Structural behaviour of structures in fire

COST Integrated Fire Engineering and Response

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Structural behaviour of structures in fire

Tomaž Hozjan

Faculty of civil and geodetic engineering

University of Ljubljana, Slovenia

Lesław Kwaśniewski

Warsaw University of Technology, Poland

PLAN FOR PRESENTATION

- objectives and applications of structural fire analysis
- requirements of structural fire analysis
- types of FE analysis and solution methods
- types of structural analysis
- challenges
- further developments
- possible test scenarios
- temperature dependent mechanical properties
- thermal properties
- fire loading
- thermal conditions
- fire resistance
- mesh density study
- units
- a few words about ls-dyna
- example 1, 2, and 3
- verification and validation of computer simulations

OBJECTIVES AND APPLICATIONS OF STRUCTURAL FIRE ANALYSIS

- to predict the effects of fires in buildings
- fire resistance and the structure's performance under heating and cooling
- can be applied in the design of fire protection systems
- for evaluation of fire safety (safe evacuation and safe firemen work)
- addendum of experiments (large specimens, loading and boundary condition, interpretation of results)
- virtual testing
- parametric studies

FIRE PARTS WITHIN EC (part 1-2): structural fire design

- EC 1 : ACTIONS on STRUCTURES
- EC 2 : CONCRETE STRUCTURES
- EC 3 : STEEL STRUCTURES
- EC 4 : COMPOSITE STRUCTURES
- EC 5 : TIMBER STRUCTURES
- EC 6 : MASONRY STRUCTURES
- EC 9 : ALUMINIUM ALLOYS STRUCTURES

REQUIREMENTS OF STRUCTURAL FIRE ANALYSIS

- type of analysis
- solution methods
- thermal conditions
- geometry representation
- temperature dependent material properties
- mechanical boundary conditions and loading

TYPES OF FE ANALYSIS AND SOLUTION METHODS

- global vs. component analysis
- structural, thermal or coupled structural-thermal
- dominantly Finite Element (FE) Method
- explicit or implicit methods for time integration
- general purpose commercial programs and research oriented specialized unique programs

DIFFERENT DESIGN APPROACHES

- Load bearing resistance of a structure during fire can be analysed on the levels of member, part of structure and entire structure.
- Member analysis can be performed using experiments, simple and advanced calculation models.
- Advanced calculation model (ACM) is a Finite Element (FE) model able to solve numerically, with reliable approximation, the partial differential equations describing member's response for assumed fire conditions.

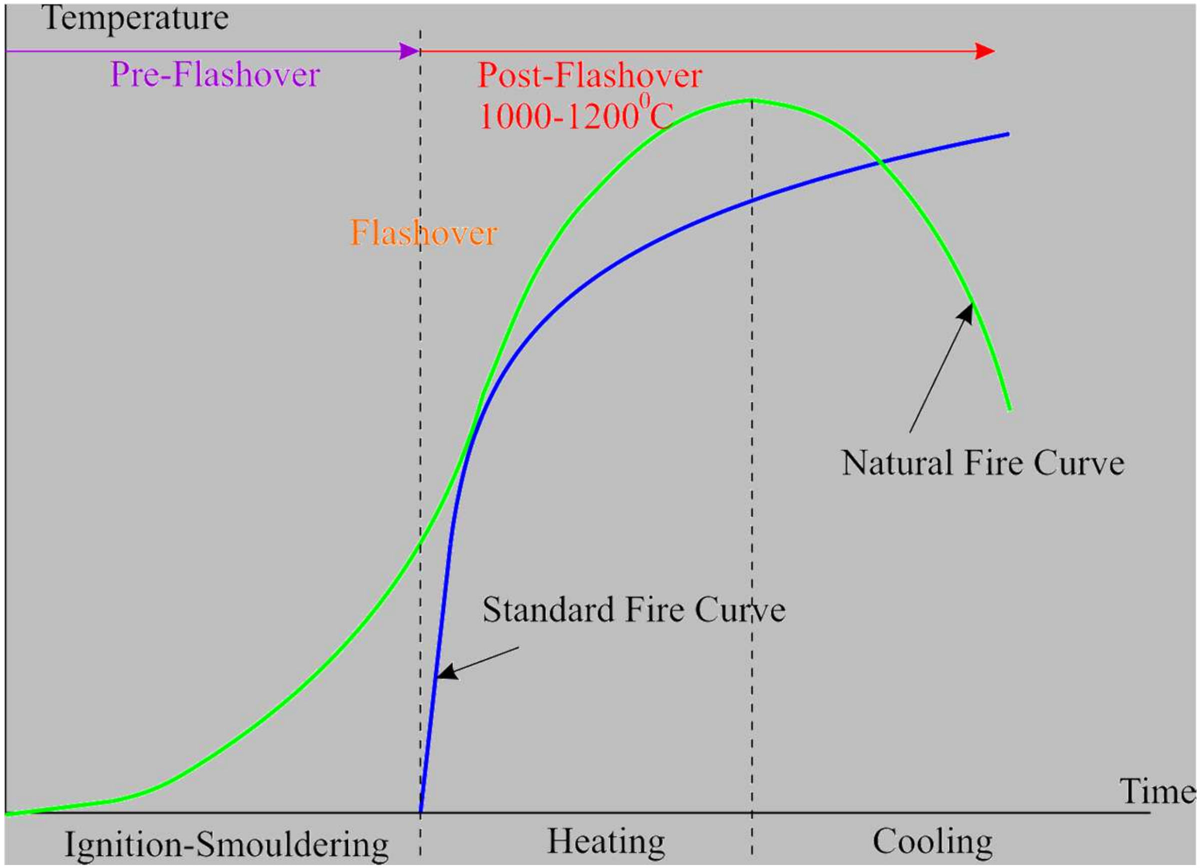
DIFFERENT DESIGN METHODS

Prescriptive approach

- Thermal action defined by standard fire curve

Performance based approach

- Physically based Thermal Actions (natural fire curves)



DIFFERENT DESIGN METHODS

Prescriptive approach

- Thermal action defined by standard fire

Type of analysis	**Tabulated data (critical temperature)**	**Simple calculation methods**	**Advanced calculation methods**
Member analysis	YES	YES	YES
Analysis of parts of the structure	X	YES, if avaliable	YES
Global structural analysis	X	X	YES

DIFFERENT DESIGN METHODS

Performance based approach

- Thermal action defined by natural fire

Type of analysis	**Tabulated data (critical temperature)**	**Simple calculation methods**	**Advanced calculation methods**
Member analysis	**X**	YES, if avaliable	YES
Analysis of parts of the structure	X	**X**	YES
Global structural analysis	X	X	YES

CHALLENGES

- time and space variation of temperatures
- temperature dependent axial and rotational restraints
- material degradation due to heating
- interactions with adjacent structural components
- additional forces imposed due to thermal deformations
- large scale models with local effects (connections)
- nonlinearities (geometrical, material, BC, loading, interactions)
- uncertainties and measurements (BC, temperature distributions)
- repeatability (sensitivity on parameter variation)
- multiphysics (thermo-hydro-mechanical interactions in concrete)

FURTHER DEVELOPMENTS

- most of the current research work on structures subjected to elevated temperatures is dedicated to steel and concrete structures
- the experimental and numerical studies show importance and complexity of beam to column connections in structural analysis
- thermo-hygro-mechanical phenomena in concrete structures resulting in additional nonlinear effects:

1. transient creep strain,
2. load induced thermal strain,
3. shrinkage,
4. pore pressures
5. (explosive) spalling?.

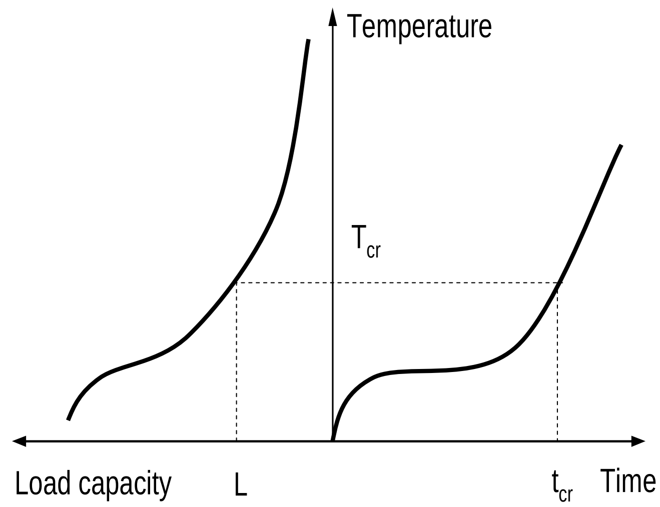
- prediction of behaviour of concrete structures and structural elements imposes the main challenge for future research
- future work in connections modeling
- FEA model verification and validation
- need for experimental benchmark problems which could be used for the FE model validation

POSSIBLE TEST SCENARIOS

- 1st scenario: increasing static loading in constant elevated temperature - critical loading for selected temperatures.
- 2nd scenario: the structure is analyzed under constant loading but at increasing temperature - critical temperature and time.
- 3rd scenario:, e.g. following experiment, both temperature and loading are time depended. Loading due to constrained thermal elongation

FURNACE TESTS

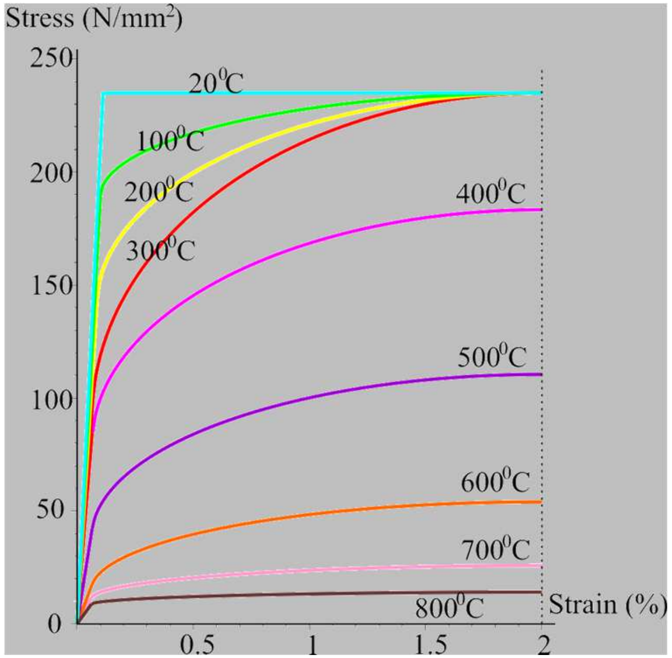
- Limitation of geometry and dimensions.
- Artificial or undetermined boundary conditions
- Effects of continuity ignored.
- Thermal expansion not restrained by by surrounding structure

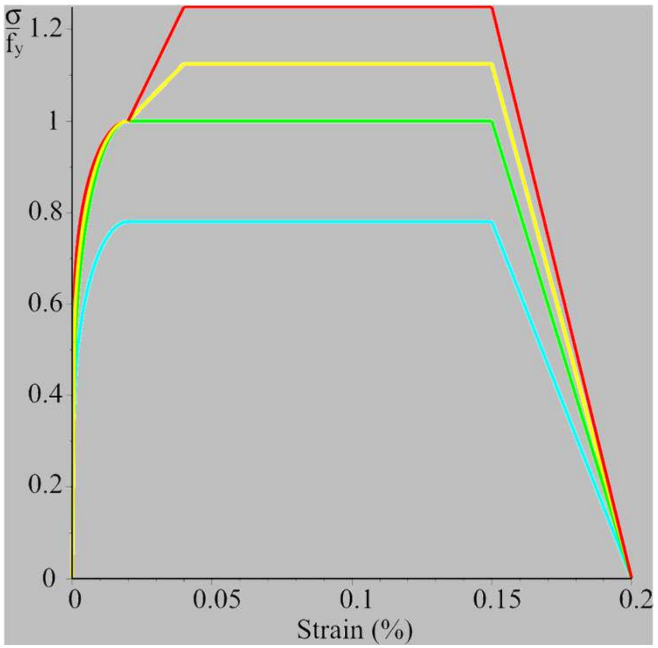


TEMPERATURE DEPENDENT MECHANICAL PROPERTIES

STRUCTURAL STEEL (EC3)

- Steel softens progressively from 100-200°C up.
- Only 23% of ambient-temperature strength remains at 700°C.
- At 800°C strength reduced to 11% and at 900°C to 6%.
- Melts at about 1500°C.
- Elastic modulus at 600°C reduced by about 70%.
- Yield strength at 600°C reduced by over 50%.

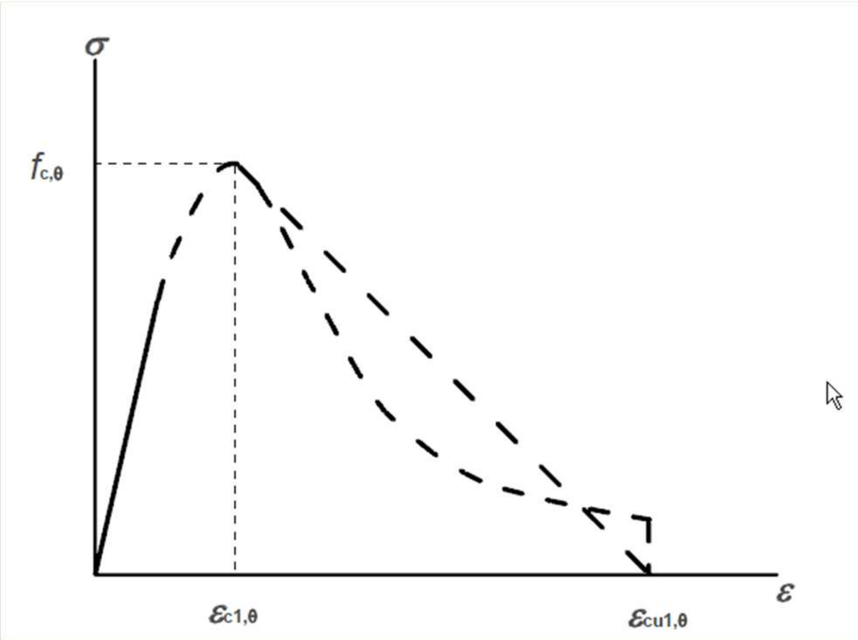


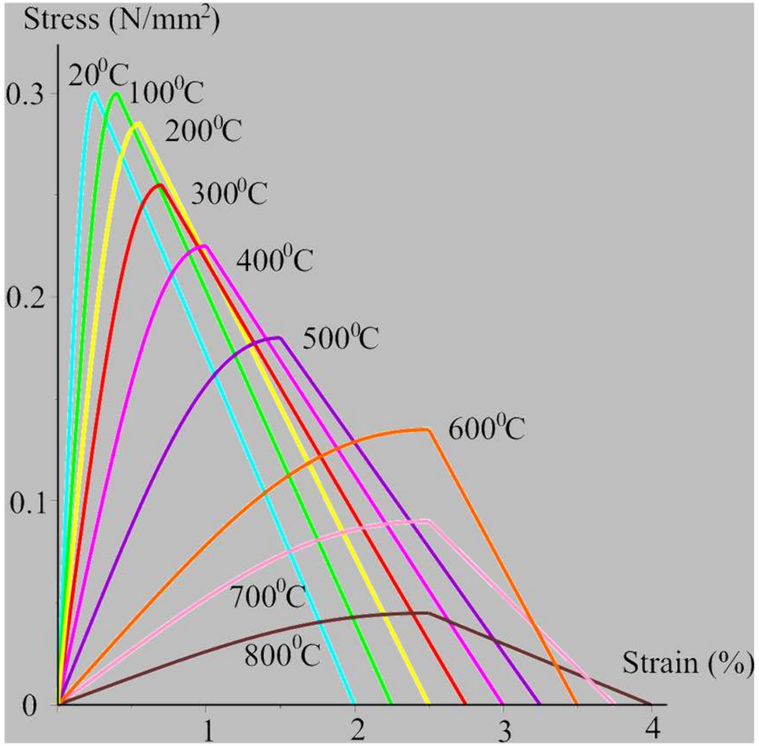


TEMPERATURE DEPENDENT MECHANICAL PROPERTIES

CONCRETE (EC2)

- Concrete loses strength and stiffness from 100°C upwards.
- Does not regain strength on cooling.
- High temperature properties depend mainly on aggregate type used.





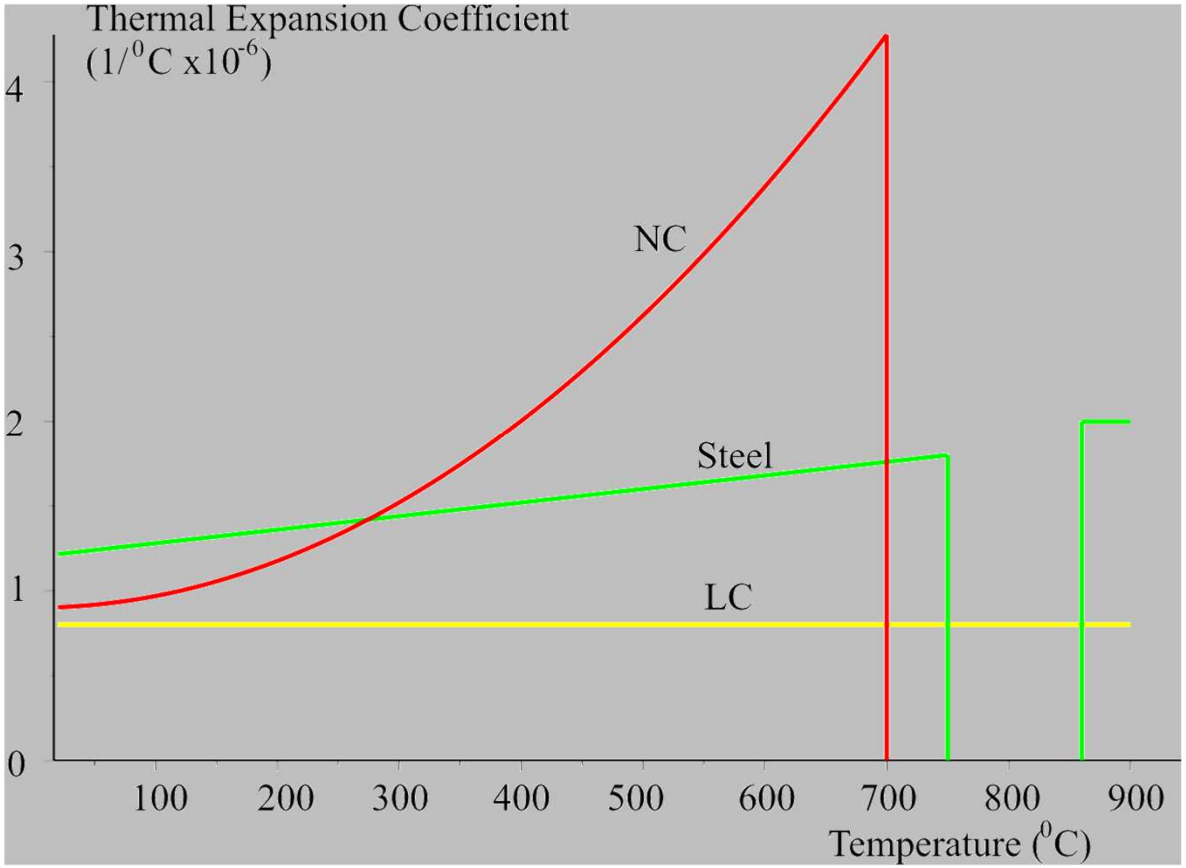
THERMAL PROPERTIES

- thermal expansion
- thermal conductivity
- specific heat

THERMAL PROPERTIES

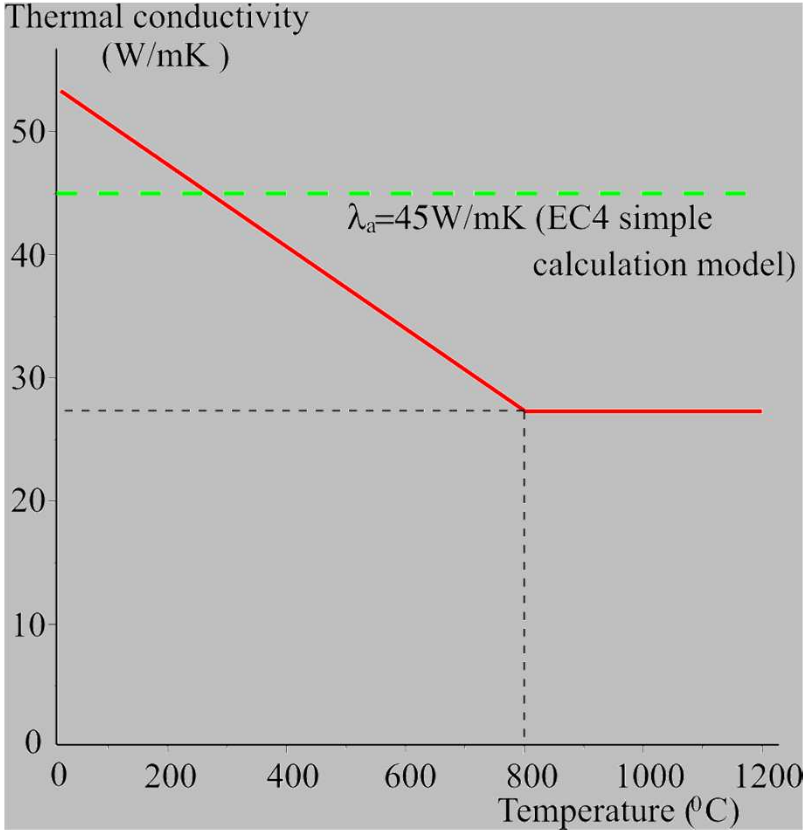
THERMAL EXPANSION

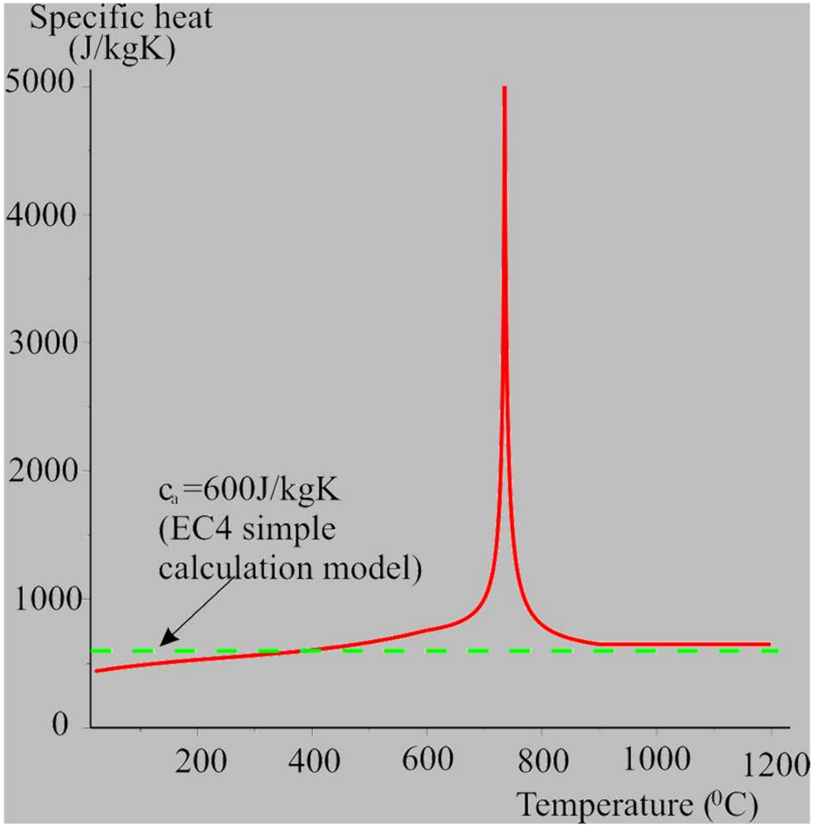
- Thermal expansion for steel reduces to zero due to cristal change at 700-800° C
- Concrete seldom reaches 700 ° C in building fires
- Uniform thermal expansion is assumed for light-weight concrete



THERMAL PROPERTIES

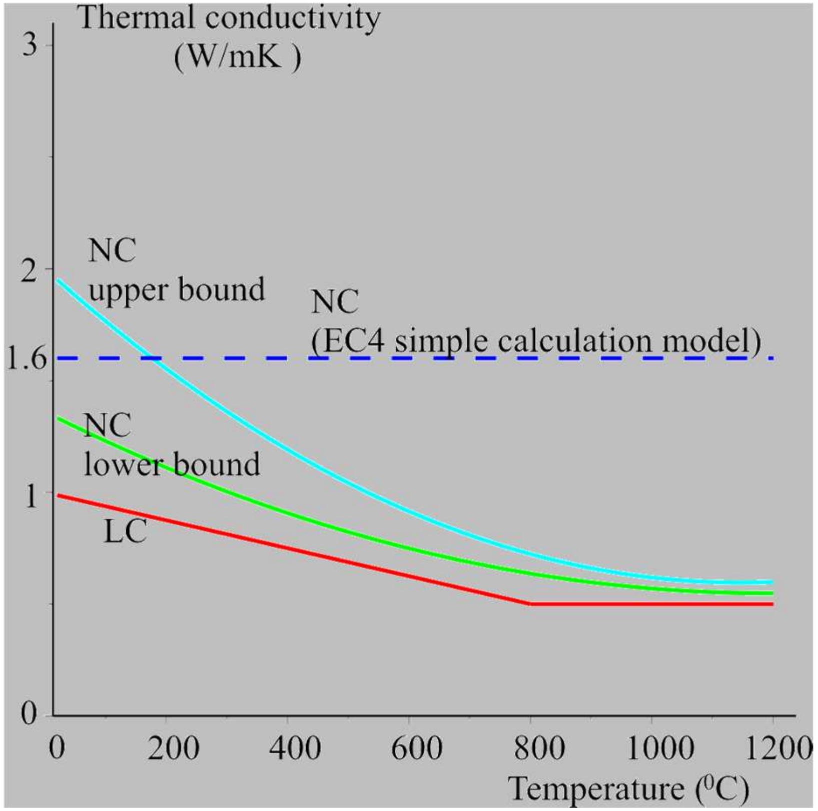
THERMAL CONDUCTIVITY AND SPECIFIC HEAT OF STEEL

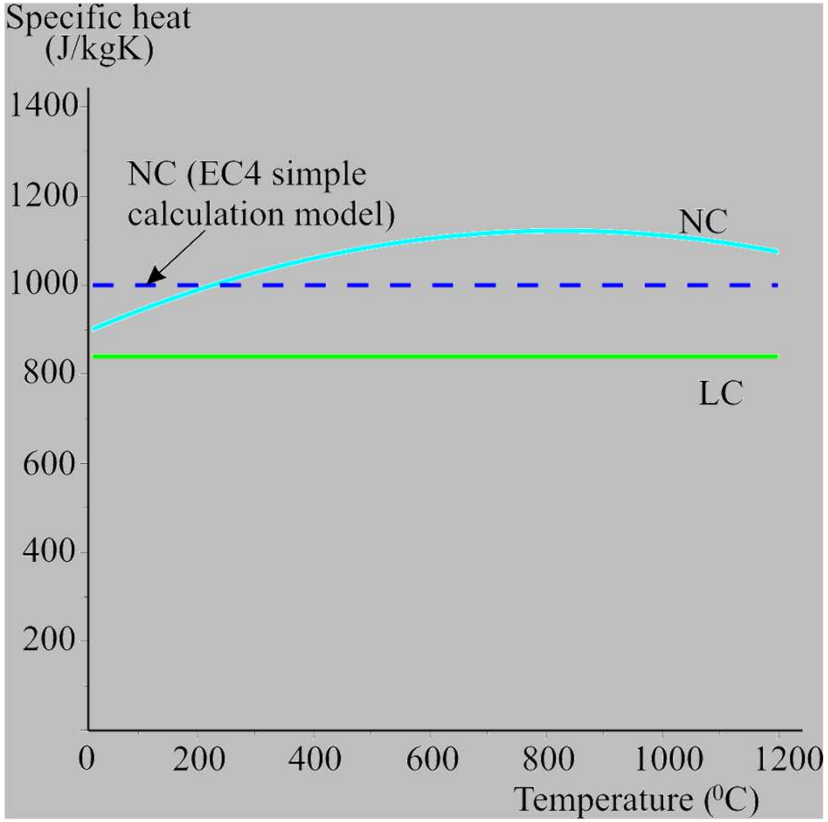




THERMAL PROPERTIES

THERMAL CONDUCTIVITY AND SPECIFIC HEAT OF CONCRETE



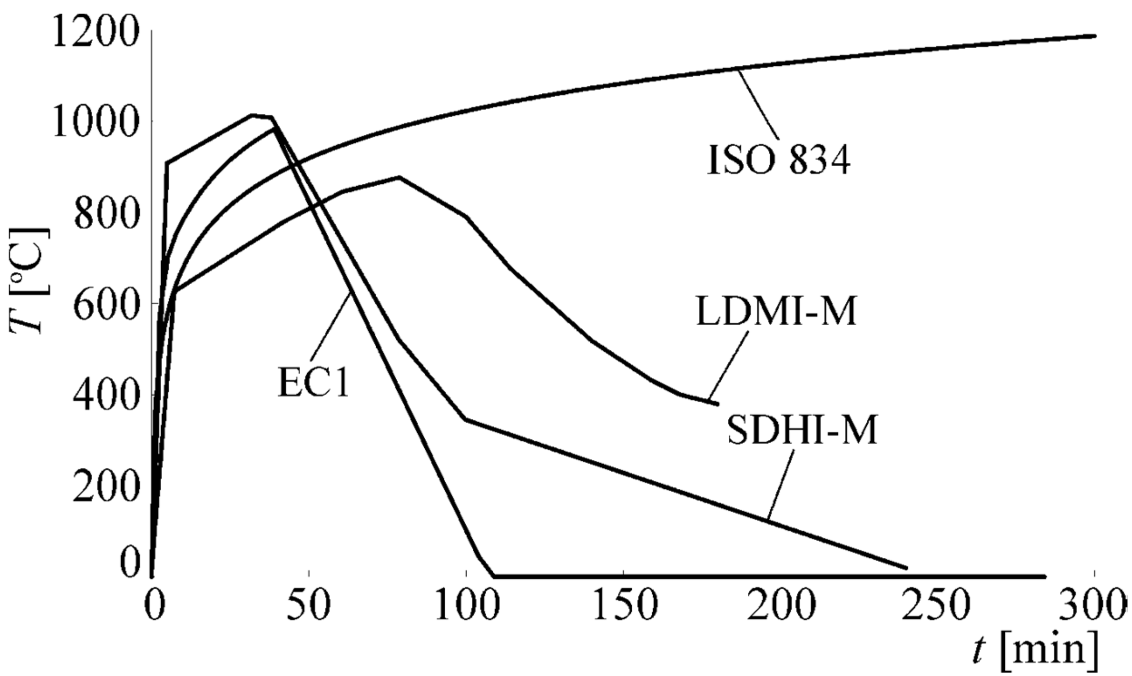


Structural behaviour of structures in fire

FIRE LOADING

STANDARD FIRE TEST CURVE (ISO834)

PARAMETRIC FIRE CURVES



THERMAL CONDITIONS

- Direct thermal loading (prescribed temperature fields)
- Constant or time dependent prescribed temperatures
- Full insulation
- Prescribed flux
- Heat transfer between a member and surroundings:
- convection:

$$\dot{h}_{net,c} = \alpha_c \left[T_S(t) - T_M(t) \right] \quad [°C] \text{ or } [°K]$$

- radiation:

$$\dot{h}_{net,r} = \varepsilon_m \sigma_{SB} \left[T_S^4(t) - T_M^4(t) \right] \quad [°K]$$

$$\dot{h}_{net,r} = \varepsilon_m \sigma_{SB} \left[(T_S(t) + 273)^4 - (T_M(t) + 273)^4 \right] \quad [°C]$$

$\sigma = 56.7 \times 10^{-12}$ [kW /m² K⁴] - Stefan–Boltzmann constant

$\varepsilon_m = 0.8$ – emissivity of the member (emissivity of the fire=1)

FIRE RESISTANCE

ACCORDING TO EUROCODES FIRE RESISTANCE CAN BE ESTABLISHED IN 3 DOMAINS:

- Time $t_{fi,d} > t_{fi,req}$ - usually requires advanced calculation models
- Load resistance $R_{fi,d,t} > E_{fi,d,t}$ - hand calculation methods used to find reduced resistance at design temperature
- Temperature: $\theta_{cr,d} > \theta_d$ - the most common simple method used to find critical temperature for loading and compare with design temperature

MESH DENSITY STUDY
(based on Richardson extrapolation)

- Discretization error

$$E = f_h - f_{exact} = Ch^p + H.O.T.$$

....

- Order of convergence

$$p = \frac{ln\left(\frac{f_3 - f_2}{f_2 - f_1}\right)}{l\,n(r)}$$

- Estimate of the asymptotic solution

$$f_{h=0} \cong f_1 + \frac{f_1 - f_2}{r^2 - 1}$$

- E_1 - the estimator of the relative error

$$E_1 = \frac{\varepsilon}{r^p - 1}, \qquad \varepsilon = \frac{f_1 - f_2}{f_1}$$

NASA NPARC Alliance Verification and Validation, Examining Spatial (Grid) Convergence, http://www.grc.nasa.gov/WWW/wind/valid/tutorial/spatconv.html).

UNITS

			UNIT SYSTEM			
			mm, s, t		m, s, kg	
	Property	Example property	Quantity	Unit	Quantity	Unit
	Length			[mm]		[m]
	Time			[s]	[s]	
	Mass			[tonne]		[kg]
MECHANICAL	Force	1kN	1000	[N]	1000	[N]
	Stress	Elastic modulus of steel	2.10E+05	[MPa]	2.10E+11	[Pa]
	Density	Density of steel	7.85E-09	[t/mm^3]	7.85E+03	[kg/m^3]
	Velocity	80km/h	22.22 E3	[mm/s]	22.22	[m/s]
	Acceleration	gravity	9.81E+03	[mm/s^2]	9.81	[m/s^2]
	Energy	1 kJ	1.00E-06	[mJ]	1000	[J]
	Power	1 kW	1.00E+06	[mW]	1000	[W]
THERMAL	Specific Heat	SH of steel at T=0°C	4.25E-04	[mJ/tK]	425	[J/kgK]
	Thermal conductivity	TC of steel at T=0°C	5.40E+01	[mW/mmK]	54	[W/mK]
	Stefan–Boltzmann constant		5.67E+01	[mW/mm^2K^4]	5.67E-08	[W/m^2K^4]
	Convection factor	CF of concrete	2.50E-02	[mW/mm^2]	25	[W/m^2]

NOTE ON NUMERICAL MODELS!!!

GARBAGE OUT

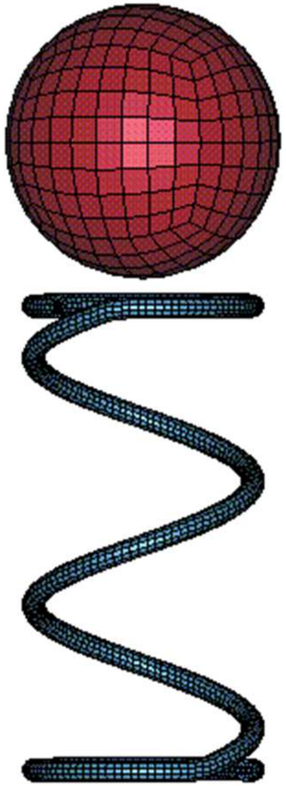
Garbage input

PERFECT Model

Perfect input

GARBAGE Model

A FEW WORDS ABOUT LS-DYNA®



- History
- LS-DYNA vs. ABAQUS
- Implicit vs. Explicit
- LSPREPOST
- LSOPT
- Examples
- Verification and validation

Marta Sitek, Lesław Kwaśniewski

Warsaw University of Technology, Poland

A FEW WORDS ABOUT LS-DYNA®
History

- LS-DYNA originated from the 3D FEA program DYNA3D, developed by Dr. John O. Hallquist at Lawrence Livermore National Laboratory (LLNL) in 1976.
- DYNA3D was created in order to simulate the impact of the Full Fusing Option (FUFO) or "Dial-a-yield" nuclear bomb for low altitude release (impact velocity of ~ 40 m/s). At the time, no 3D software was available for simulating impact, and 2D software was inadequate.
- DYNA3D used explicit time integration to study nonlinear dynamic problems.
- In 1978 the DYNA3D source code was released into the public domain without restrictions after a request from France.
- At the end of 1988 Livermore Software Technology Corporation (LSTC) was founded to continue the development of DYNA3D in a much more focused manner, resulting in LS-DYNA3D (later shortened to LS-DYNA). Since then, LSTC has greatly expanded the capabilities of LS-DYNA in an attempt to create a universal tool for most simulation needs.

A FEW WORDS ABOUT LS-DYNA®
LS-DYNA vs. ABAQUS

LS-DYNA

- Very efficient explicit part
- Implicit part not as stable as in ABAQUS
- Solver updated several times a year
- Cheap for academic use ($1000 a year (commercial very expensive)
- MPP version well optimized for multi processor calculations
- Theory manual not as good as ABAQUS manuals
- Used by 90% of automotive industry
- Graphical LSPREPOST updated every few weeks, supports all cards but many times is unstable
- Efficient contact algorithms

ABAQUS

- Efficient Implicit part (e.g. Riks analysis)
- Very good manuals
- Expensive even for academic use
- Limited usage (tokens)
- More popular at universities than LS-DYNA
- Graphical interface ABAQUS/CAE does not support all cards
- ABAQUS/CAE – mesh development is complex and limited
- Text input files *.inp have complex „encrypted" structure

A FEW WORDS ABOUT LS-DYNA®
Implicit vs. Explicit

IMPLICIT

$M\ddot{u}^{n+1} + D\dot{u}^{n+1} + K(x^n)\Delta u = P(x^n)^{n+1} - F(x^n)$

- For static and dynamic calculations
- Predictive –adaptive algorithm (increments and iterations)
- Based on Newtonian methods
- Requires inversion of large matrices
- Not feasible for multiprocessor calculations
- Problems with convergence for highly nonlinear problems (contact, failure, complex material models)

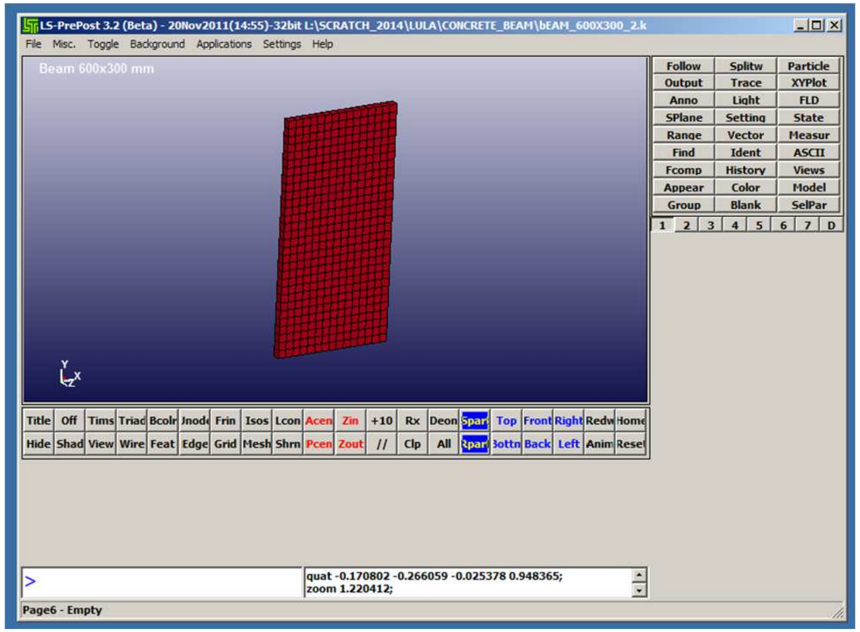
EXPLICIT

$$\ddot{u}^n = M^{-1}\,(P^n - F^n + H^n)$$

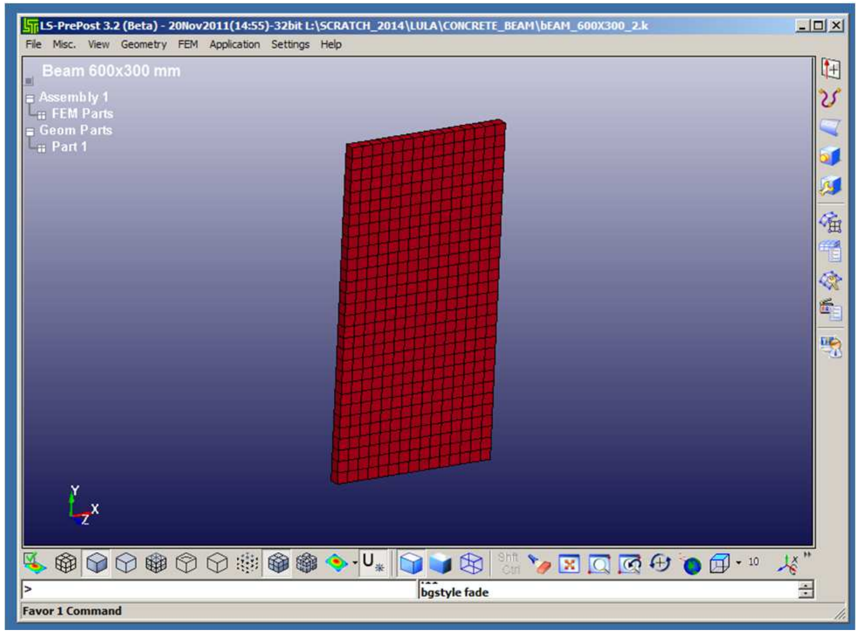
- Only for dynamics
- Based on Central Difference Method
- Requires inversion of only mass matrix
- Mass matrix must be diagonal (only linear finite elements)
- Short time (integration) steps – ruled by Courant criterion (the shorted time needed to cross a FE by stress wave)

  $\Delta t < \frac{l}{c} \quad c \approx \sqrt{\frac{E}{\rho}}$
- Only increments no iterations
- Simple solution algorithm, very feasible for highly nonlinear problems
- Dedicated for parallel processing

A FEW WORDS ABOUT LS-DYNA® LSPREPOST



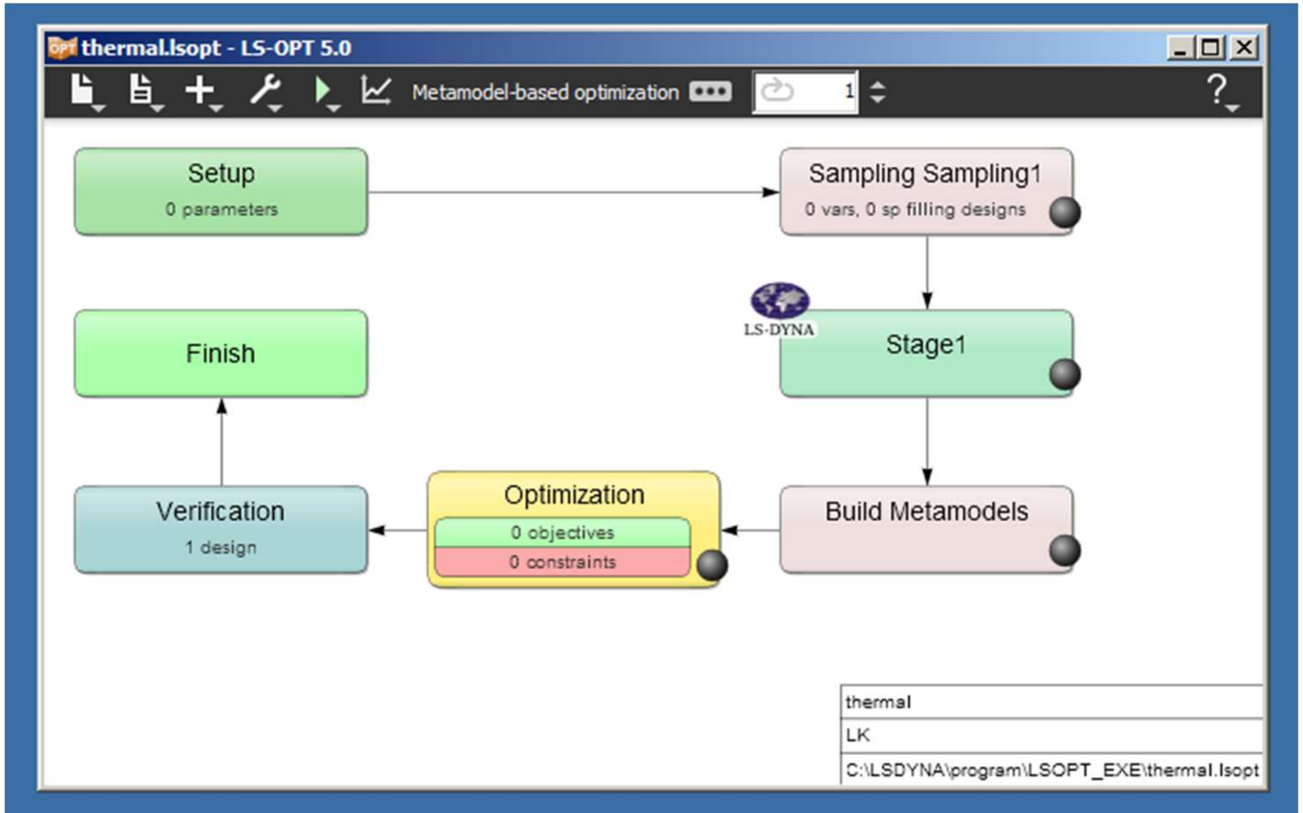
Old „skin" (F11)



New „skin" (F11)

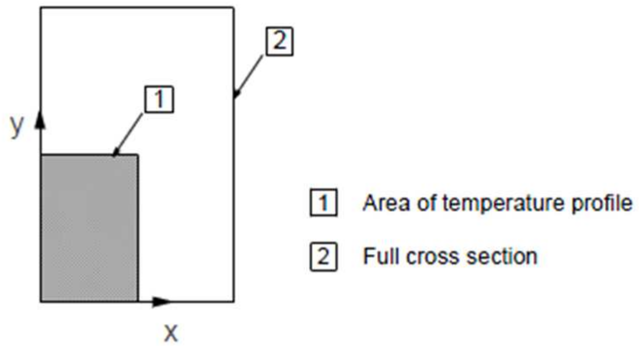
A FEW WORDS ABOUT LS-DYNA® LS-OPT®

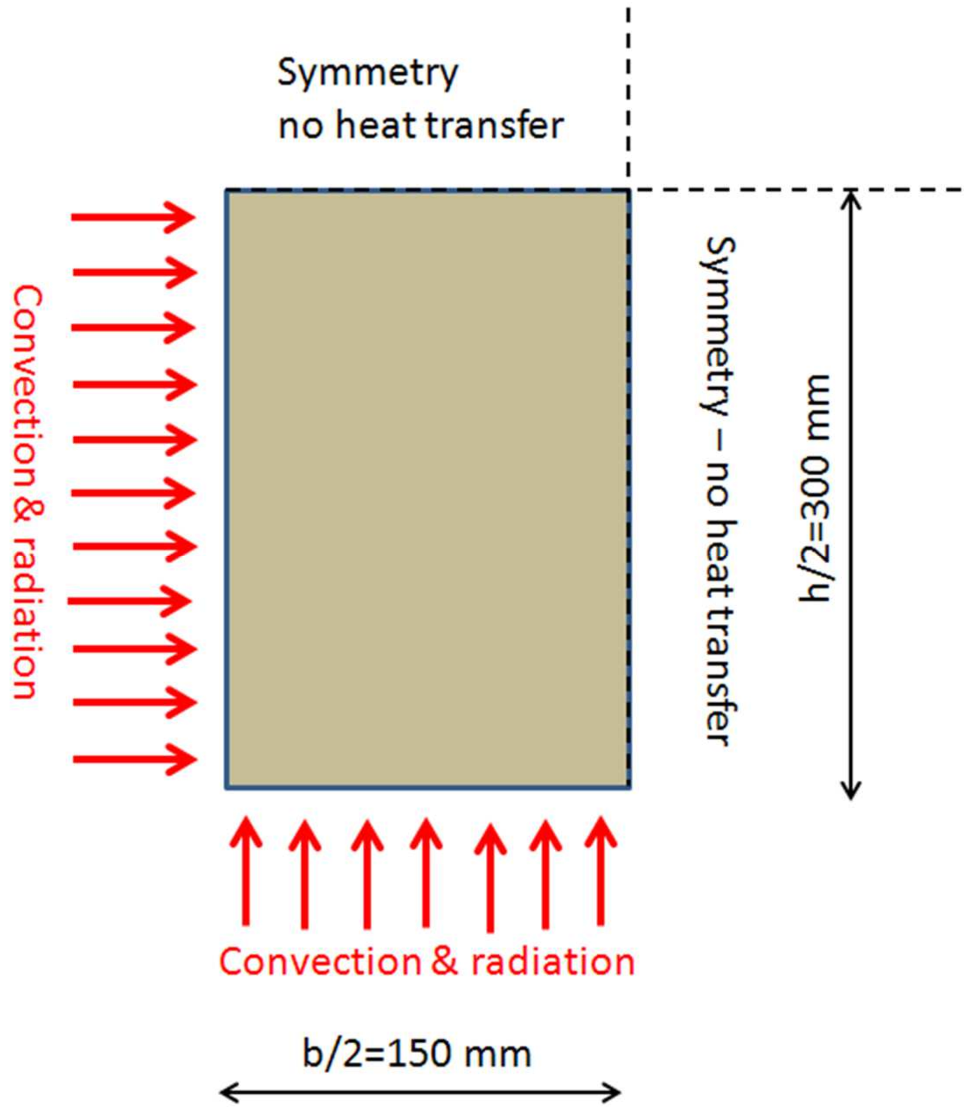
- Graphical optimization software LS-OPT® that interfaces with LS-DYNA
- Allows the user to structure the design process, explore the design space and compute optimal designs according to specified constraints and objectives.
- The program is also highly suited to the solution of system identification problems and stochastic analysis.
- LS-OPT – freeware software, can work with ABAQUS



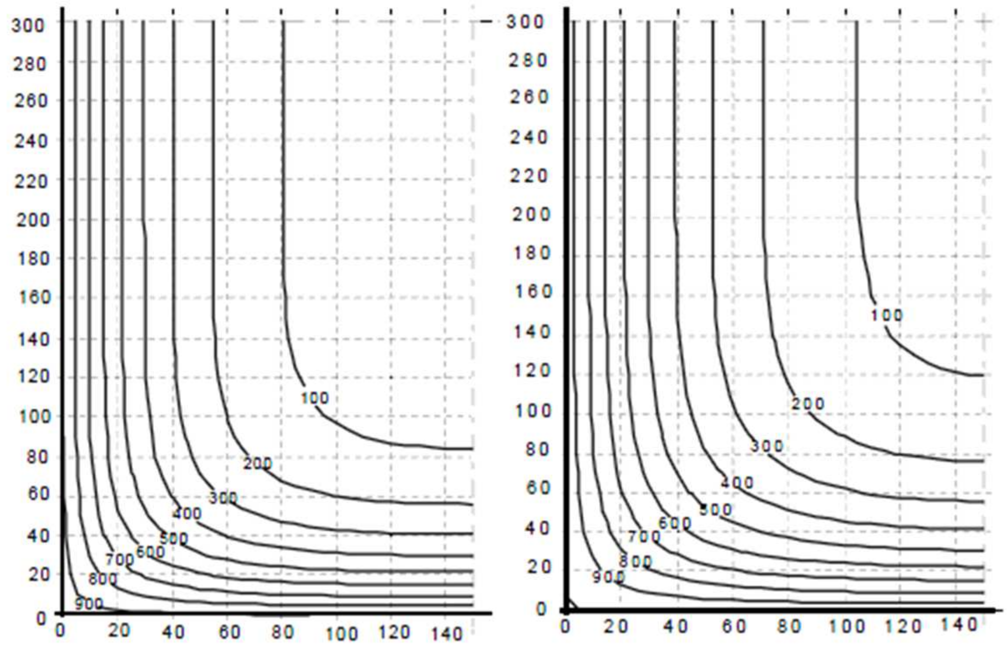
EXAMPLE 1

Transient heat transfer in the concrete beam (EC2 Annex A)



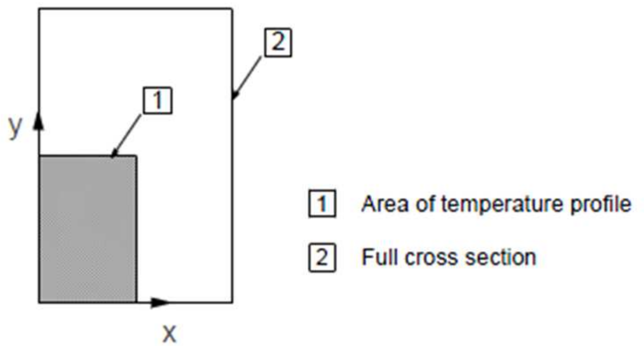


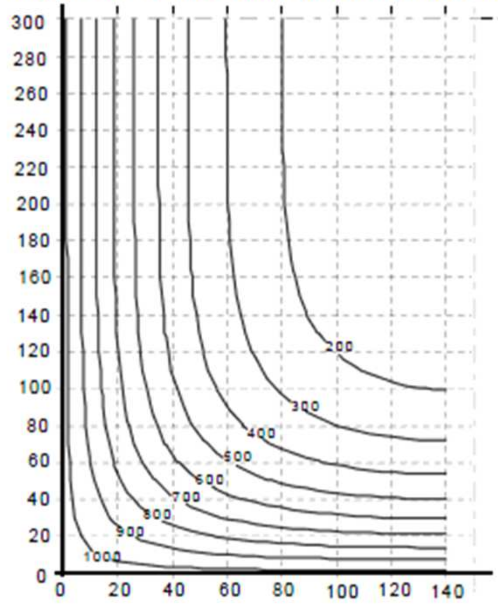
EXAMPLE 1 Transient heat transfer in a concrete beam (EC2 Annex A)



a) R60 b) R90

Figure A.7: Temperature profiles (°C) for a beam *h* x *b* = 600 x 300



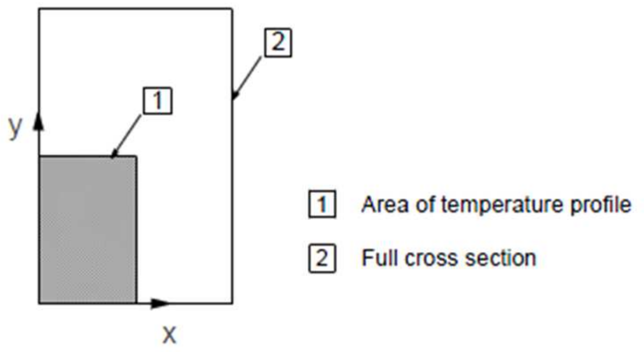


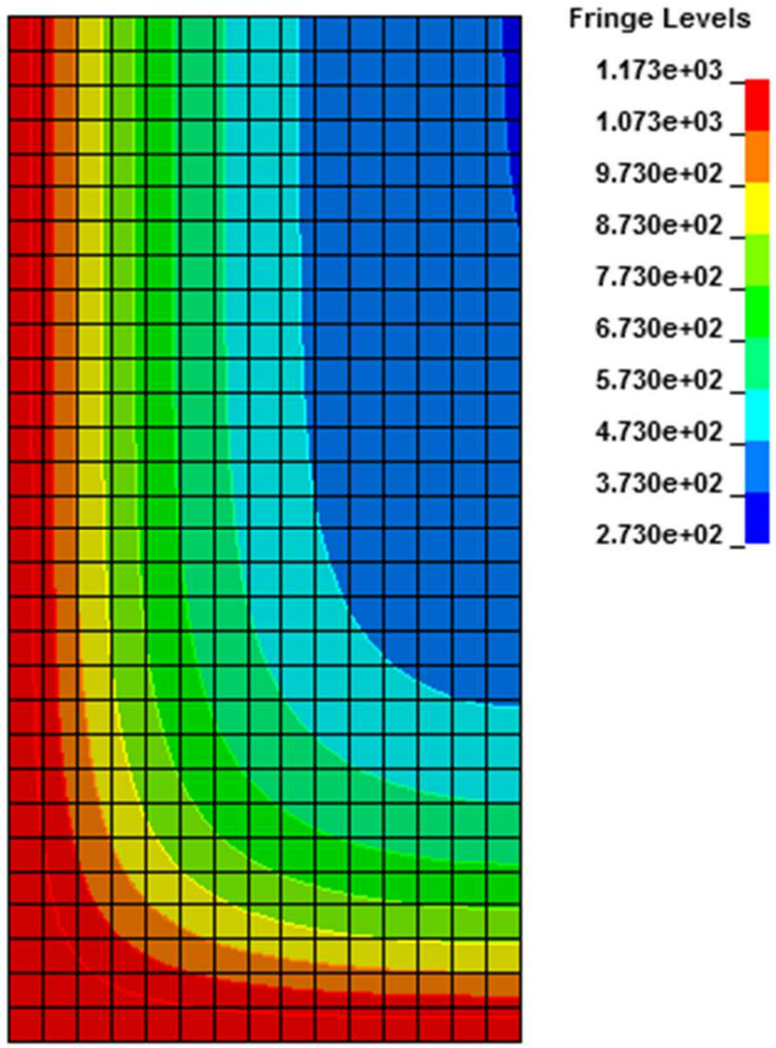
Temperature profiles for a beam hxb=600x300 – R120

According EC2 Annex A (Fig. A.8)

Figure A.8 Temperature profiles (°C) for a beam *h* x *b* = 600 x 300 - R120

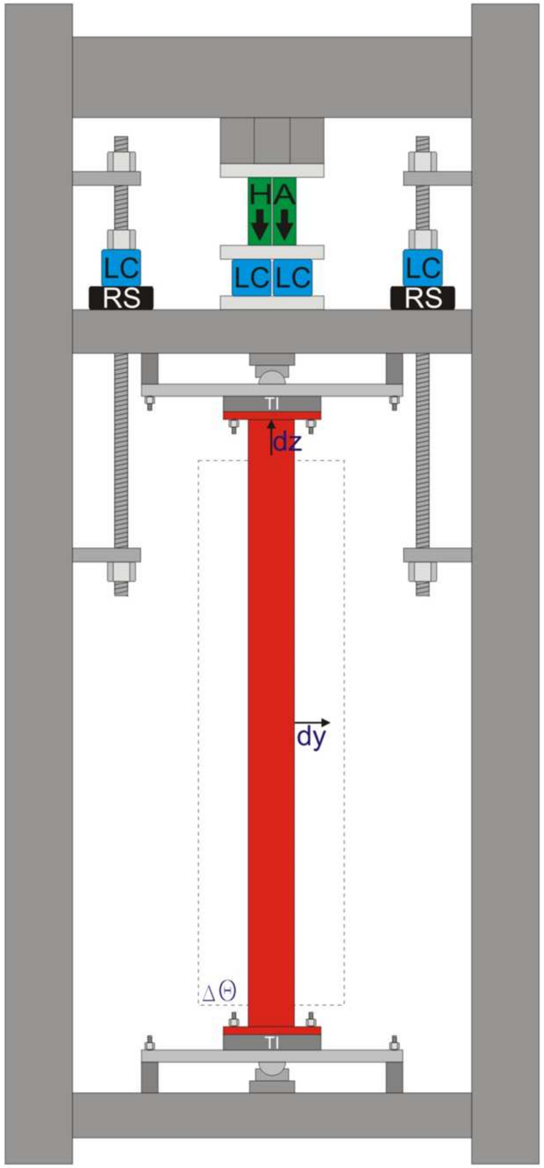
EXAMPLE 1
Transient heat transfer in a concrete beam (EC2 Annex A)



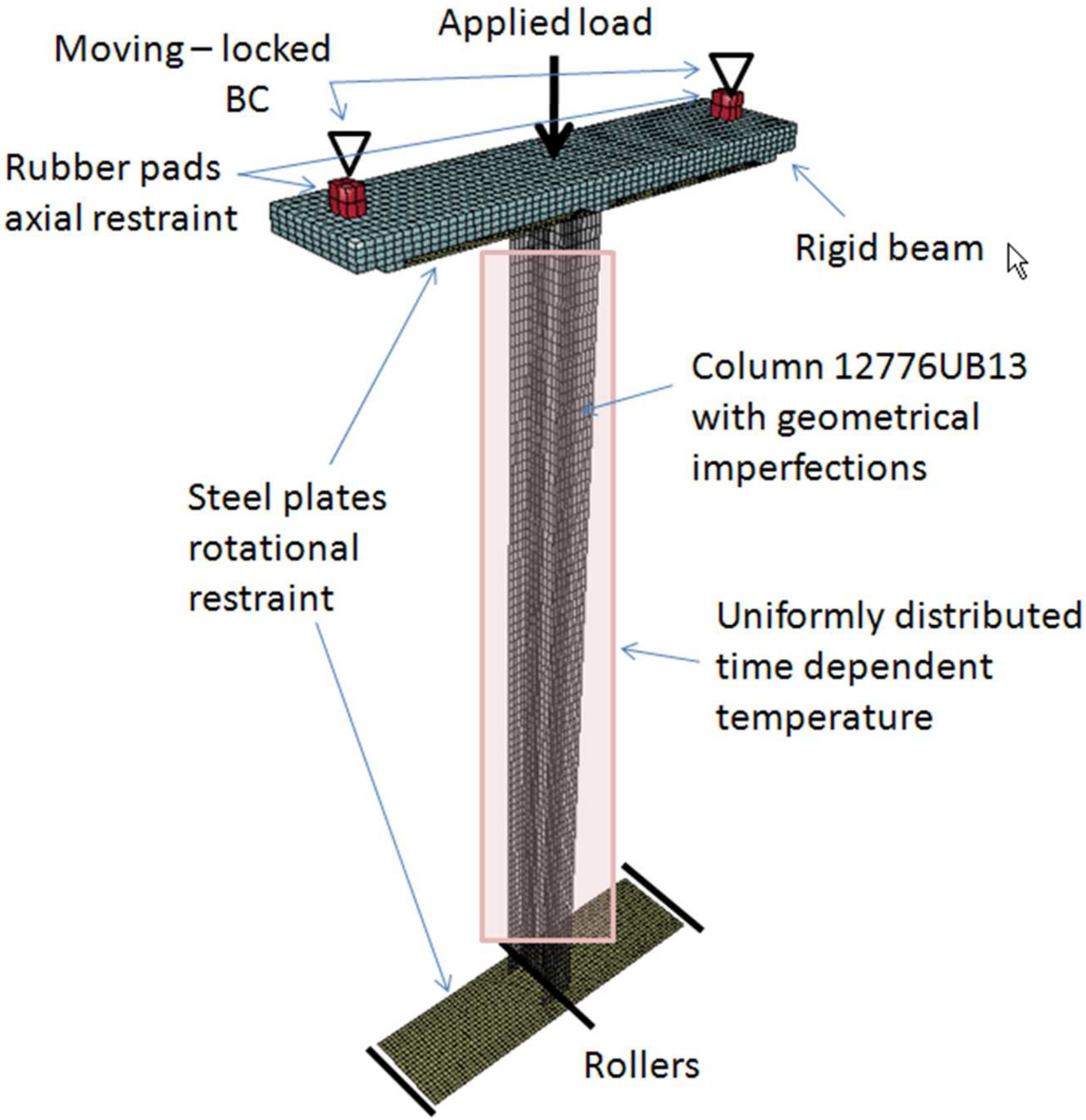


Calculated temperature profile for a beam hxb=600x300 – R120

EXAMPLE 2
Furnace test on a steel column



EXAMPLE 2
Furnace test on a steel column



EXAMPLE 3
Concrete –steel balcony

Balcony 3x3 m

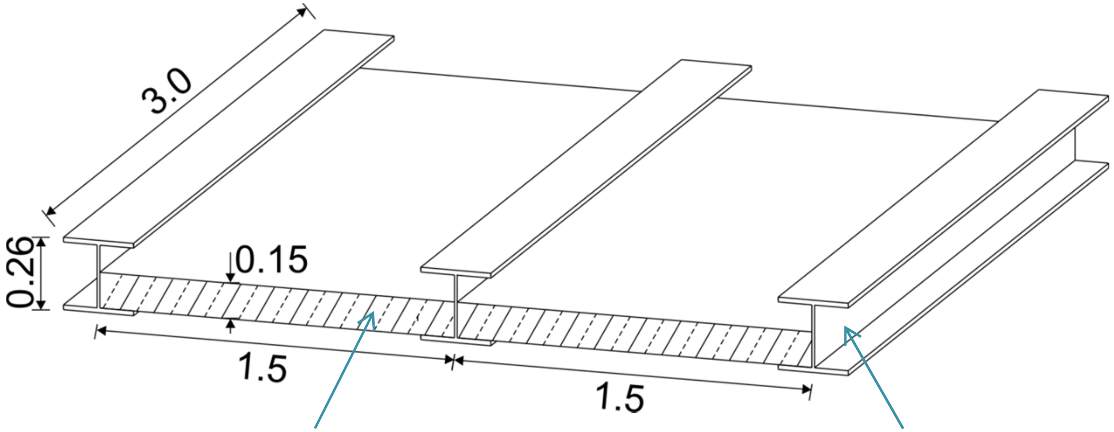
- Reinforced concrete C25/30, t_c= 15cm

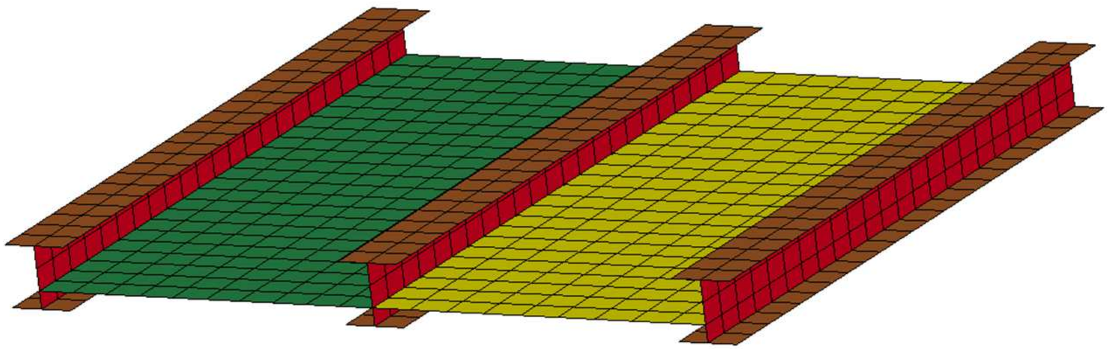
-- beams HEB260, S275

-A two-step analysis:

-- thermal (to obtain temperature curves)

- coupled thermal – structural (temperature boundary condition)





FEM mesh

EXAMPLE 3
Concrete –steel balcony

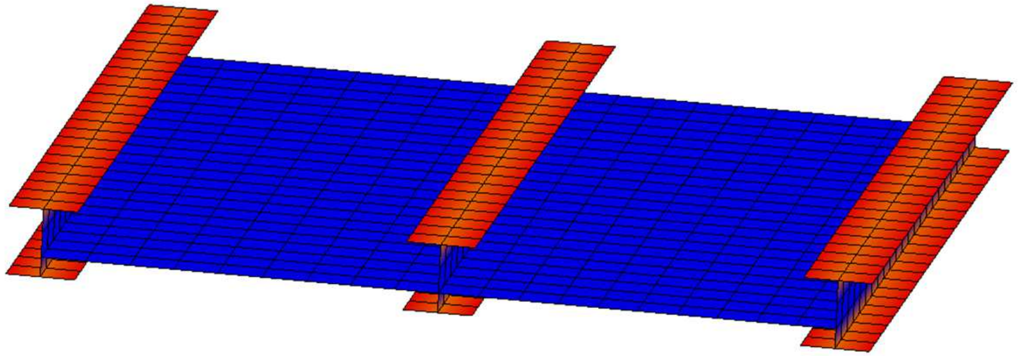
Quasi-static analysis using explicit time integration

Time scaling

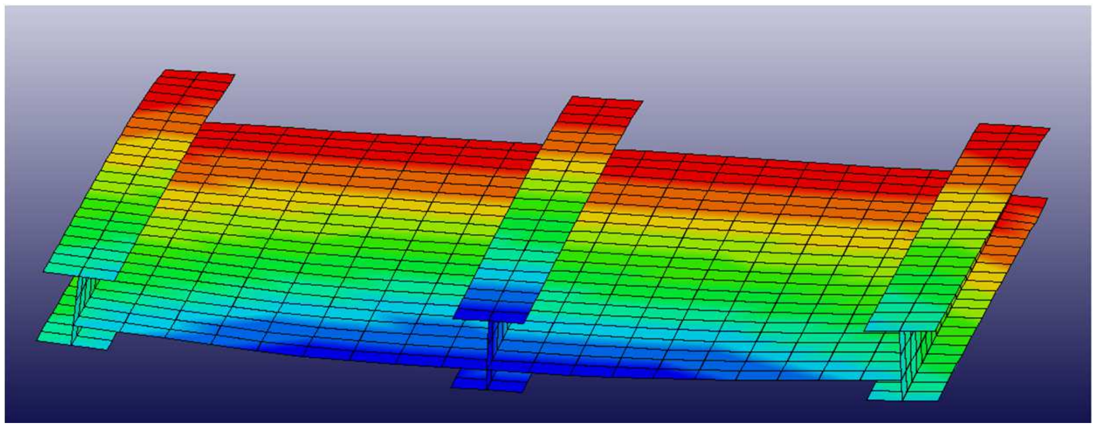
Large global viscous damping

Material Model 172 (EC2) for concrete, based on Eurocode 2

Material model MAT 4 for steel (elastic plastic thermal)



Temperature distribution



Deflection at t=50min

VERIFICATION AND VALIDATION OF COMPUTER SIMULATIONS

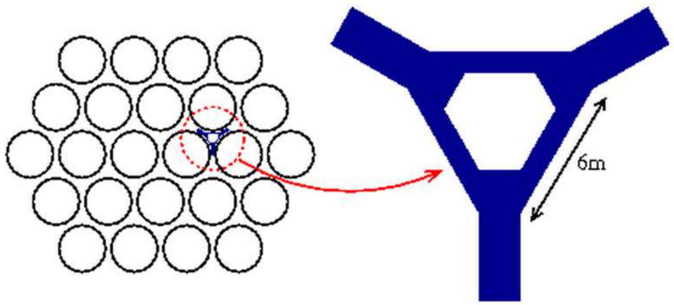
The sinking of the Sleipner A offshore platform

http://www.ima.umn.edu/~arnold/disasters/sleipner.html

The failure involved a total economic loss of about $700 million.

Failure in a cell wall, resulting in a serious crack and a leakage that the pumps were not able to cope with. The wall failed as a result of a combination of a serious error in the finite element analysis and insufficient anchorage of the reinforcement in a critical zone.

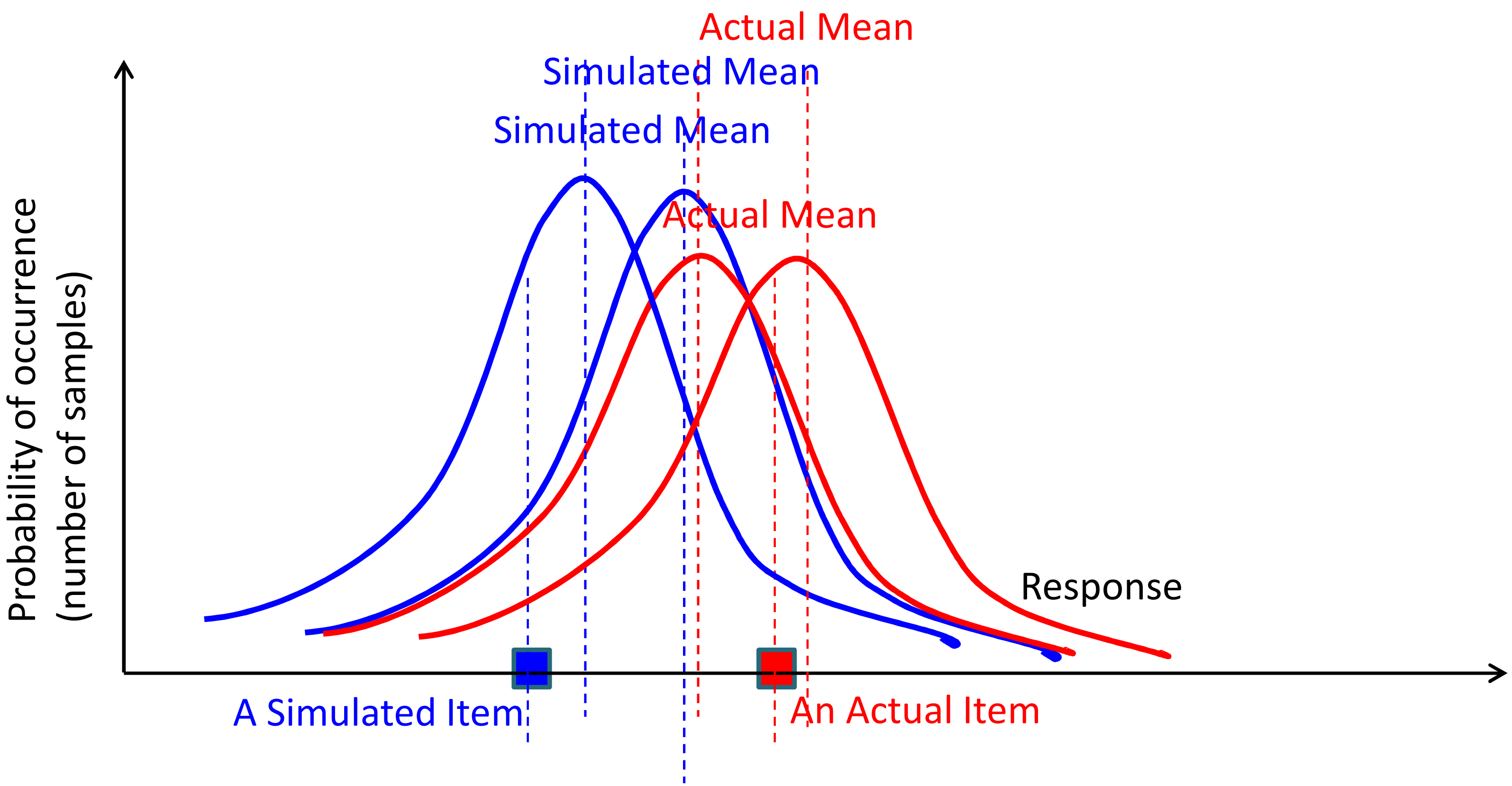
The post accident investigation traced the error to inaccurate finite element approximation of the linear elastic model of the tricell (using the popular finite element program NASTRAN). The shear stresses were underestimated by 47%, leading to insufficient design. In particular, certain concrete walls were not thick enough.



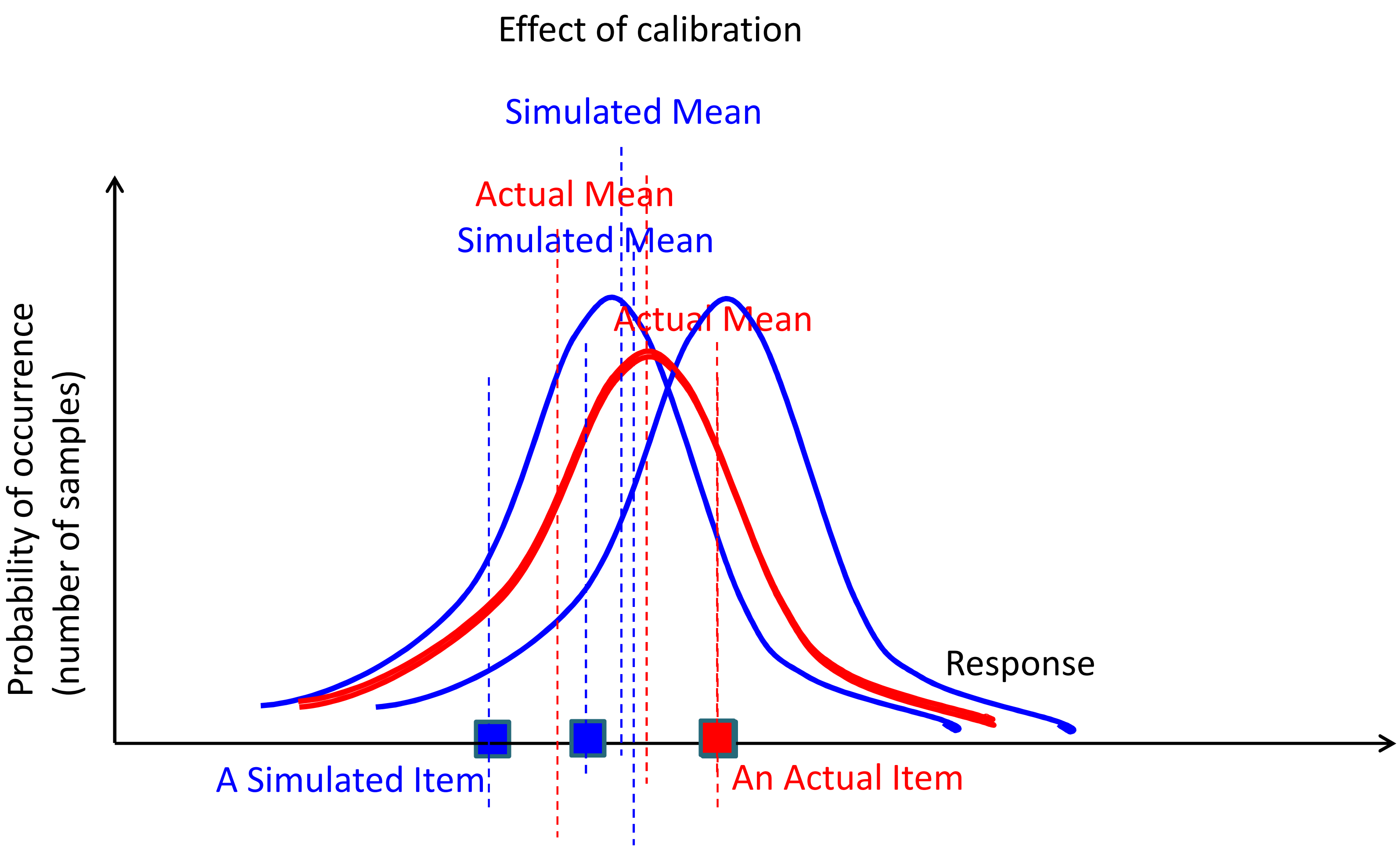
VERIFICATION AND VALIDATION OF COMPUTER SIMULATIONS

FE model well replicates the experiment

FE model poorly replicates the experiment



VERIFICATION AND VALIDATION OF COMPUTER SIMULATIONS



Thank you!