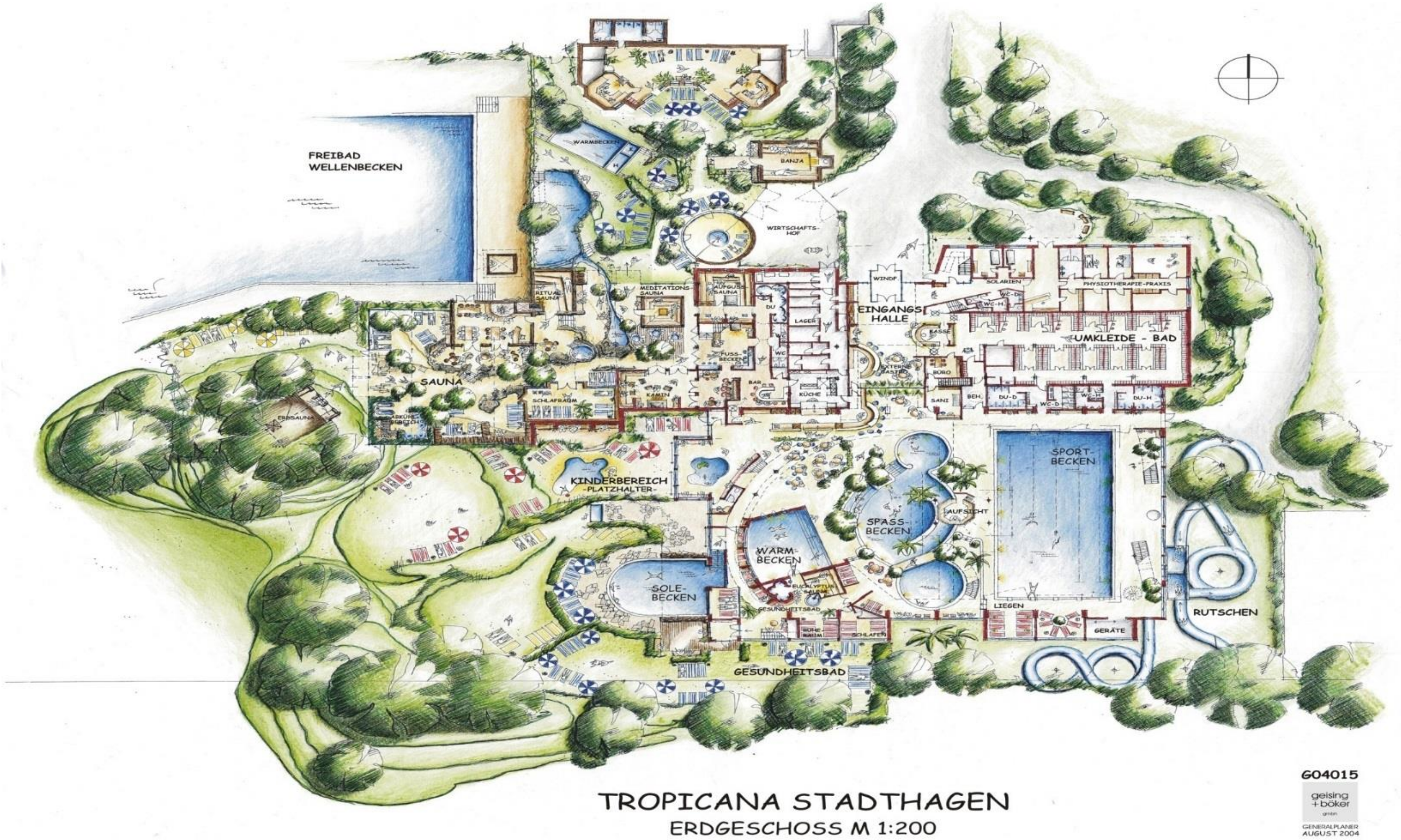
Vision and Constraints

Architects vision:

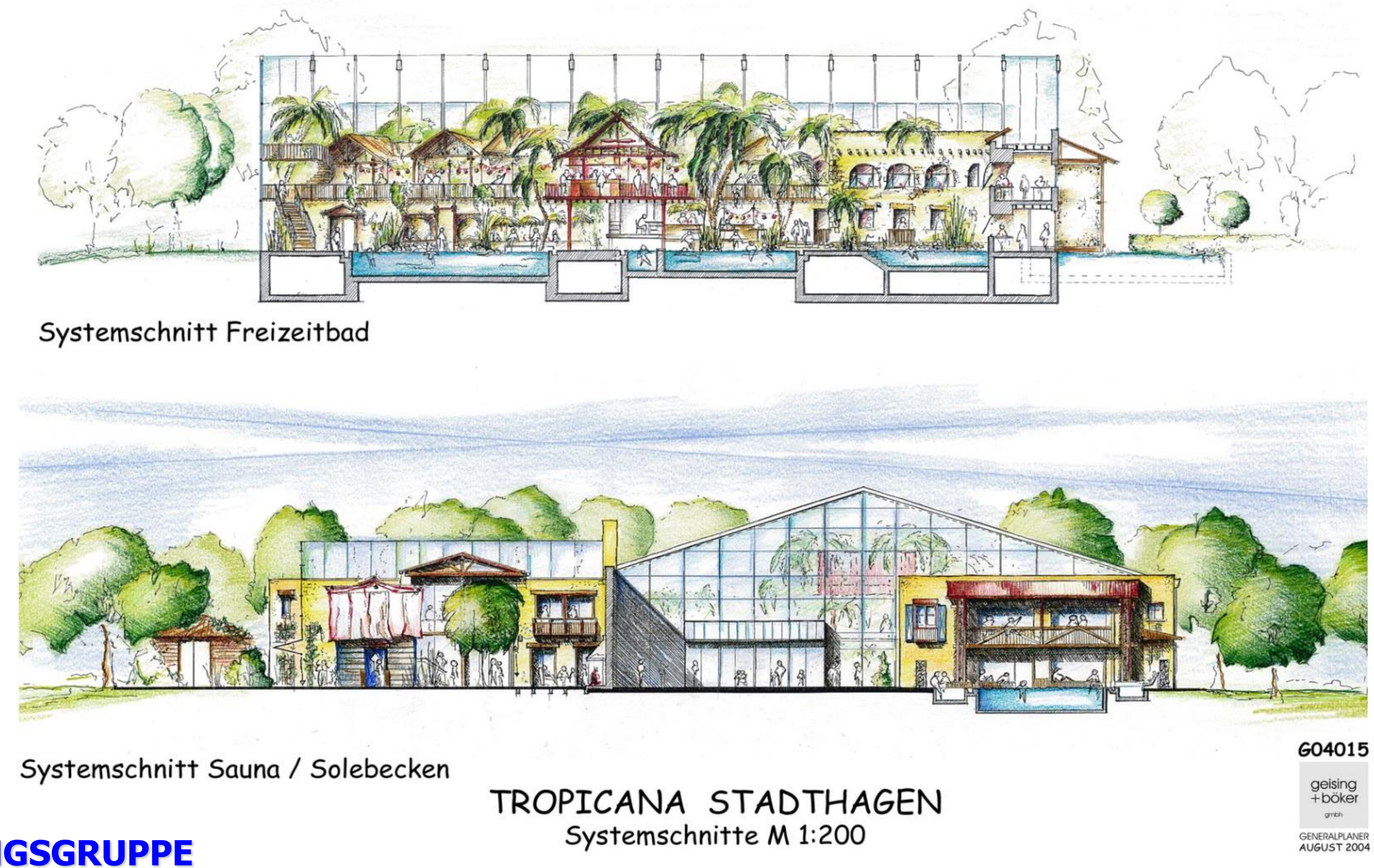
- Integrate the pool with leisure attractions and create an open air pool which can be used throughout the year.
- (location is Germany where summer is restricted to about 8 weeks per year.)

Constraints:

- Structure should be affordable and the leisure park should generate a maximum possible degree of attraction.
- Comply with the building rules and regulations including the fire protection concept for the users and so on......



PLANUNGSGRUPPE
DRÖGE · BAADE · NAGARAJ



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Concept and Feasibility

- Architects concept:
- Low cost superstructure with a green house effect for winter use and a retractable roof for summer use.

- Feasibility:
- Such a system is available in Canada which complies with the concept and is within the proposed budget level.

Fire Design

- System is available only as a Package
  i.e. Structural +Retracting system as a kit and is made of aluminium.
- Fire design becomes an essential part of structural engineering:
  - The roof structure has to establish a fire rating for 30 min.
  - No coating available for aluminium structures.
  - The building can provide max. Exits and hence reduce the egress time for escape
  - The structure should retain stability for at least 30 min. to enable the fire fighters to enter and rescue persons trapped inside.

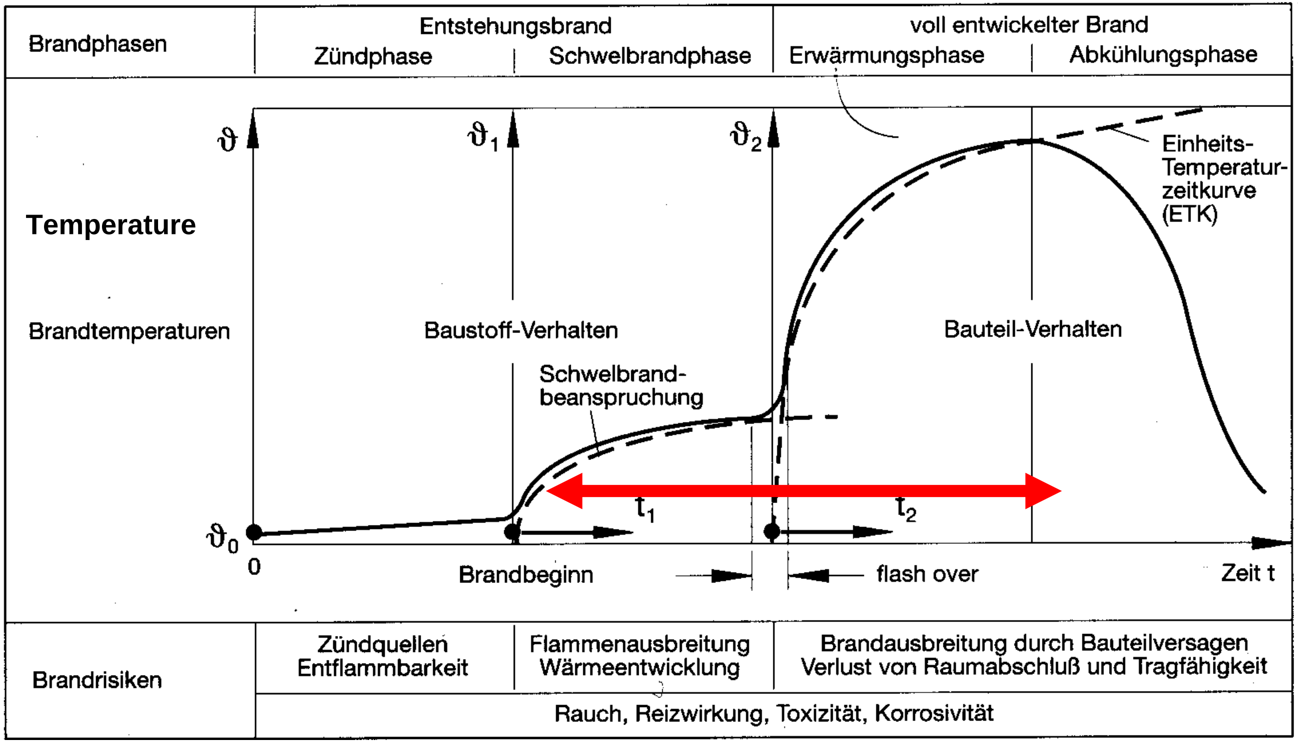
Integrated Analysis

- Method of structural stability analysis:
  3D – Second order structural analysis of the superstructure with temperature dependant material properties.

- What is the temperature where ?

- CFD Analysis including ....

Phases of a fire – Flash Over



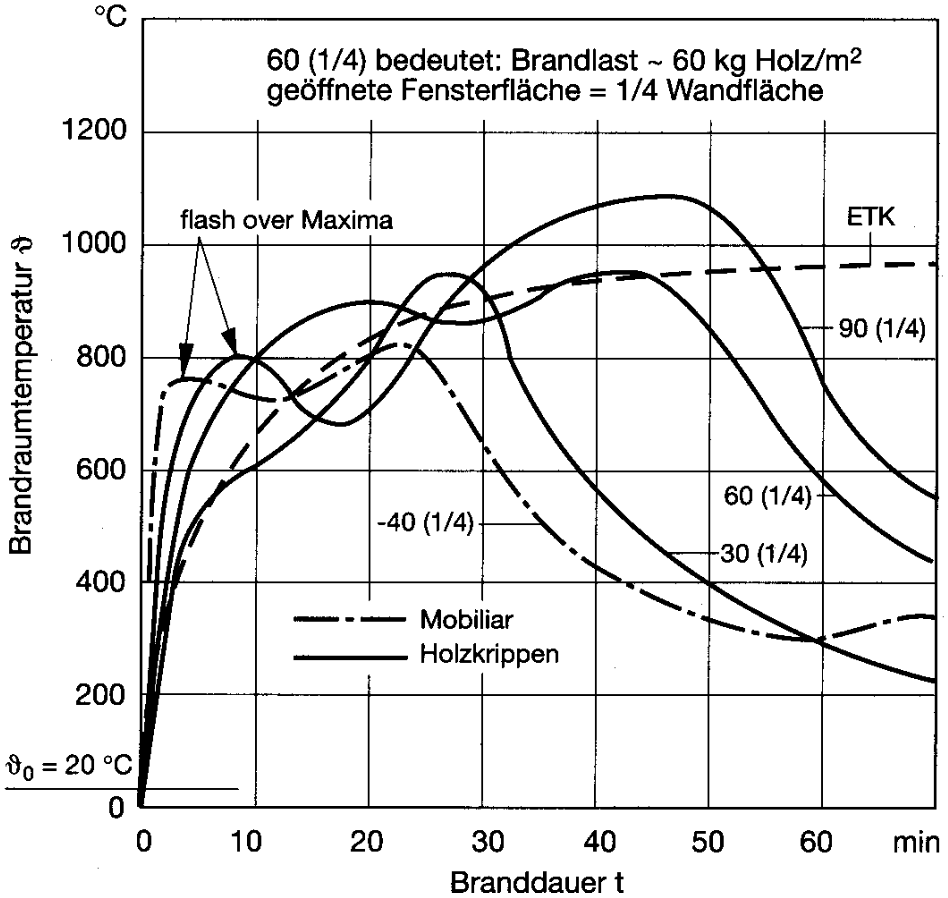
Design fire

- Temperature-Time curves, e.g. ISO-Fire (ETK)
- Fire Simulation model with the following parameters:
  - Fire Loads
  - Ventilation conditions
  - heat loss through the boundary surfaces

Natural fire

Heat release curves:

- constant design fire (independent of the time)
  - steady state
  - constant energy release rate
  - max. fire diameter
- Time dependant growing design fire.
  - Heat release rate
  - Fire diameter
  - Fire burning speed
- Combustion



Analysis Possibilities

- Zone models (MultiRoomFireCode)
  - Subdivision of the System in few (2 to 20) zones with a uniform behaviour
  - Mass and Energy conservation within zones
  - Momentum conservation only within plumes
  - Requires good knowledge of users
- Field models (CFD)
  - Navier-Stokes Equations + turbulent Flow
  - Numerical intensive
  - Oxidant distribution is very important (Ventilation)
  - Easy to use ?

Effects to be considered

- Energy balance
  - Energy produced by combustion
  - Energy exhausting with ventilation
  - Energy absorbed by walls and windows and internal bodies (Convection, Conduction, Radiation)
  - Energy within smoke
- Mass balance
  - Ventilation (Inflow and Outflow)
  - Combustion process itself

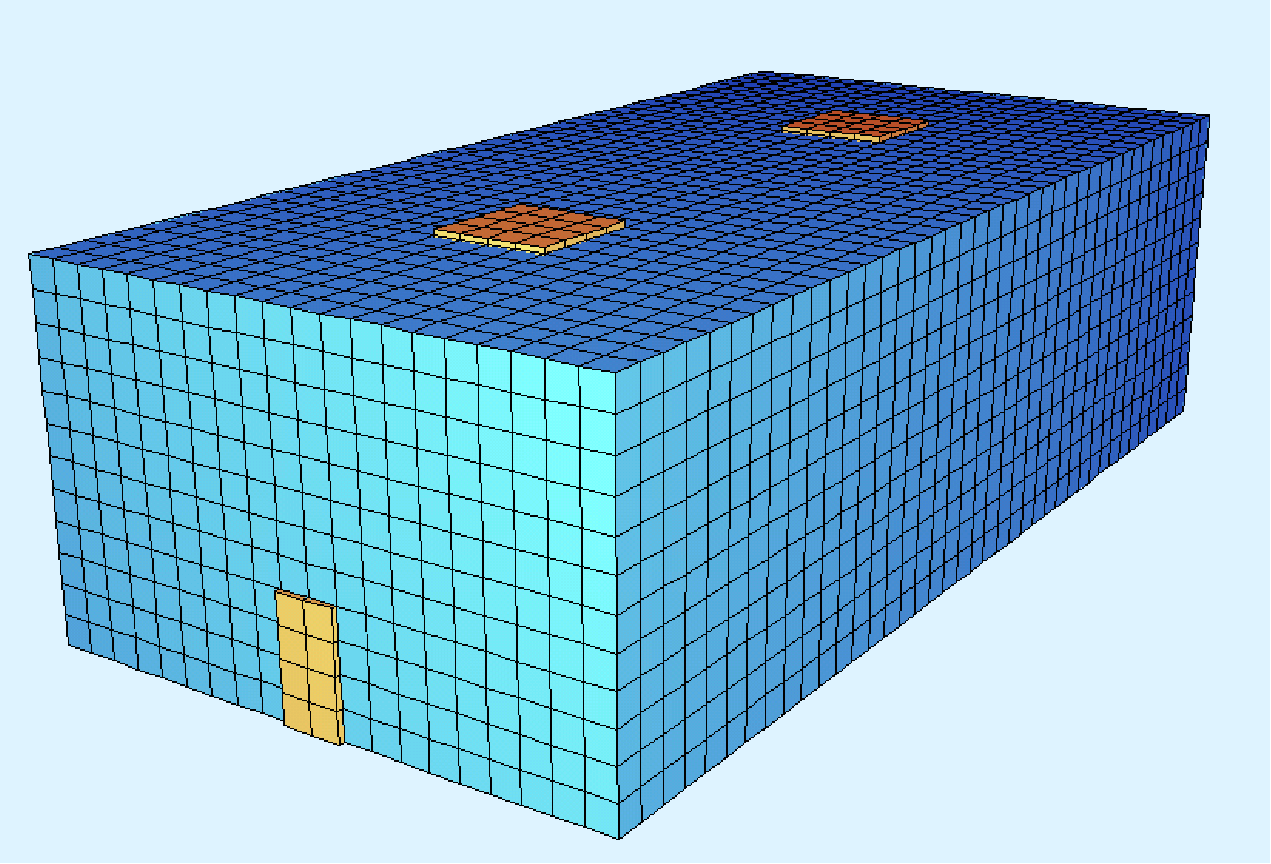
Complex Part - Combustion

- Two basic parameters:
  - H_u = calorific power (kWh/kg),
    Very specific for all materials (4.8 – 33.6)
  - H_u/r = Air requirement (kWh/kg air)
    rather constant for many materials (0.81 – 0.98)
- Subdivision of fire condition
  - Ventilation controlled (stoichiometric) / Fire load controlled
- Ventilation model seems mostly unfavourable
- „Heat release curves“ cannot be transferred easily

„Easy Part“ – CFD + Temperature

- Given Heat load in KW over time or from combustion process
- Turbulent air flow including buoyancy
- Radiation boundary condition for walls
- Convection and conduction
- Inflow and outflow Boundary conditions
  Many changes during the fire possible
- Great uncertainty:
  The outer atmospheric conditions (wind pressure)
- Many Parameters ! Too many ?

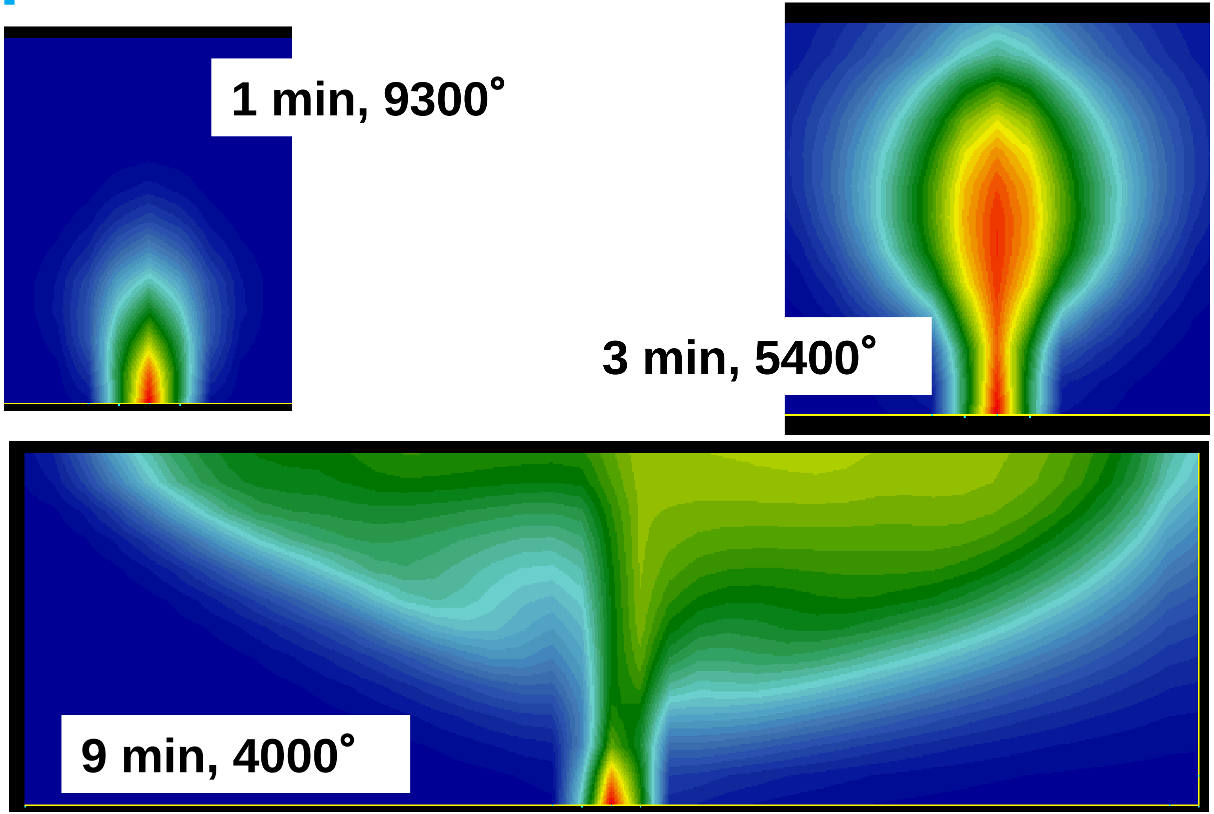
Example



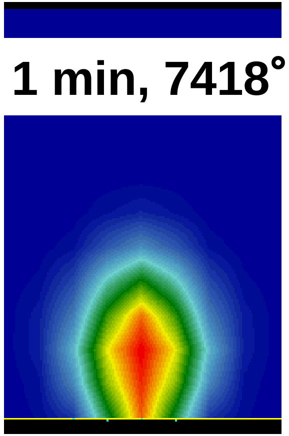
How to start ?

- 2 D ! Only 480 Volumes
- Simple heat source 1 m^2 with 500 / 1000 kW
- No radiation or heat dissipation by walls
- Mesh Size
  - Start with a coarse structured mesh !
  - unstructured mesh may violate symmetry
  - Adaptive mesh ?
- Steady state / Transient (= Time Step Size) ?
- Boundary Conditions for CFD (Software PHYSICA)
  - Pressure, velocity, IN-OUT

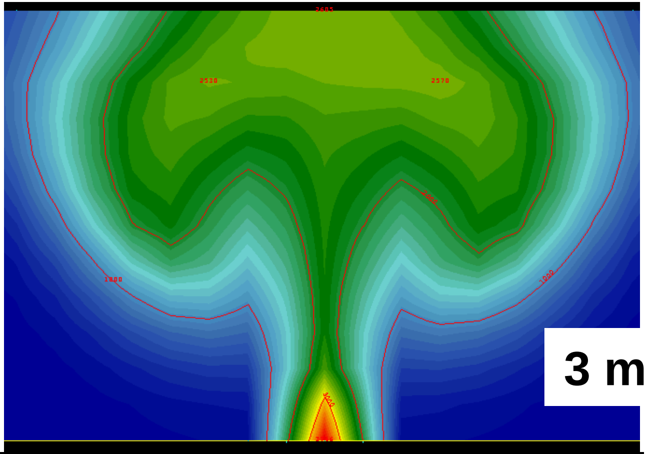
Temperature with Δt = 60 sec



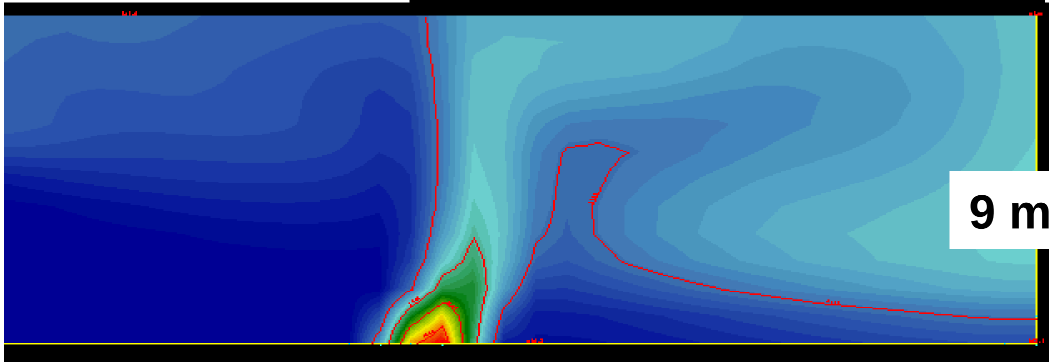
Temperature with Δt = 5 sec



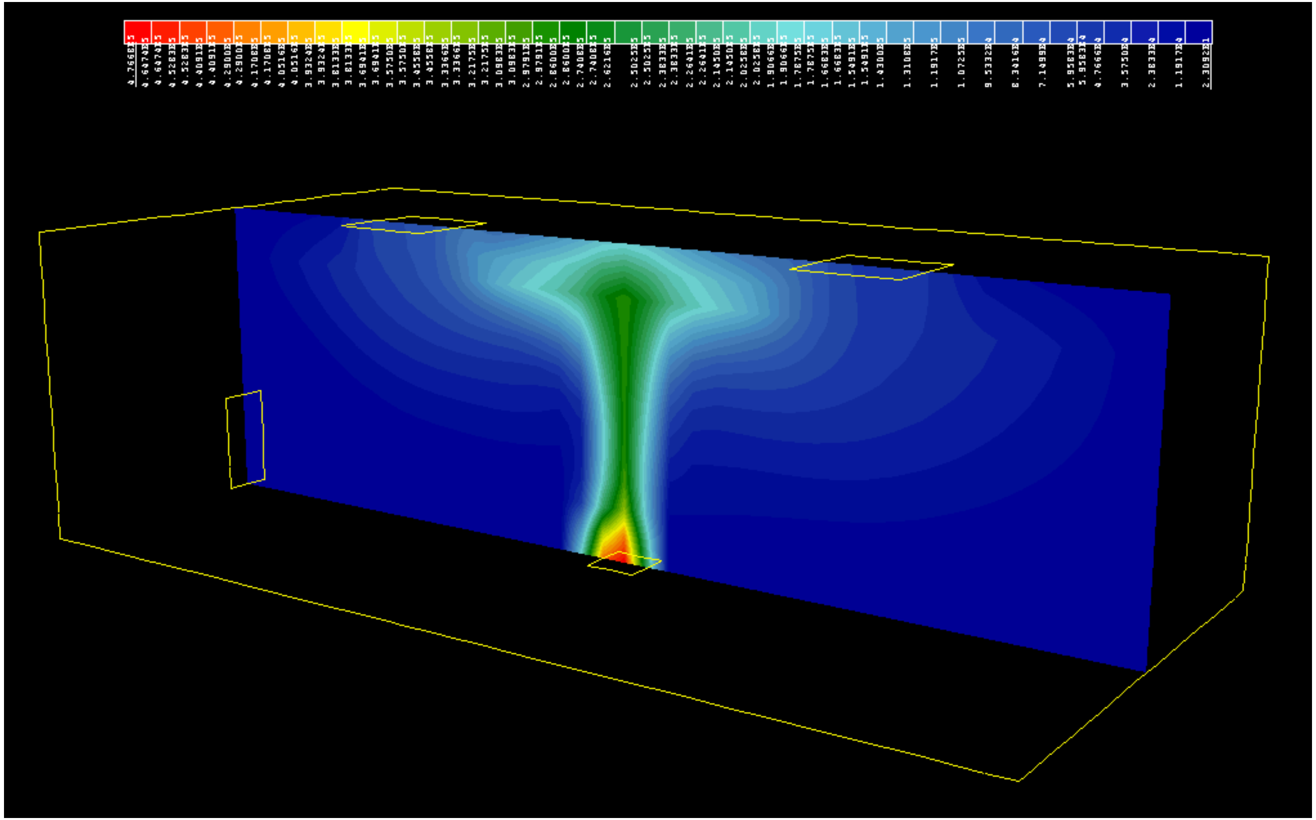
1 min, 7418°



3 min, 3746°



9 min, 4560°



Analysis in 3D ?

Remarks and questions

- Temperatures are clearly to high, even if we cut off the very high values within the fire. The expected high temperature zone at the ceiling does not show up.
- Mesh refinement does not show significant changes.
- One major problem seems the start phase
- The reference 3D solution obtained with 380000 volumes shows „only“ about 120 degree temperature at the ceiling. This software uses more sophisticated modules (LES Turbulence module, Internal combustion) but is that the problem ?
- What is wrong then ????

Don‘ts to be learned from this

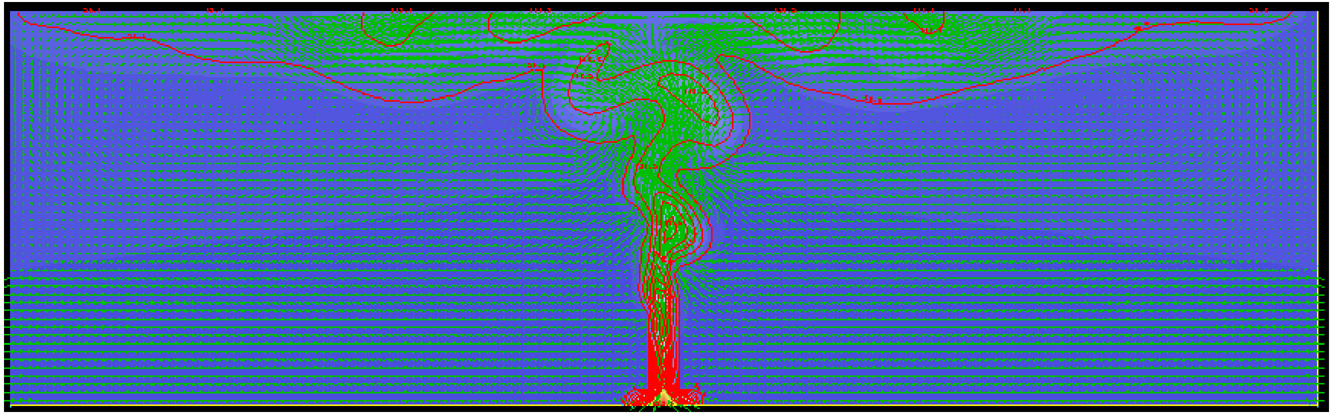
- Do not include more physical effects if you have not understood / established the simple ones.
- CFD does not allow for a rough estimate as with structural mechanics. If your mesh size is to large or the time step to large, effects will not become smaller but may be eliminated completely.
- Don‘t believe physical constants from other examples (Thermal expansion coefficient of air was to small by a factor of 1000!)
- Don‘t believe in symmetric boundary conditions (The reference example was symmetric, our example was not, this effect caused a lot of doubts)

Time step size

- Total time is here 30 Minutes, but may be up to 360 Minutes
- Mesh size is between 0.125 and 0.5 m
- Flow velocity is about 5 m/sec

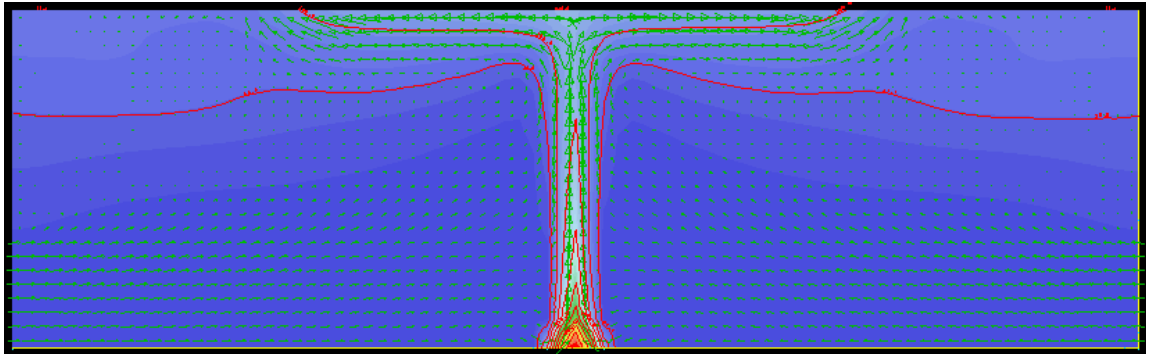
  => Good time step is of order 0.025 seconds
  yielding 72000 time steps !
- We should use adaptive time steps!
  - Rather small for the start up phase & to model turbulent fluctuations
- We have a steady state solution after a few minutes!

But still no convergence with time step 10 secs



Internal small time step 0.1 sec
prevents solution to become complete garbage
Convergence achieved with 0.01 sec internal time step
(FALSE_TIME_STEP for HEAT and FLOW)

Reasonable Solution !

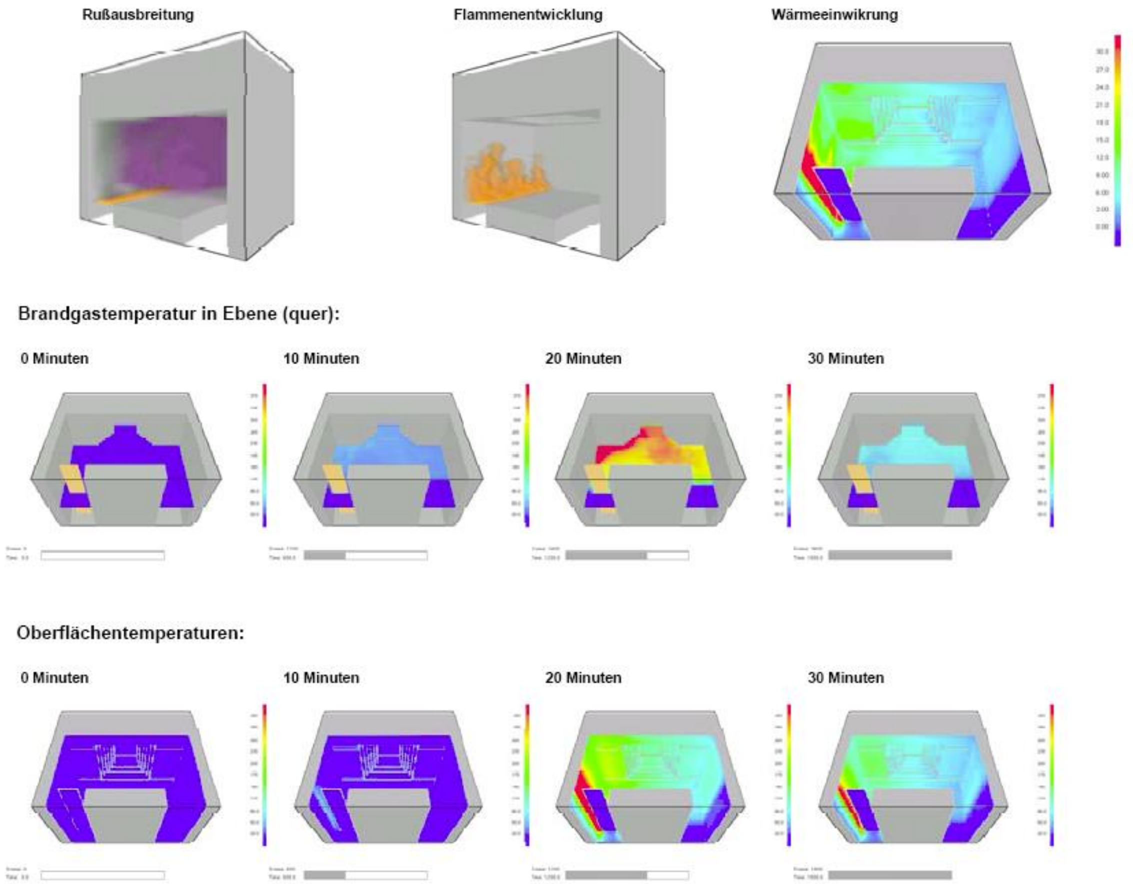


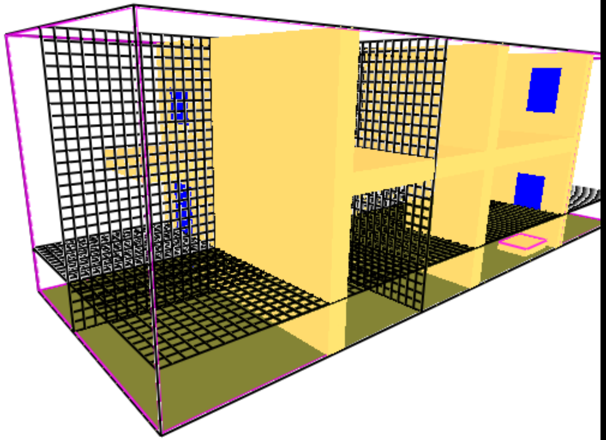
Mesh / Time	Δt = 0.01	Δt = 0.1	Δt = 1.0	Δt = 10
0.250 / 30 sec	143 °	168°	168°	132°
0.250 / 30 min		128°	129°	128°
0.125 / 10 sec		143°	142°	144°
0.125 / 30 sec		141°	143°	-

What follows from that

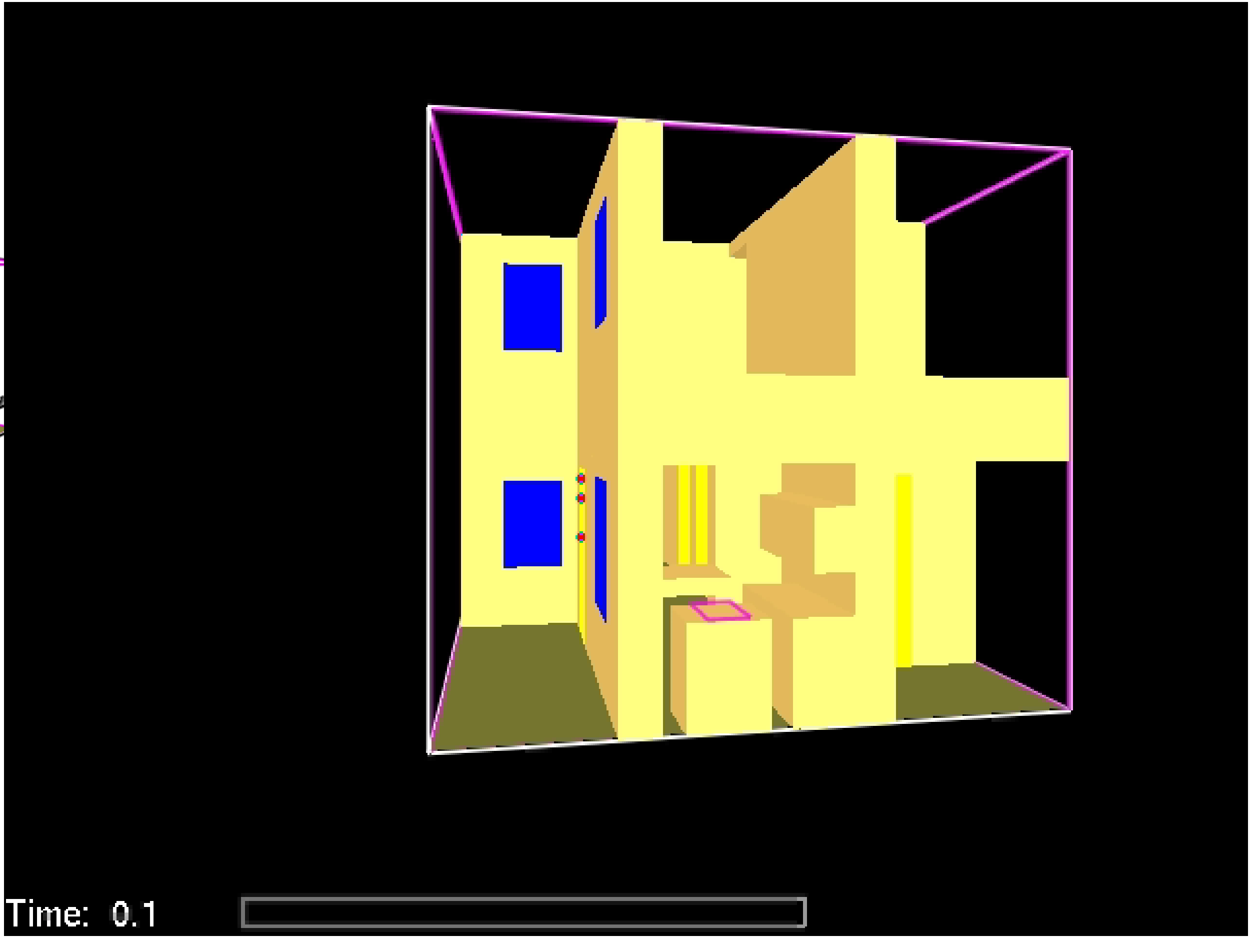
- CFD does not allow for a rough estimate as with structural mechanics. If your mesh size is to large or the time step to large, effects will not become smaller but may be eliminated completely.
- But Mesh refinement or 3D system (Standard advice from experts) does not show significant changes. The basic error was a faulty material constant taken from another example!
- One major problem is the time step! In the initial phase we need a very small time step, to be allowed to become larger then, but 120 or even 360 minutes of fire will create an excessive number of time steps.
- It is not a good idea just to include more physical effects if you have not understood / established the simple ones.

Fire in a Metro Station





http://www.fire.nist.gov



Risk of Fire

- Most casualties due do fire are due to suffocation. i.e. smoke and fumes are most critical.
- Sometimes the failure of the structure becomes the essential problem
- The WTC was the only high rise building designed for an impact but not for the consecutive fire event which happened in reality.
- Last not least, no distinct "loading assumption" will match reality.

Engineering Methods ?

- What has become best practice for the structural design itself, a detailed analysis of ultimate limit states, is still not the standard for fire protection.
- Dominant is the classification of burnable materials
- Which is impossible for a slender column
- As the safety level for the reinforcements have been reduced with the newer safety concepts ($1.35*1.15 < 1.75$) the hot design has become more relevant.

Engineering Methods for Fire Design

- Analysis of the fire in a building
- Analysis of the fumes and smoke
- Analysis of the fire effects on structural elements
- Resistance of structural elements in fire
- Efficiency of smoke extractors
- Analysis of people evacuation
- Evaluation of fire fighting measures

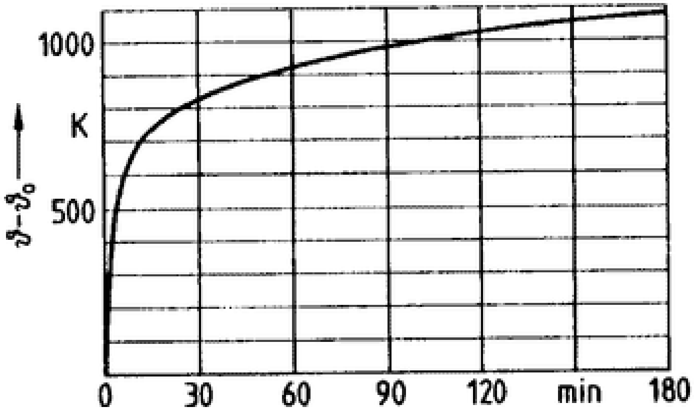
Detailed (CFD) analysis require experience and can't be used by everybody as a general tool.

Structural hot design may be used by a broader range of engineers.

Back to the Roots

- If the standard rules of construction are not sufficient
- But If we do not need to model a natural fire
- We make a hot design with a classified (ISO) temperature curve

$$T = 20 + 345 \cdot \log^{10}\left(8 \cdot t + 1.0\right)$$



Natural fires
EN 1991-1-2

t^*	$= t \cdot \Gamma$	[h]
mit		
t	Zeit	[h]
Γ	$= [O/b]^2 / (0{,}04/1\,160)^2$	[–]

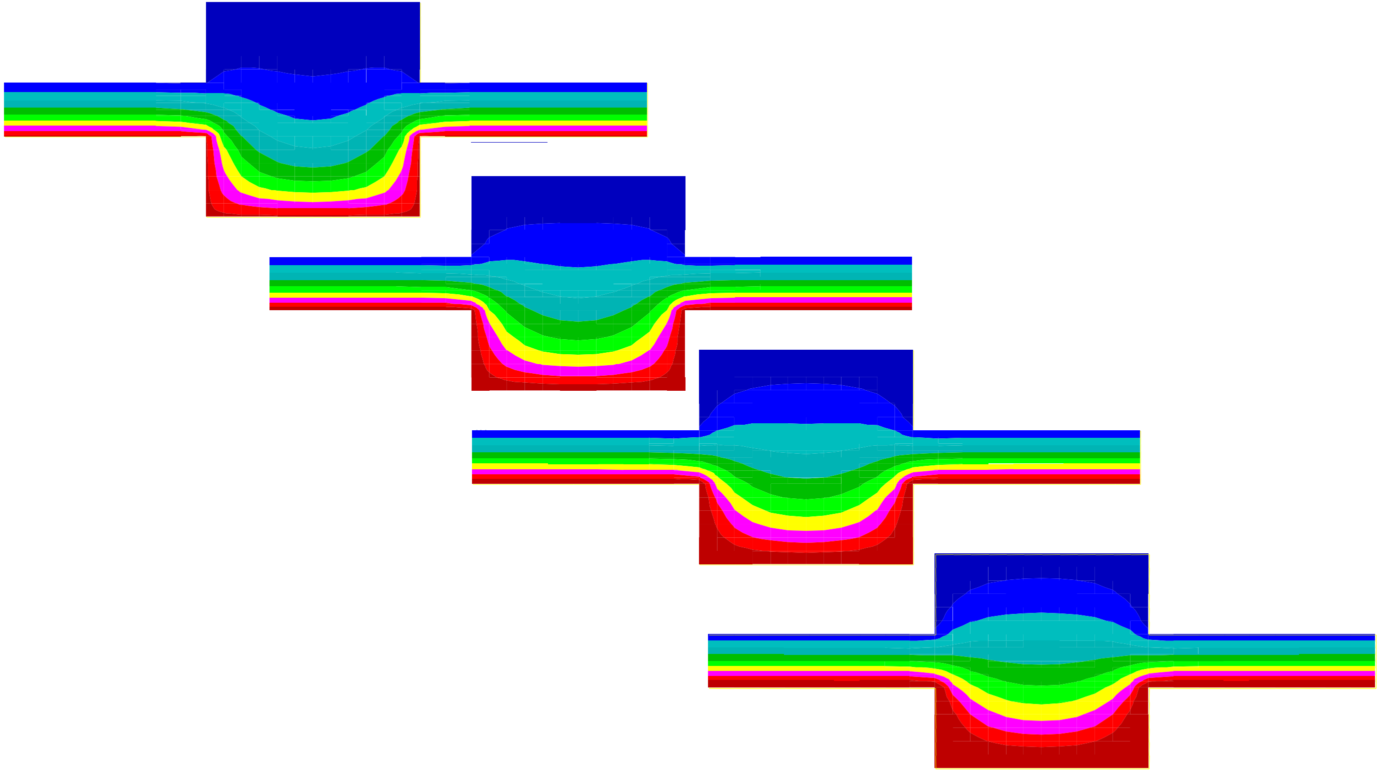
$$\Theta_g = 20 + 1\,325\,\left(1 - 0{,}324\,e^{-0{,}2\,t^*} - 0{,}204\,e^{-1{,}7\,t^*} - 0{,}472\,e^{-19\,t^*}\right)$$

λ	Wärmeleitfähigkeit der Raumhülle	[W/mK]
O	Öffnungsfaktor: $A_v \sqrt{h_{eq}} / A_t$ in den folgenden Grenzen: $0{,}02 \le O \le 0{,}20$	[$m^{1/2}$]
A_v	Gesamtfläche der vertikalen Öffnungen in allen Wänden	[m^2]
h_{eq}	gewichtetes Mittel der Fensterhöhen in allen Wänden	[m]
A_t	Gesamtfläche der Raumhülle (Wände, Decke und Boden, einschließlich der Öffnungen)	[m^2]

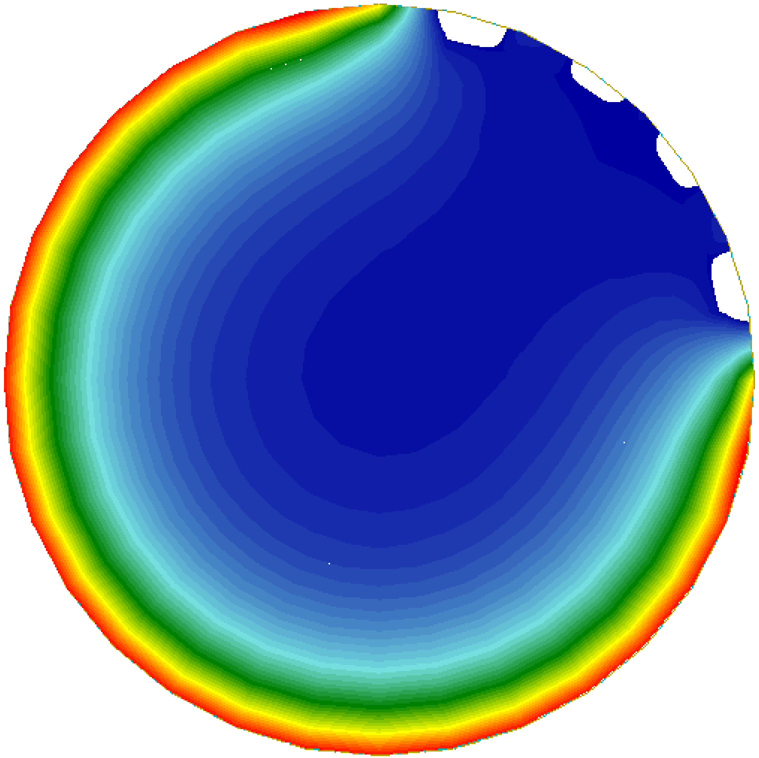
Sectional Hot Design

- First Stage: Heat flow
  - Standard Fires given as Temperature over Time
  - Radiation + convective boundary conditions
  - Temperature dependant material constants
- Second Stage: Section design
  - Non uniform temperature elongation
  - Temperature dependant material strength
- “Only” Problem: One-Way coupling of Multi-Physics
  - Finite Element mesh of the section for both stages

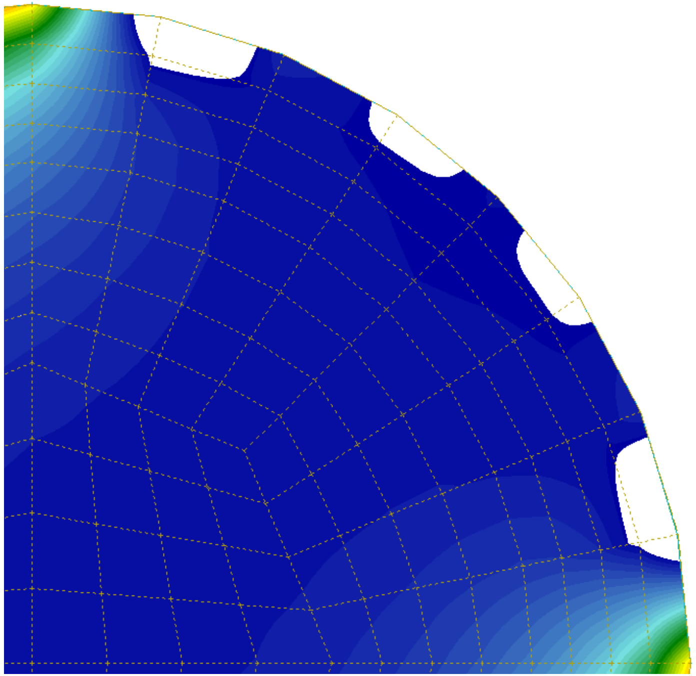
Example: F60, F90, F120, F180



Strange results ?

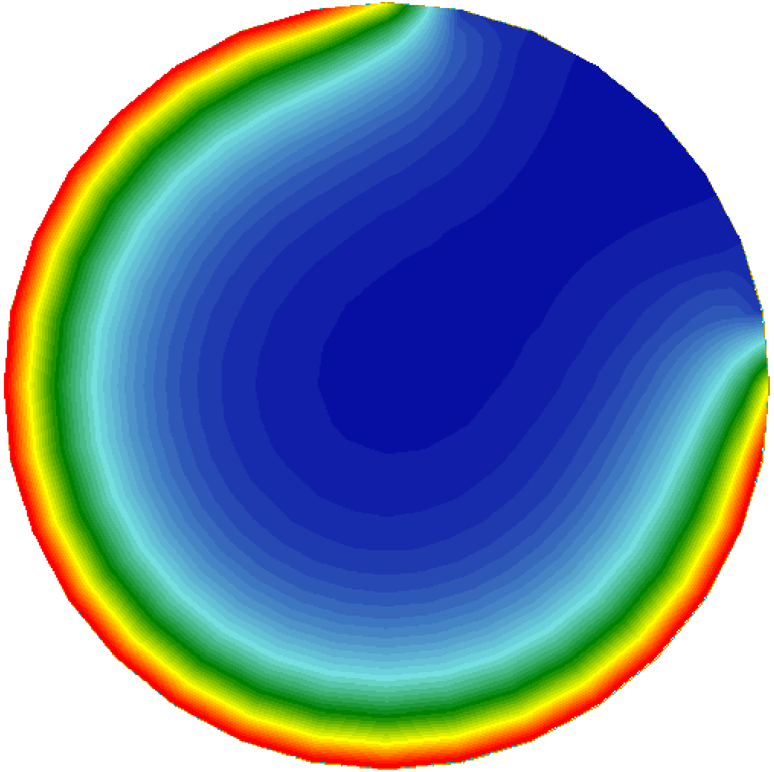


Oscillations between nodes

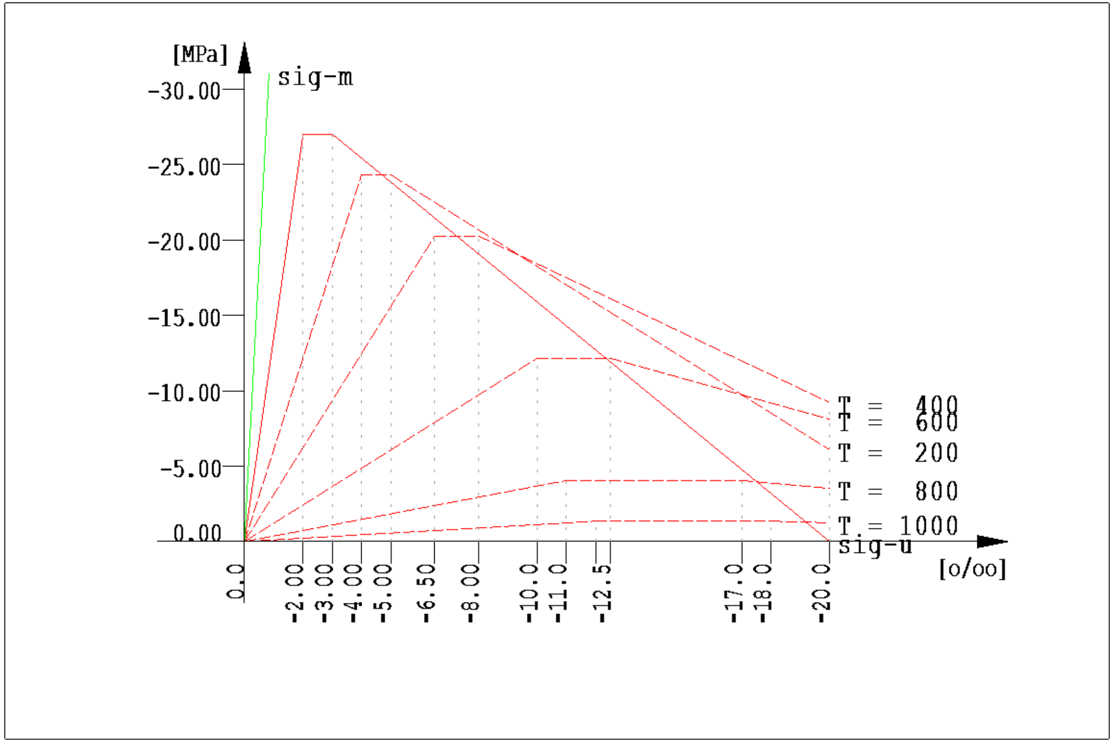


- Typical reason for those effects is violation of the DMP
- Not expected here (lumped consistency)
- But we have a similar effect, the so called „robin“ boundary condition combined with a consistent conductivity selected in W/h instead of KW/h

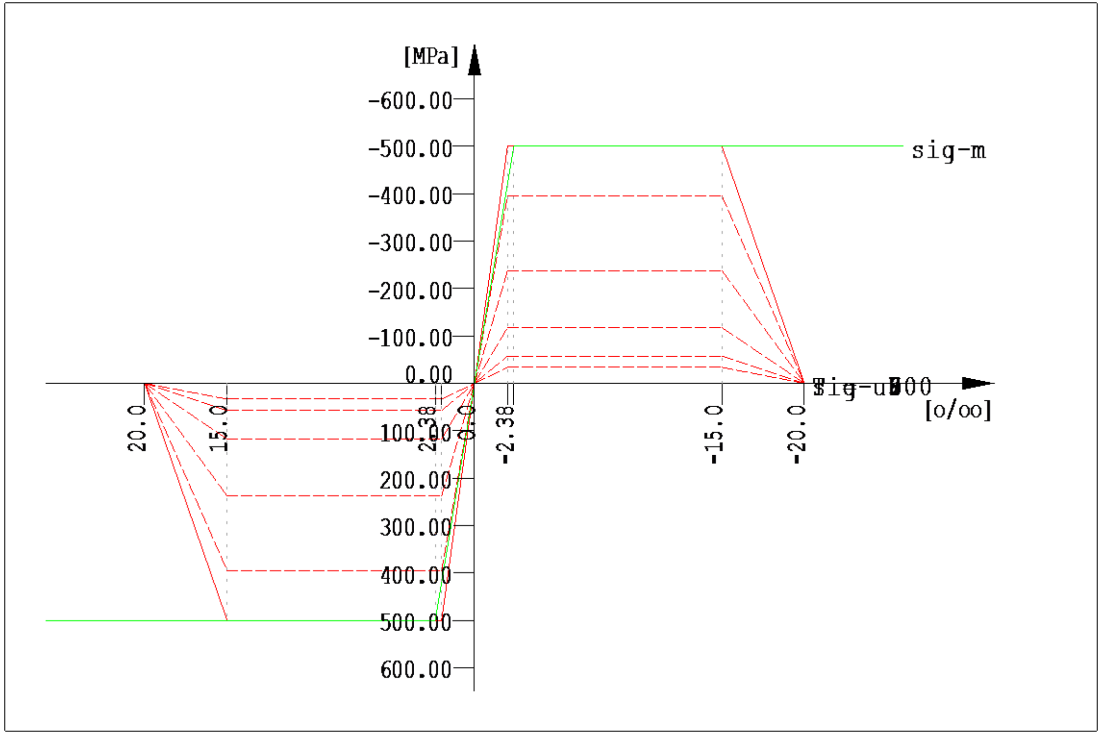
Corrected Material Parameters



Concrete - Material properties

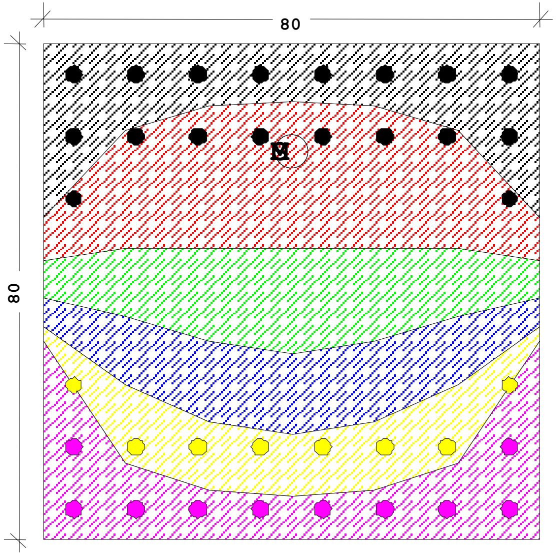


Steel - Material properties



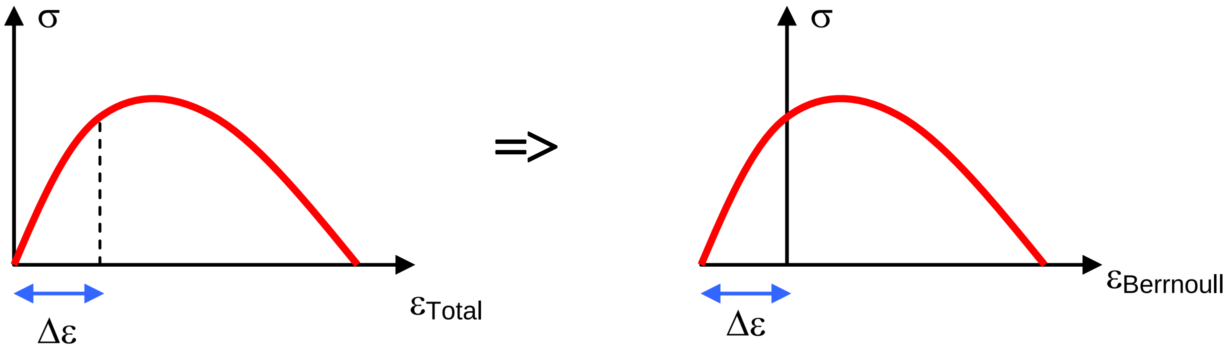
Manual Work may be needed

- Define a material for every temperature range
- Subdivide the section according to temperatures
- Provide temperatures for every rebar



Treatment of Isothermal zones

$$\sigma(\varepsilon) = \sigma\left(\varepsilon_s - y \cdot k_y + z \cdot k_z - \varepsilon_{fi}(\Theta)\right)$$



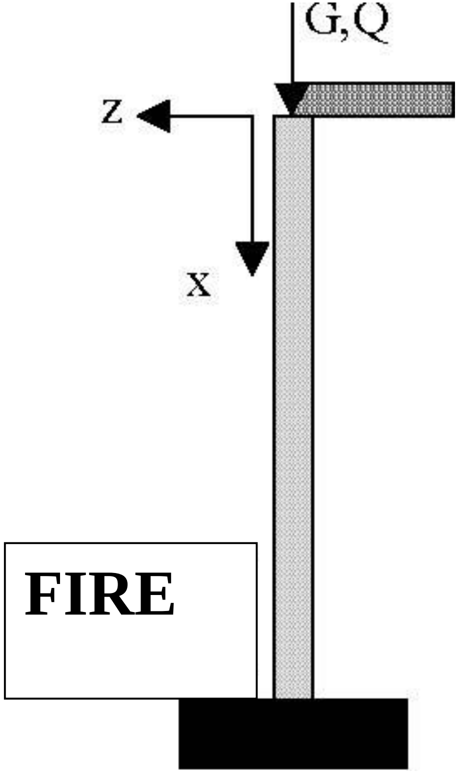
Structural Hot Design

- In most cases fire is not everywhere but confined to some parts of the structure (CFD or expertise)
- Large deformations might occur
- If deformations are restrained,
  structures may get considerable loadings
- Runaway effects and load redistributions will occur
- Non linear analysis is necessary with rather complex mechanisms
- Example:
  A heated beam getting normal forces will buckle, but as it buckles the load decreases immediately and the deformed beam may still contribute with its bending stiffness.

Cardington Fire Test

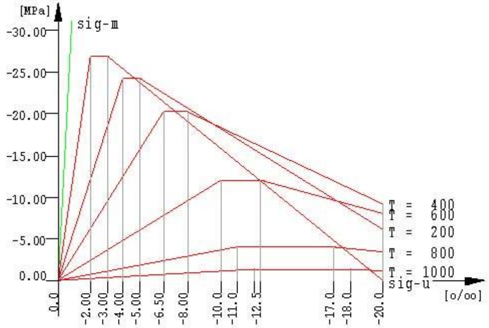
- Real scale experiment by British Steel 1998

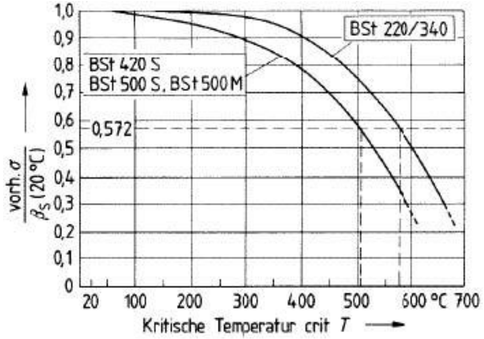
Column Example



- Concrete Column
  size 800 x 800 mm
- Column height 16.5 m
- Fire only on one side
- Eccentric load on column caused by destroyed roof above the fire
- Deflection of unconstrained column head: ca 1400 mm

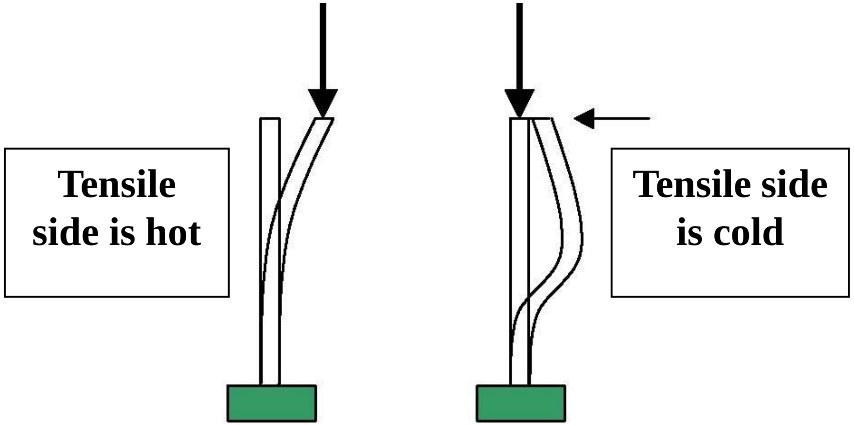
“Easy” step





- Just take the non linear strength values from the design codes:
- However, there were different hints, but no real specification about the strength of cold deformed steel grades of high strength reinforcements for temperatures above 600 degree Celsius.
- If the sectional program does not allow for FE-sections one might use composite sections with different materials for any temperature level (If that possibility does exist!)

What will really happen ?

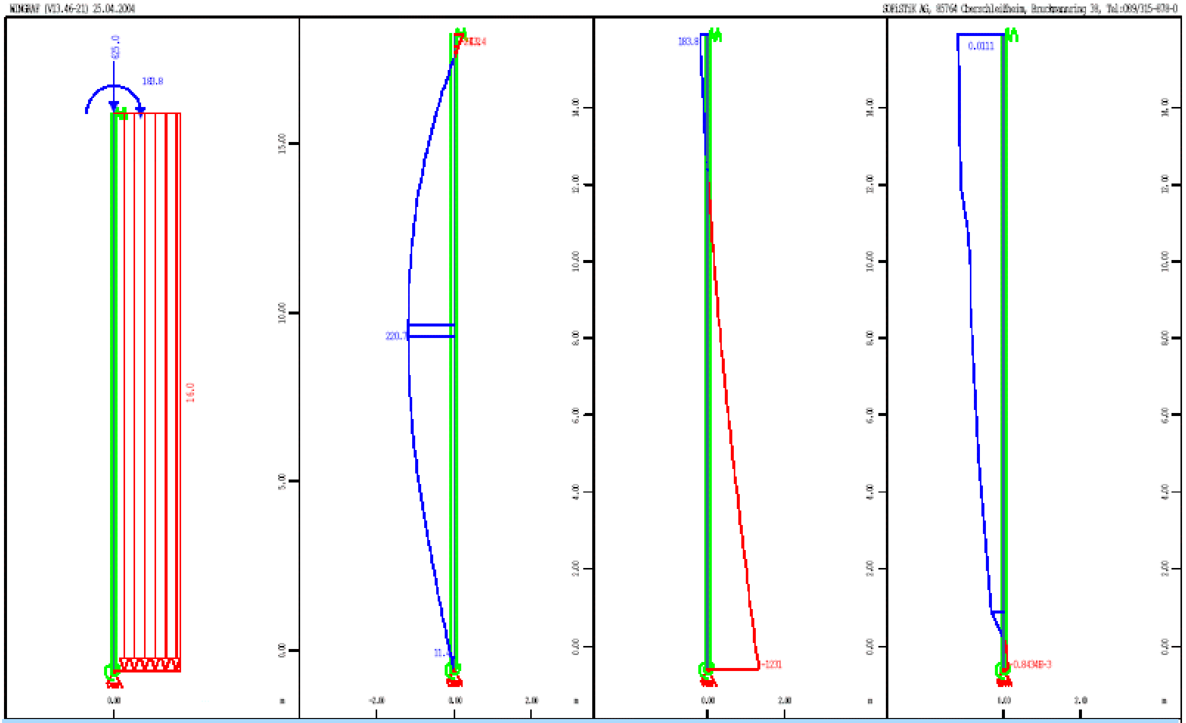


- Even smaller Restraining forces from the cool structure will change the behaviour of the column considerably.
- Cracked zone moves from the hot to the favourable cool side!
- There might be some considerable forces on the column itself !
- Last not least: What is the behaviour of the foundation ?

Steps of Analysis

- The top of the column has an elastic stiffness of itself with a value of 750 kN/m (elastic) and
  - An elastomer with a stiffness of 1875 kN/m
  - The bracing structure itself with 25000 kN/m
  - Thus we need a complex non linear link element to model this.
- The bending moment at the bottom of the column becomes for the elastic column between 24000 and 45000 kNm.
  - Non linear Analysis with full strength of the column reduces this value to 4000 kNm.
  - Non linear Analysis with reduced strength of the column reduces this value to 2900 kNm.
  - Non linear Analysis with reduced foundation stiffness yield a value of 1230 kNm and 44 mm top displacement

Final Results



Loadings Deflections Moments Stiffness

Remarks

- We have started with a FE-transient thermal Analysis
- Sometimes there should be a point, where we can stop our analysis earlier, but here we were obliged to go until the very last end.
- This last end was the rotational stiffness of the foundation. This value was the least precise given and has greatest importance on the results.
- The thermal distribution along the height of the column was selected on the recommendations of a fire protection engineer.
- However his assumption, that it should be favourable to have less heat at the bottom of the column, just proofed to be the other way round, it was unfavourable.

Conclusions

- In general we do not want to go to deep into the details
  That is the difference between an engineer and a scientist.
- There is always the choice between a general but not optimal analysis and many detailed analysis cases.
- If we go a small step towards the more detailed analysis we may encounter effects taking us deeper into the subject.
- There is the danger to spend to much effort on a detail which is not so important over all. Some of the „run away“ effects are easy to handle, some are not.
- However the most important step is from the design fire to the natural fire. 200 degrees are considerably less than 800!

Beyond Fire => Blast

- It is a more and more common problem to deal with accidents or terror attacks where an explosion takes place
- There are three physical effects to be considered:
  - The combustion of the explosive itself
  - The spread of the pressure waves
  - The dynamic reaction of the structure
- The first two problems have to be dealt with hydrodynamic codes (e.g. Autodyne)

Peak side-on overpressure

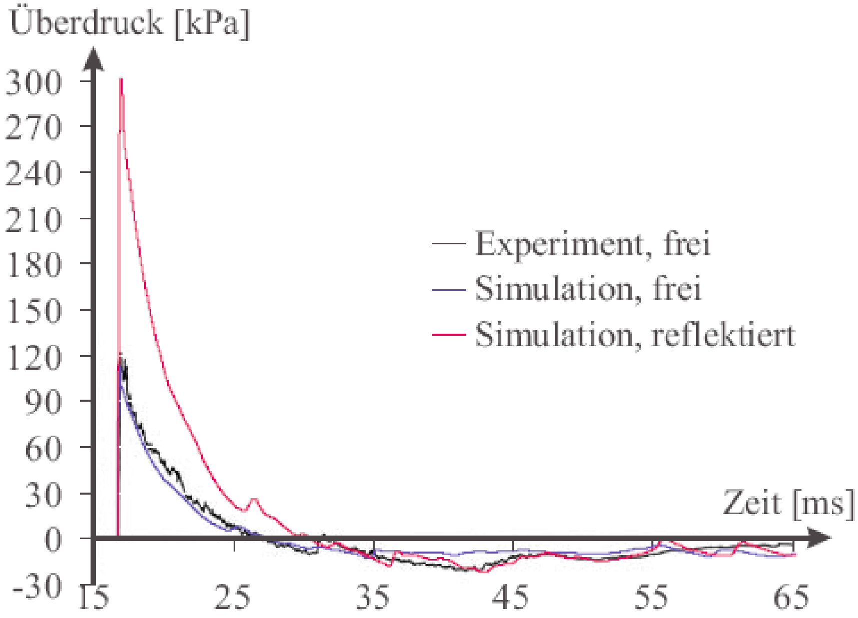
- Formulas by Kinney and Graham, „Explosive Shocks in Air“

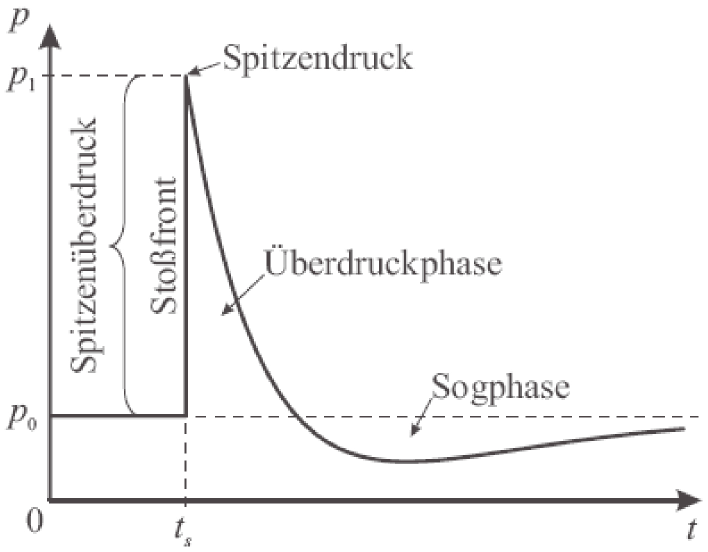
$$p_{so} = p_0 \frac{808\left[1+(z/4{,}5)^2\right]}{\sqrt{1+(z/0{,}048)^2}\,\sqrt{1+(z/0{,}32)^2}\,\sqrt{1+(z/1{,}35)^2}}$$

$$z = \frac{a/(1\mathrm{m})}{\left(m_{TNT}/(1\mathrm{kg})\right)^{1/3}}$$

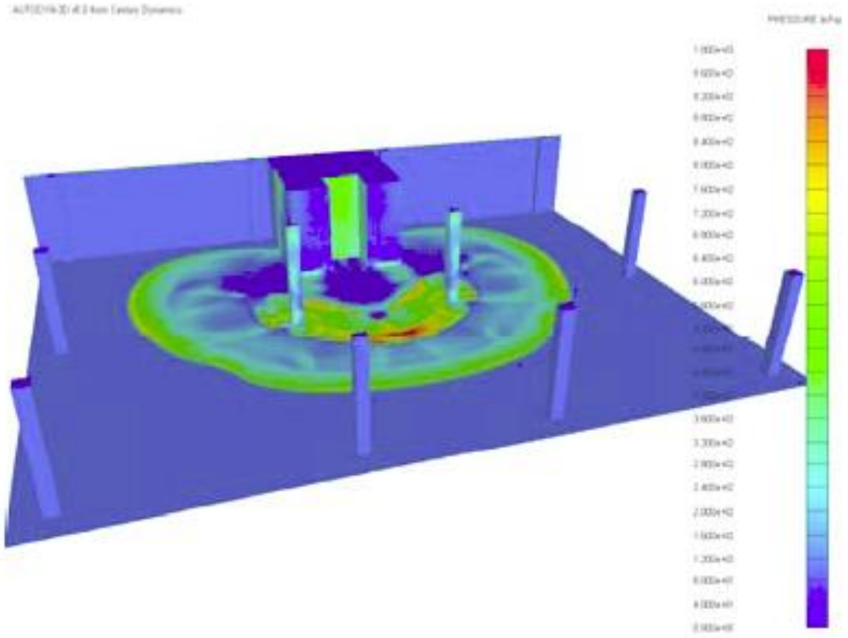
$$t_d = \left(\frac{m_{TNT}}{1\mathrm{kg}}\right)^{1/3} \frac{980\,\mathrm{ms}\left[1+(z/0{,}54)^{10}\right]}{\left[1+(z/0{,}02)^3\right]\left[1+(z/0{,}74)^6\right]\sqrt{1+(z/6{,}9)^2}}$$

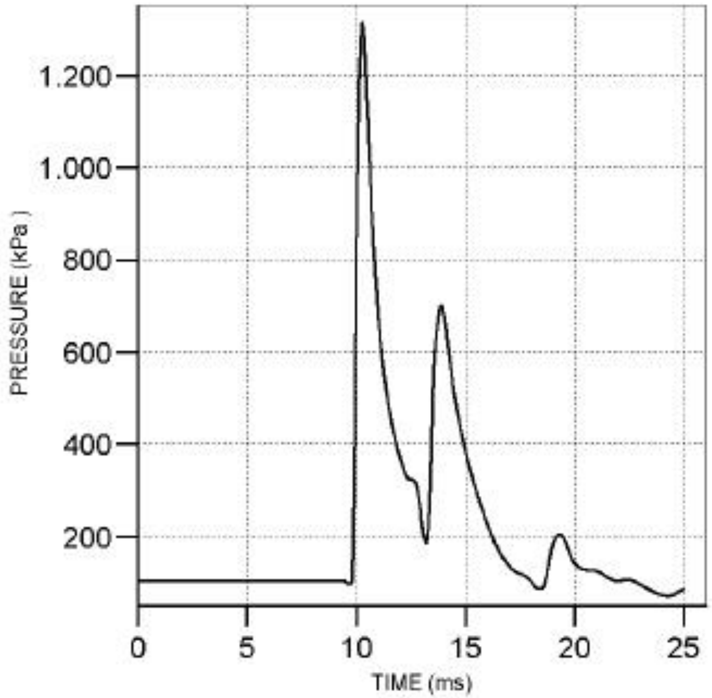
Complete pressure function





Explosion in a Garage



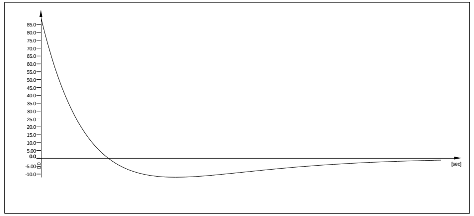


Dynamic Reaction

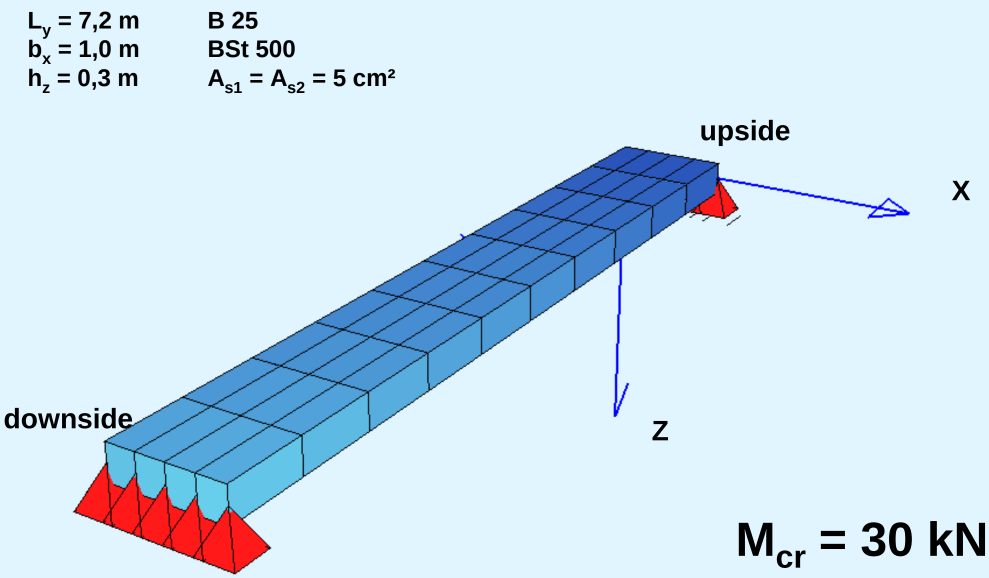
- e.g. values by contractor:
  - Max. pressure 88,72 kN/m²
  - Momentum of Explosion 0,5468 (kN/m²)*sec
- Which Function ?
- The momentum is the Integral of the pressure over time

$$p_0(t) = p_{so}\left(1 - \frac{t}{t_d}\right)e^{-\alpha\frac{t}{t_d}}$$

$$I = p_{so}t_d\left(\frac{1}{\alpha} - \frac{1-e^{-\alpha}}{\alpha^2}\right)$$

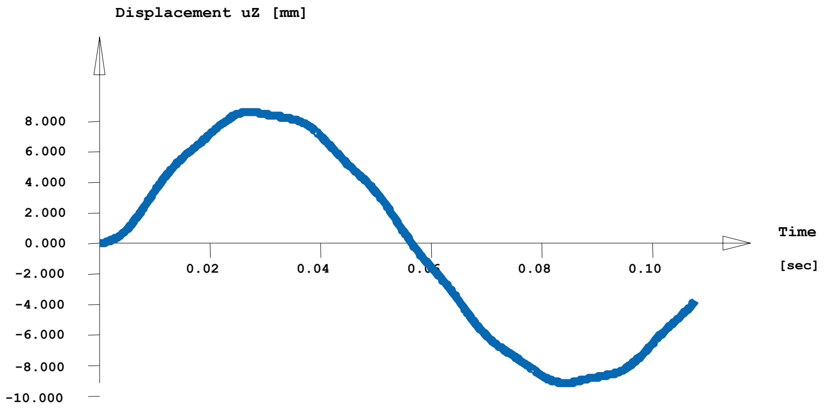


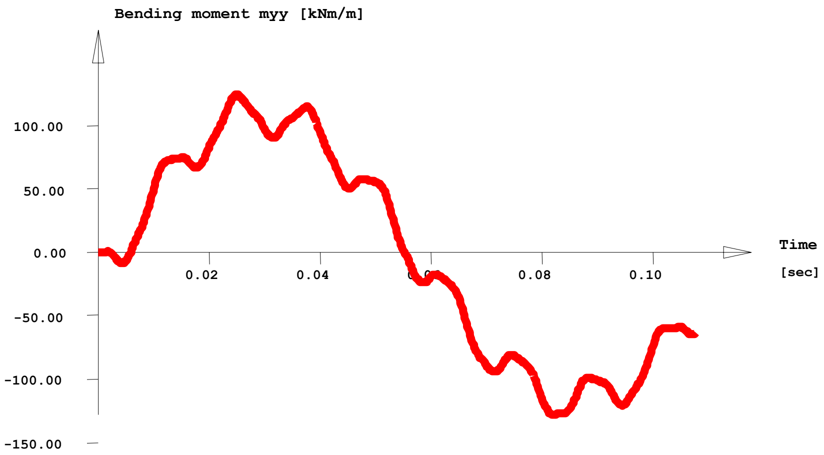
The system of a wall



M_{cr} = 30 kNm
M_u = 57 kNm

Linear Response



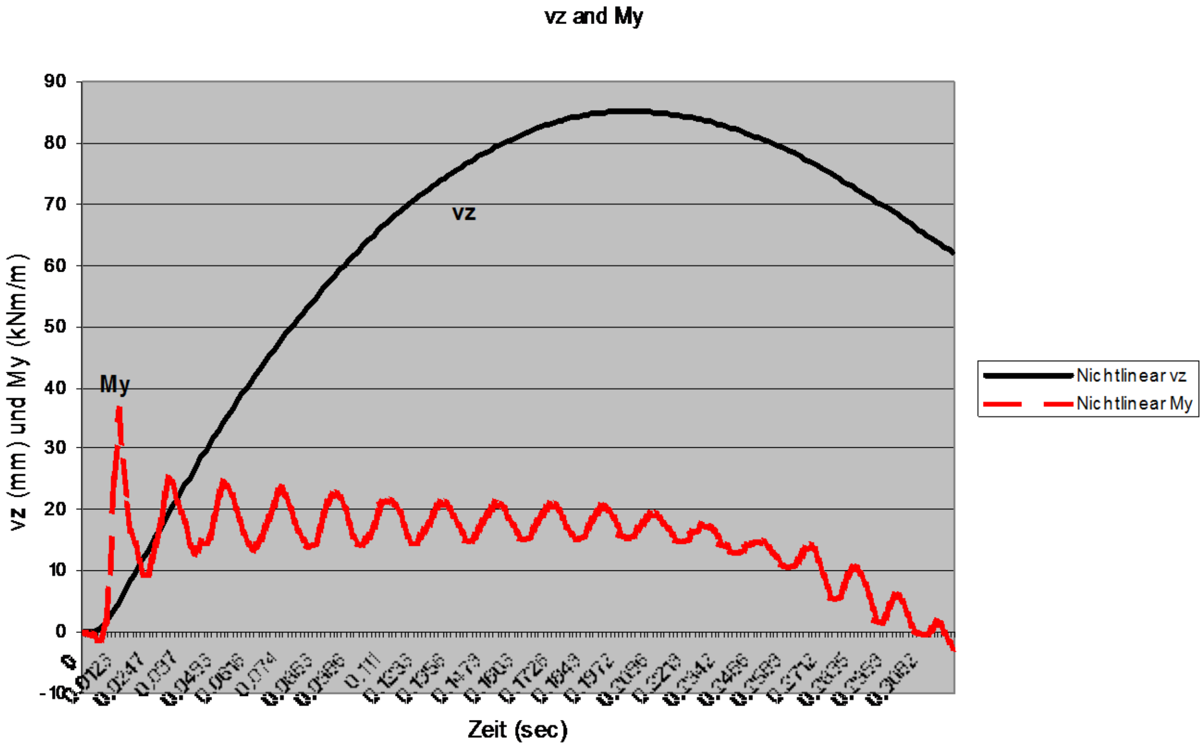


Influence of the load function

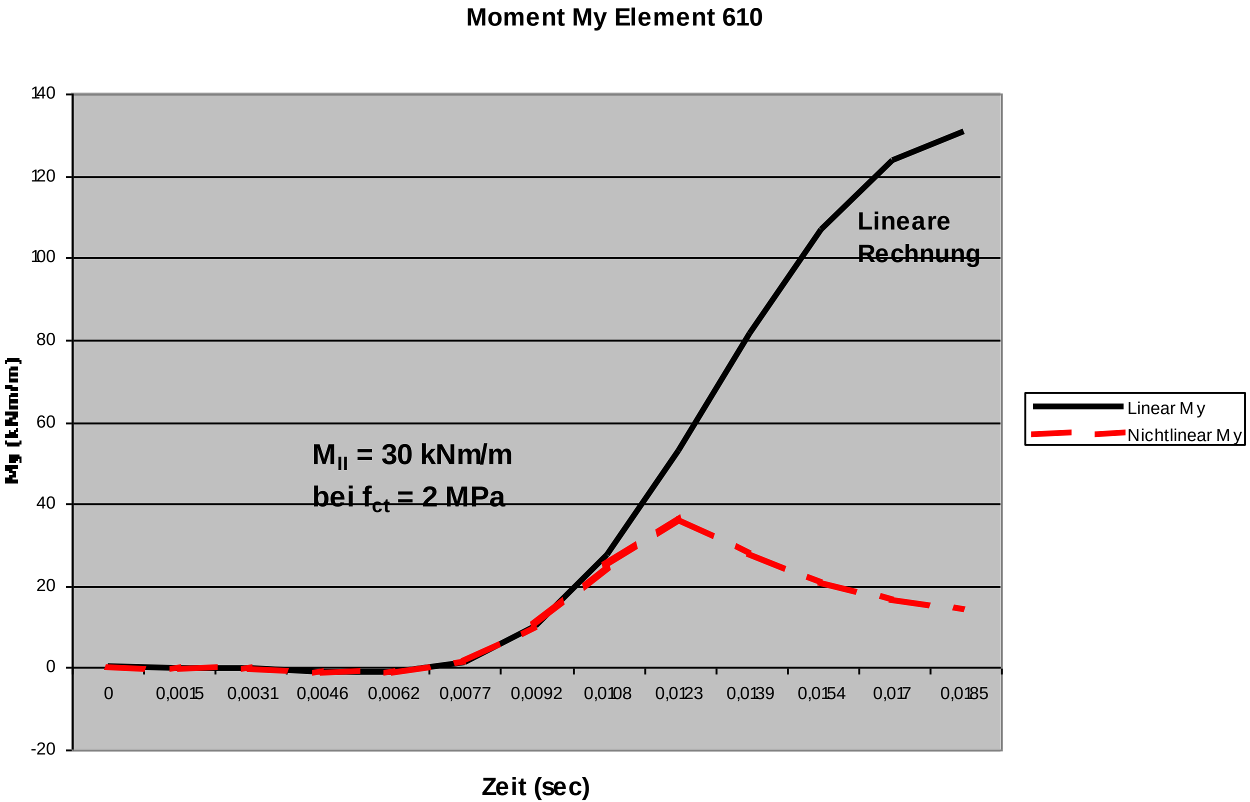
	$\alpha = 0$	$\alpha = 1.0$	$\alpha = 1.5$	$\alpha = 2.0$
Deflection [mm]	14.69	13.87	9.17	7.84
Moment [kNm]	201.1	189.8	128.2	113.1

M_{cr} = 30 kNm
M_u = 57 kNm

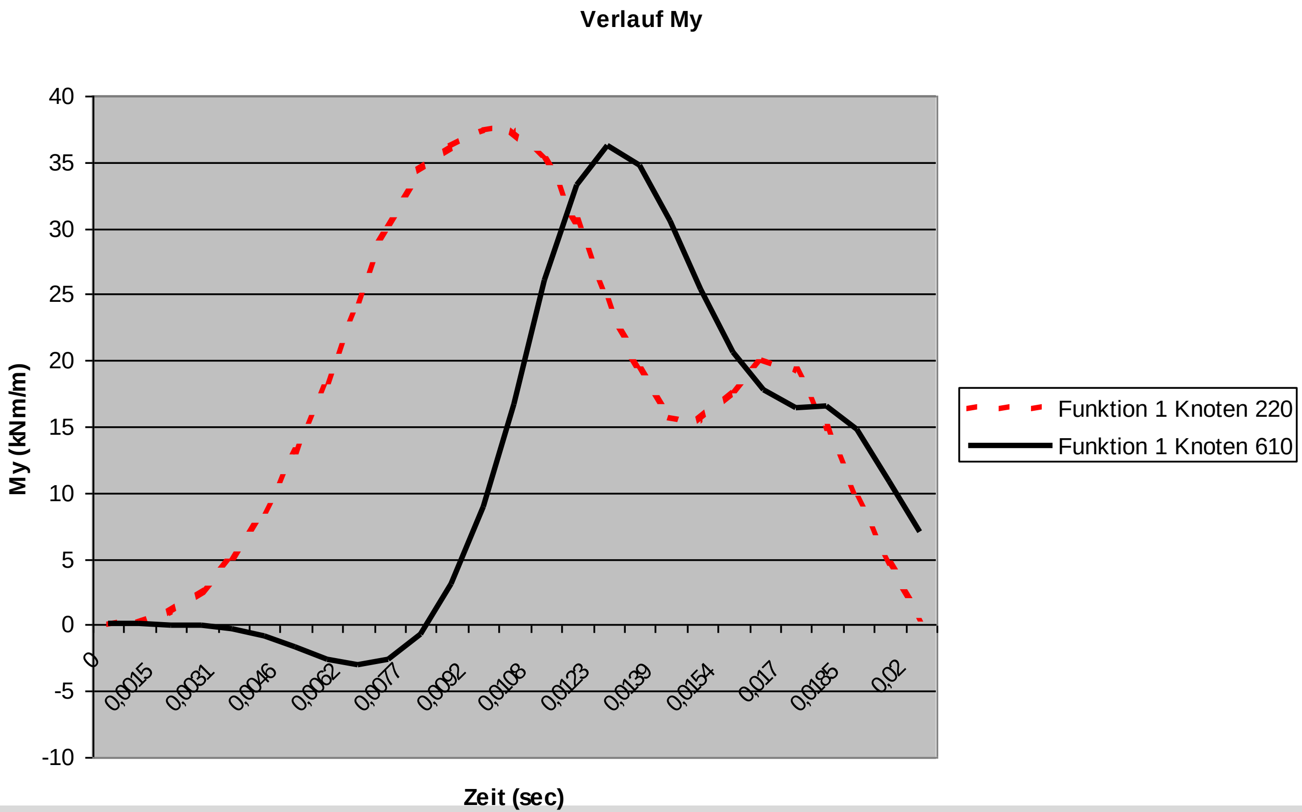
Non linear Analysis



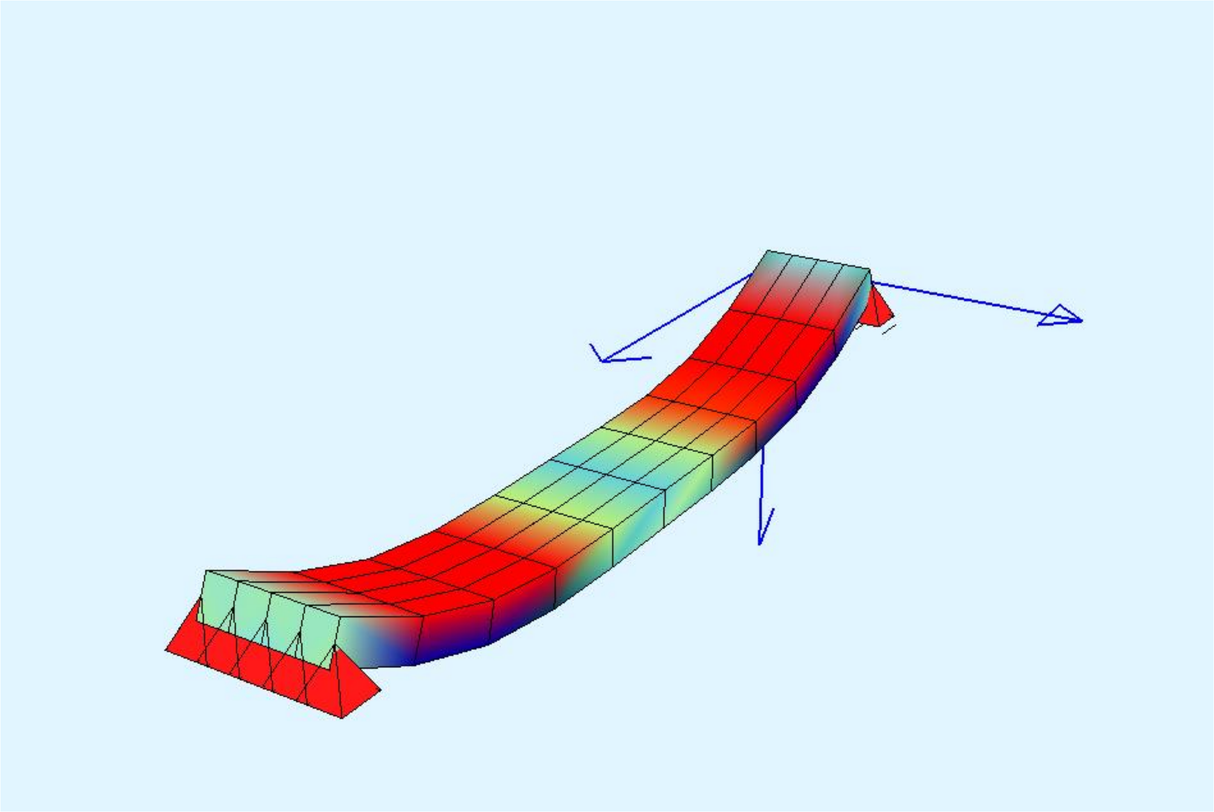
Start up phase



Transient Moments



Deformation t = 0.0077 sec



Deformation t = 0.0139 sec