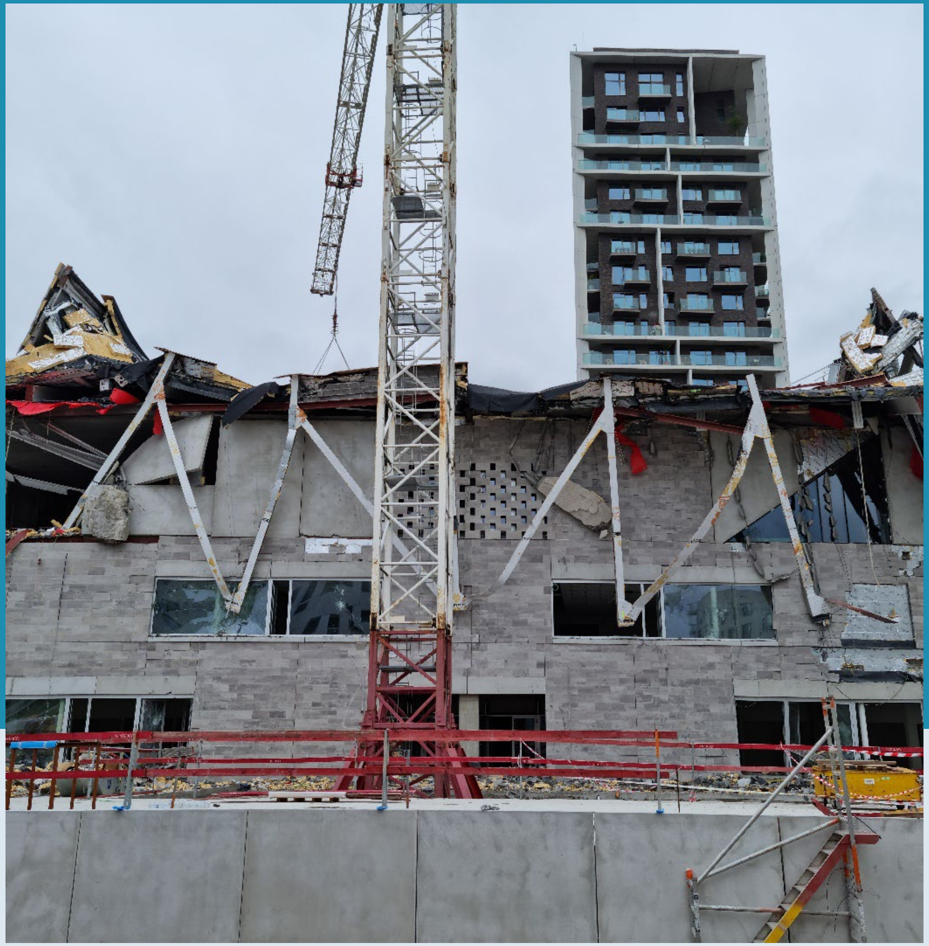
KU LEUVEN

Upcoming robustness rules according to Eurocodes, challenges and opportunities for steel constructions



Tom Molkens

Content

- Robustness
- Eurocode program
- Actual robustness rules
- Upcoming robustness rules
- TR
- Research
- Resilience of steel to fire

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus

Robustness ?

Definition robustness = Challenge

- Cambridge dictionary: The quality of being strong, and healthy or unlikely to break or fail
- Oxford Learner's Dictionaries: Strong and healthy

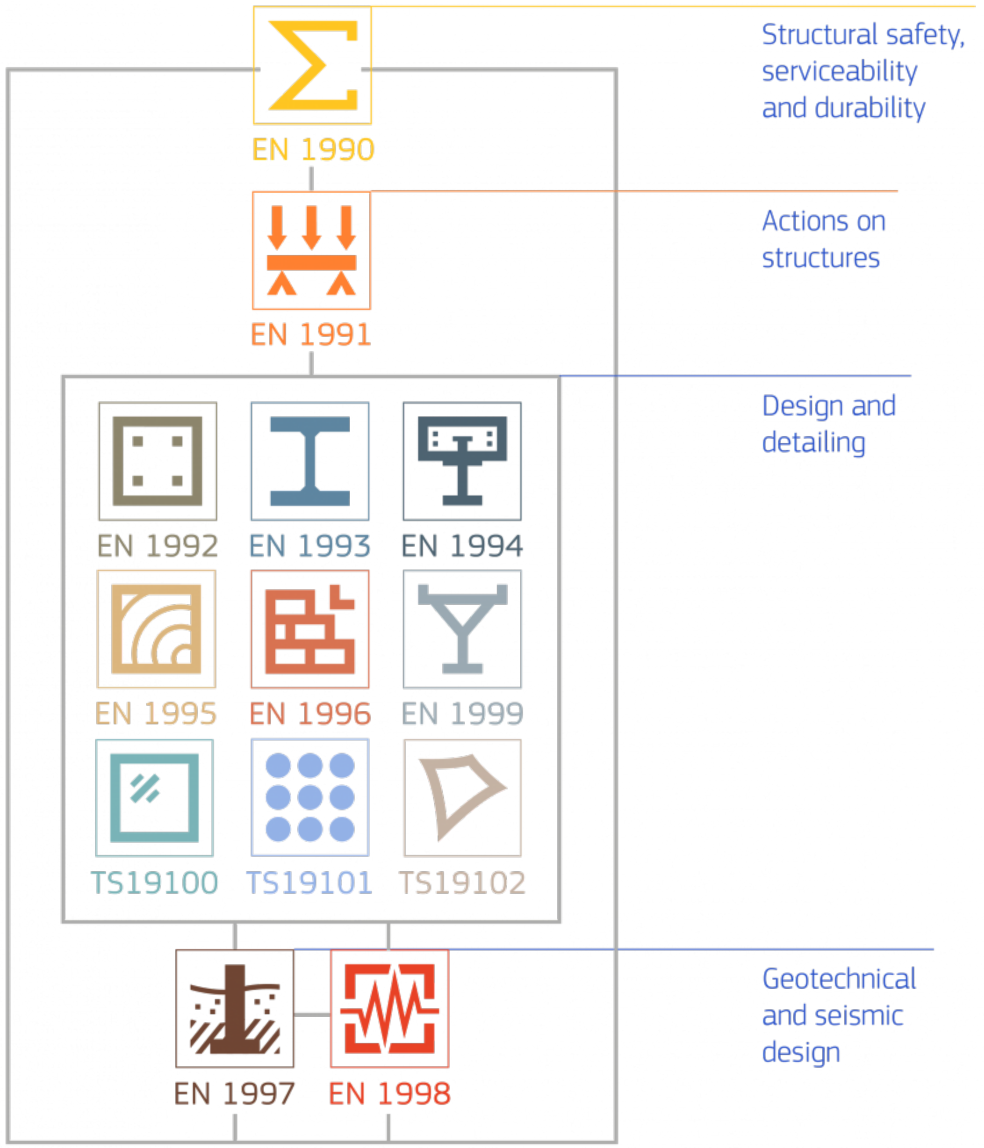
Linked in some way

Definition resilience = Opportunity (for steel)

- Cambridge dictionary: The ability of a substance (system) to return to its usual shape after being bent, stretched, or pressed
- Oxford Learner's Dictionaries: The ability of ~~people or~~ things to recover quickly after something unpleasant, such as shock, injury, etc.

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

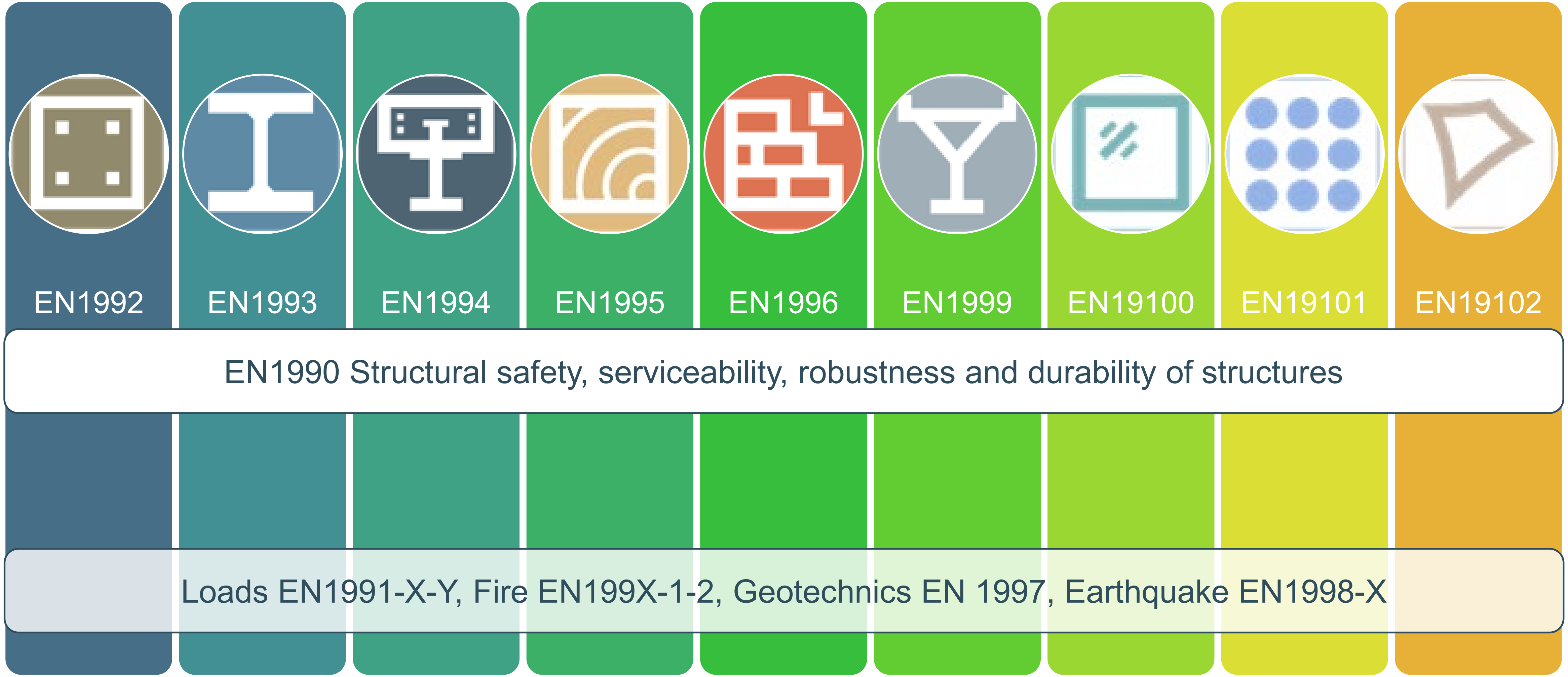
Eurocode program



Robustness ?

Standard	Robustness	Robust	Resilience
EN1990 (prEN)	1 (→ 64)	0	0
EN1991-1-7	13	1	0
EN1992-1-1	0	1	0
EN1993-1-1 (prEN)	2 (→ 4)	0	0
EN1994-1-1	0	0	0
EN1995-1-1	0	0	0
EN1996-1-1	2	1	0
EN1999-1-1	2	1	0

Eurocode program



Eurocode program

EN1992 | EN1993 | EN1994 | EN1995 | EN1996 | EN1999 | EN19100 | EN19101 | EN19102

EN1990 Structural safety, serviceability, robustness and durability of structures

Report of Project Team WG6.T2 Robustness Rules in Material Related Eurocode Parts

Loads EN1991-X-Y, Fire EN199X-1-2, Geotechnics EN 1997, Earthquake EN1998-X

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

Eurocode program

- Mandate M/515: Development of 2nd generation of EN Eurocodes
- WG6.T2 Project Team:

Prof. Bassam Izzuddin
- Imperial College
- Requirements for design

Prof. Paolo Martinelli
- Politecnico di Milano
- EN1995
- EN1996

Prof. Alan O'Connor
- Trinity College
- Chair

Prof. Beatrice Belletti
- University of Parma
- EN1992

Prof. Tom Molkens
- KU Leuven university
- EN1993
- EN1994
- EN1999

Outcomes:

- Technical regulation
- JRC-report: Guidance on the design for structural robustness

Actual robustness rules

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1990

April 2002

ICS 91.010.30

Supersedes ENV 1991-1:1994

English version

Eurocode - Basis of structural design

Eurocodes structuraux - Eurocodes: Bases de calcul des structures

Eurocode: Grundlagen der Tragwerksplanung

This European Standard was approved by CEN on 29 November 2001.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Management Centre or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Management Centre has the same status as the official versions.

CEN members are the national standards bodies of Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom.

EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

Management Centre: rue de Stassart, 36 B-1050 Brussels

Ref. No. EN 1990:2002 E

Actual robustness rules

Eurocode 0 (2002), section 2.2 Reliability management:

- (5) The levels of reliability relating to structural resistance and serviceability can be achieved by suitable combinations of … e) other measures relating to the following other design matters:
  - …
  - the degree of robustness (structural integrity)
  - …

Eurocode 1-1-7 (2006), section 1.5.14 Robustness:

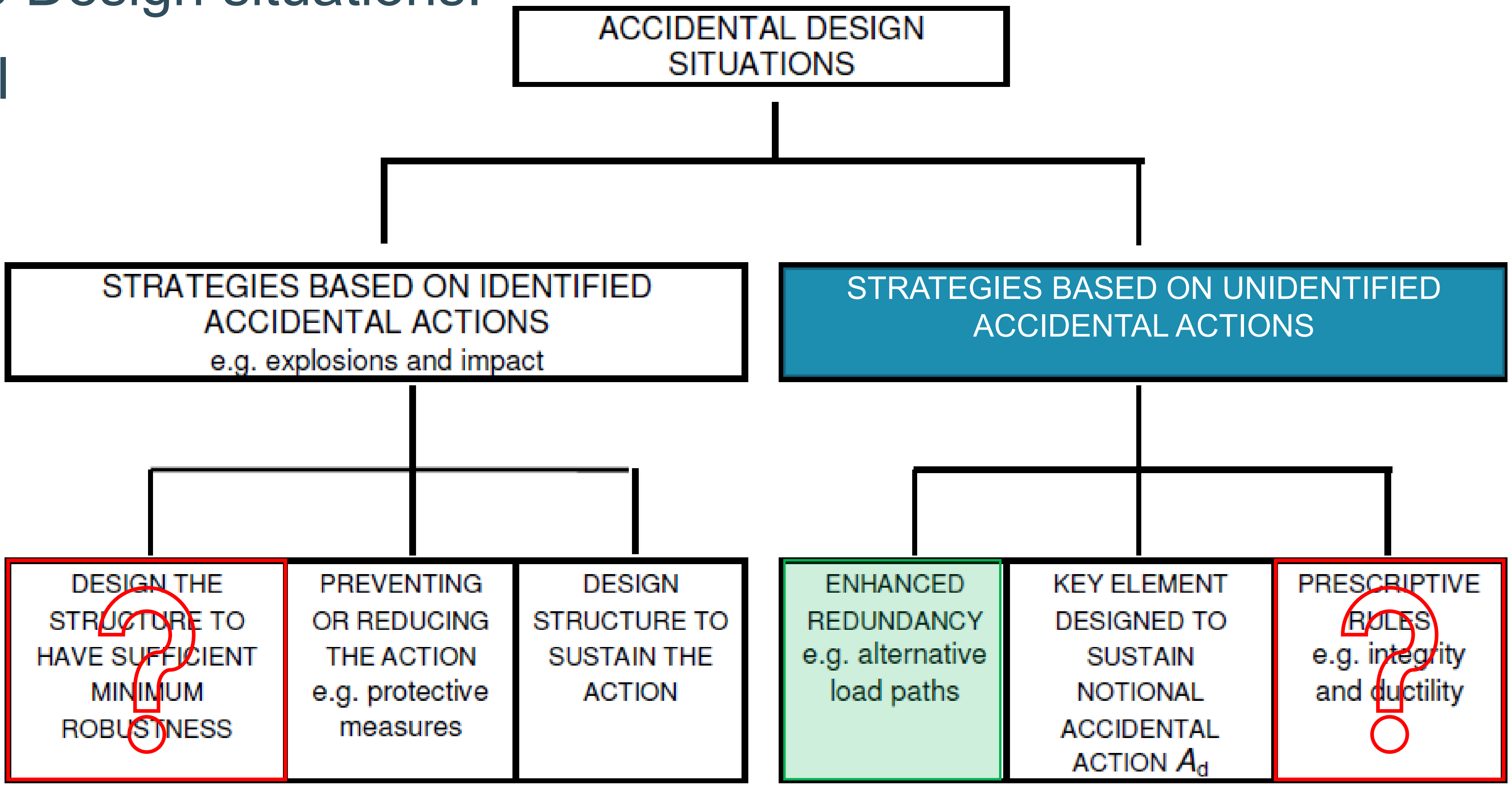
Appears in the actions on structures part?
Fire already covered by EN199X-1-X

- the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause.

Actual robustness rules

Eurocode 1-1-7, section 3 Design situations:

- Strategies for accidental design situations



Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

Actual robustness rules

Eurocode 1-1-7, section 3 Design situations:

- Note 3: Strategies based on unidentified accidental actions cover a wide range of possible events and are related to strategies based on limiting the extent of localised failure. The adoption of strategies for limiting the extent of localised failure may provide adequate robustness against those accidental actions identified in 1.1(6), or any other action resulting from an unspecified cause. Guidance for buildings is given in Annex A (Informative).
- 1.1(6) EN 1991-1-7 does not specifically deal with accidental actions caused by external explosions, warfare and terrorist activities, or the residual stability of buildings or other civil engineering works damaged by seismic action or fire, etc.

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus

Upcoming robustness rules

CEN/TC 250

Date: 2023-07

prEN 1990-1: 2023

Secretariat: BSI

Eurocode — Basis of structural and geotechnical design — Part 1: New structures

Eurocode — Grundlagen der Tragwerksplanung und geotechnischen Bauwerken — Teil 1: Neue Tragwerken

Eurocode — Bases de calcul des structures et géotechniques —Partie 1: Nouveaux structures

ICS:

CCMC will prepare and attach the official title page.

Upcoming robustness rules

Eurocode 0, section 0.2 Introduction to prEN 1990-1 (2023):

- This document gives the principles and requirements for safety, serviceability, robustness, and durability of structures that are common to all Eurocodes parts and are to be applied when using them.

Eurocode 0, section 3.1.2.30 Robustness:

Appears in the basis of structural design part!

- ability of a structure to withstand unforeseen adverse events without being damaged to an extent disproportionate to the original cause

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

Upcoming robustness rules

Eurocode 0, section 4.4 Robustness:

(1) A structure should be designed to have an adequate level of robustness so that, during its design service life it will not be damaged by unforeseen adverse events, such as the failure or collapse of a structural member or part of a structure, to an extent disproportionate to the original cause.

NOTE 1 Progressive collapse is an example of a damage that is disproportionate to the original cause.

NOTE 2 For most structures, design in accordance with the Eurocodes provides is assumed to provide an adequate level of robustness without the need for any additional design measures to enhance structural robustness.

→ Weaking the objectives (legal issues in some countries)

(2) Design measures to enhance structural robustness should be applied when specified by the relevant authority or, where not specified, as agreed for a specific project by the relevant parties.

NOTE 1 Guidance on additional design measures to enhance structural robustness for buildings and bridges is given in Annex E (Informative).

NOTE 2 Further guidance can be given in the National Annex. → Making normative by individual countries?

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus

Upcoming robustness rules

Eurocode 0, annex E
Design situations:

- Design for identified accidental actions and design strategies for enhanced robustness

Design for accidental actions (EN 1991) Explicit design of the structure (e.g. against explosion, impact)		Design for enhanced robustness (EN 1990) Strategies based on limiting the extent of damage		
Design structure to resist the action[a]	Prevent or reduce the action e.g. protective measures, control of events	Alternative load paths either providing adequate deformation capacity and ductility or applying prescriptive design rules	Key elements i.e. designing selected members to resist notional action(s)	Segmentation i.e. separation into parts

[a] Structural design against identified accidental actions can incorporate specifically designed members, which fail partially or fully, provided their failure does not lead to further structural collapse as agreed with the authorities (for strategies and methods to limit the extent of damages, see E.3 and E.4).

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

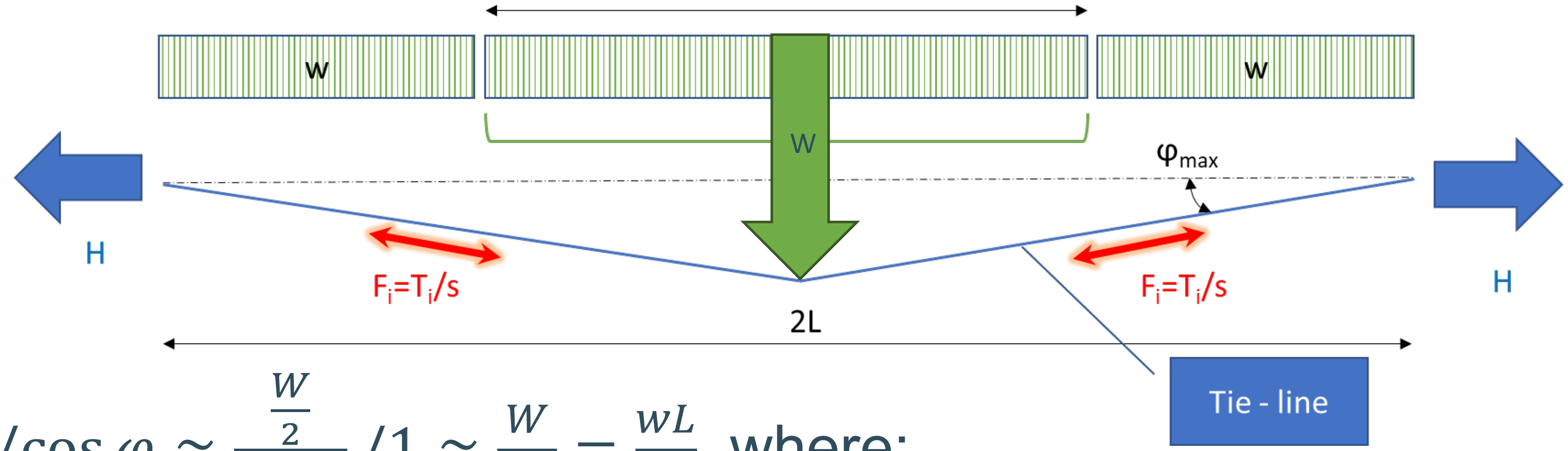
Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus

Technical regulation

Technical regulation

Physical background: **sudden column loss scenario & tying forces**

- Static scheme



- Formulation: $F_i = H\,/\cos\varphi \approx \frac{\frac{W}{2}}{\tan\varphi}/1 \approx \frac{W}{2\varphi} = \frac{wL}{2\varphi}$, where:
  - F_i = Tying force per unit (T_i/s with T_i = tying force and s = spacing)
  - $W = w{\cdot}L$ = Load effect on the column, w = Load effect on the beam (with length L) supported by the 'lost' column
  - φ = Rotation ductility, expressed in rad

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

Technical regulation

Comparative study:

- UFC 4-023-03: Design of Buildings to Resist Progressive Collapse (DoD, 2005, updated 2009).
  - Required/assumed rotational ductility: 0.2 rad
  - Formulation: $F_i = 3wL \overset{\varphi=0,2}{\Longleftrightarrow} 2.5wL$, difference factor 1.2
  - Dynamic Amplification Factor (DAF) = 1.2, need for high damping value ?
- EN 1991-1-7:
  - Formulation: $F_i = 0.8wL \overset{\varphi=undefined}{\Longleftrightarrow} \varphi = \frac{1}{2 \cdot 0.8} = 0.625rad$ (32°)
  - With DAF = 1.2 → $\varphi = \frac{1.2}{2 \cdot 0.8} = 0.75rad$ (37°!) … assumptions no longer valid!

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

Technical regulation

New proposal upcoming Technical Regulation (TR), enhanced robustness:

- Tying force: $T = \eta \cdot \rho \cdot \left(\frac{i_f}{\bar{\alpha}}\right) \cdot P$, where: → $T = 2 \cdot 1 \cdot 2.5 \cdot w \cdot L$
  - T = tying force
  - η = dynamic amplification factor corresponding to sudden column loss
  - ρ = reduction factor that allows for such effects as strain-hardening, contributions of infill walls/infill panels and interaction between tying and flexural actions (taken conservatively as 1) → Opportunity for steel
  - i_f = tying force intensity factor (3.0 assumed in UFC and 0.8 in EN)
  - $\bar{\alpha}$ = normalised rotation ductility $\bar{\alpha} = \alpha/0.2$ to allow for different levels of chord rotation ductility α (rad) in different materials and forms of construction
  - $P\ (= W)$ = Load effect on the column

Izzudin B., Sio B., *Rational Horizontal Tying Force Method for Practical Robustness Design of Building Structures*, Engineering Structures, 252(1), 113676, 2022.

Technical regulation

New proposal upcoming Technical Regulation (TR), enhanced robustness:

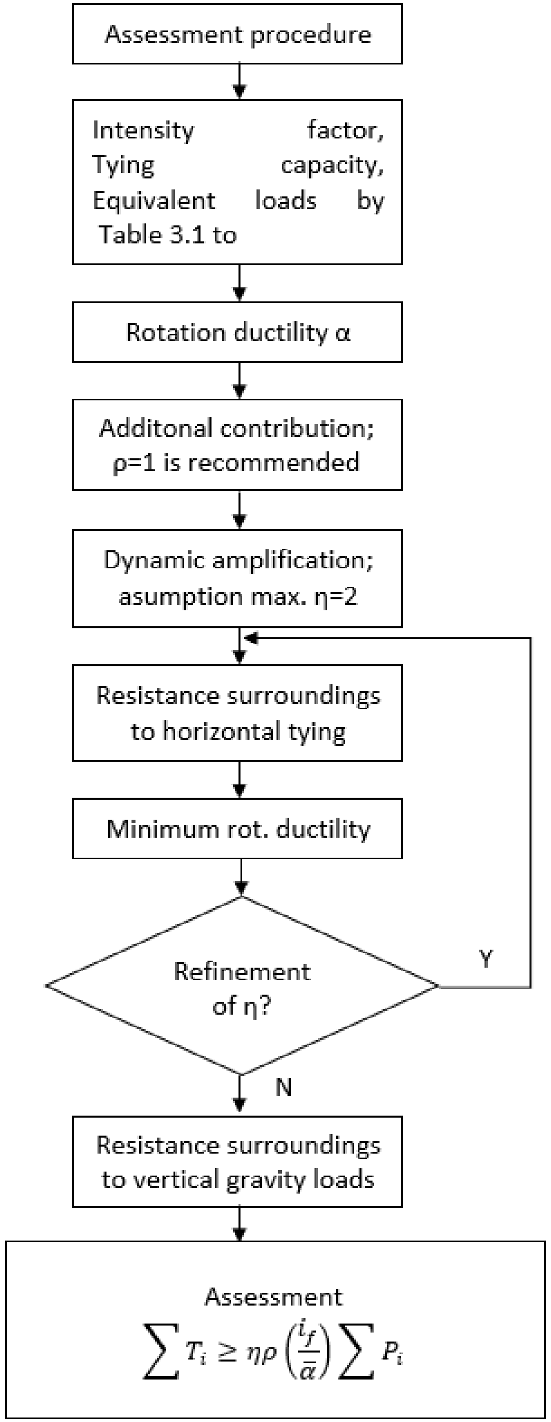
- Dynamic amplification factor η :
  - Need for a minimum chord rotation α_{min} to develop tying forces (otherwise bending capacity should be sufficient).
  - Based on energy balance principles,
  - based on advanced numerical simulations,
  - **by the use of a realistic upper bound = 2.0**
- Only a verification strategy can be followed, assuming that the α_{min}–requirement is fulfilled, calculating deformations, confirming initial hypotheses.
- Minimum resistance and stiffness of surrounding structure is also obliged!

Izzudin B., Sio B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Technical regulation

New proposal upcoming Technical Regulation (TR),

- Assessment procedure

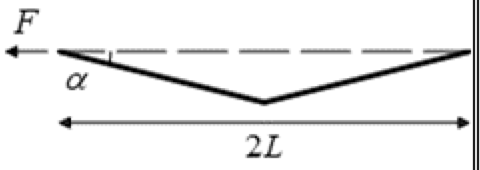
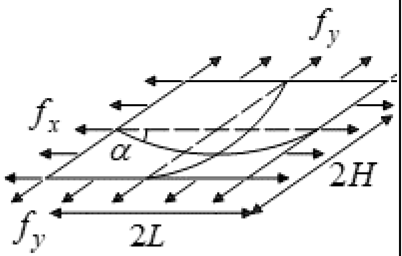
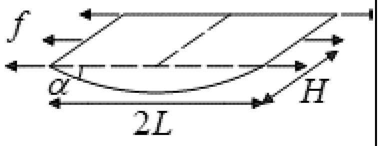


O'Connor et Al. *Report of Project Team WG6.T2 Robustness Rules in Material Related Eurocode Parts*, Final draft for informal enquiry WG6T2, 30th of October 2020.

Technical regulation

New proposal upcoming Technical Regulation (TR), enhanced robustness:

- Tying force T and intensity factor i_f for different systems

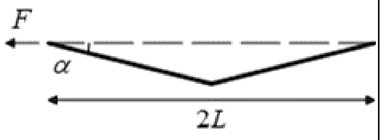
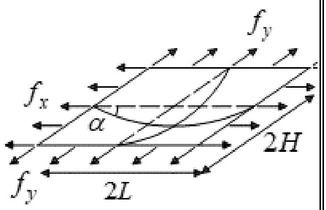
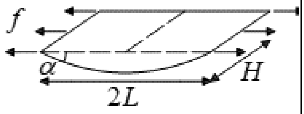
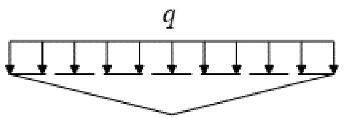
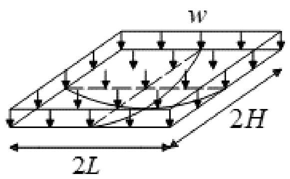
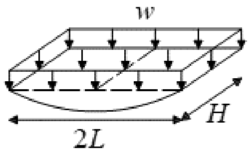
	Tying via beam	Two-way tying via floor	One-way tying via floor
			
Intensity factor: i_f	2.5	3.125	3.125
Equivalent tying force: T	F	$f_x H + f_y L\left(\frac{L}{H}\right)$	$\frac{f\,H}{2}$

André et al., *Guidance on the design for structural robustness*, JRC-technical report, 2023?.

Technical regulation

New proposal upcoming Technical Regulation (TR), enhanced robustness:

- Load effect on the column P :

	Tying via beam	Two-way tying via floor	One-way tying via floor
			
Loading			
Equivalent load: P	qL	$w L H$	$\frac{w L H}{2}$
Redistributed load amplification	$0.25 + 0.75\eta$	$0.3056 + 0.6944\eta$	$0.3056 + 0.6944\eta$

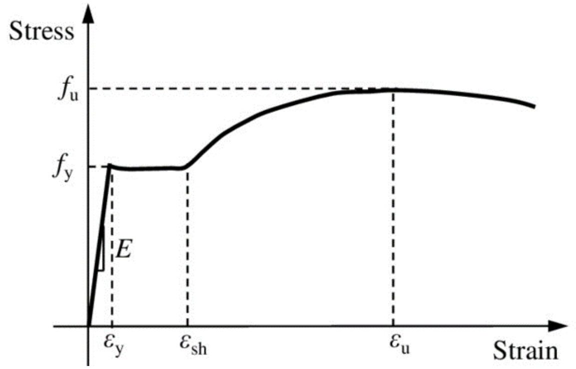
André et al., *Guidance on the design for structural robustness*, JRC-technical report, 2023?.

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

Technical regulation

New proposal upcoming Technical Regulation (TR), enhanced robustness:

- Reduction factor ρ : → **Conservatively: $\rho = 1$**
    - Strain hardening & overstrength → data out of EN1998 (also used for the verification of connections).



Steel Grade	γ_{rm}
S235	1,45
S275	1,35
S355	1,25
S460	1,20

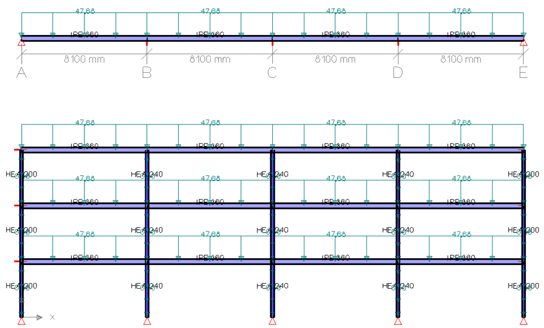
    - Contribution of partition walls (UFC & ACI).
    - Interaction between tying and flexural action (→ **research**).

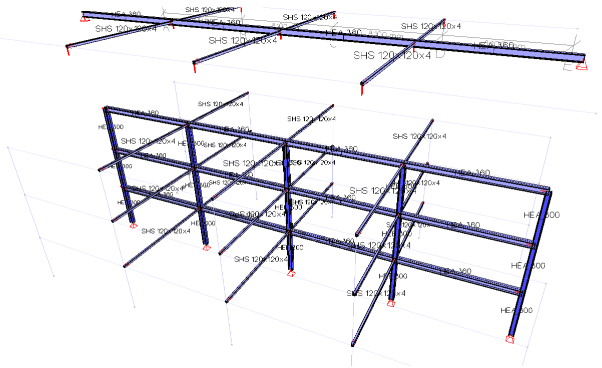
Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

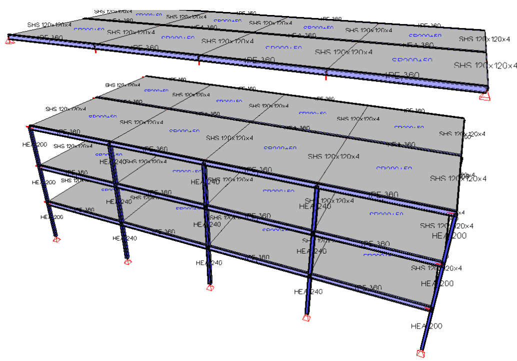
Technical regulation

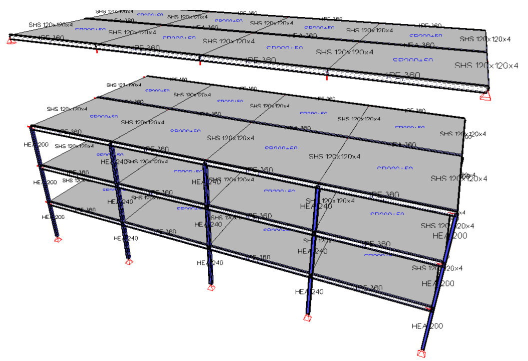
New proposal upcoming Technical Regulation (TR), enhanced robustness:

- Different strategies are possible for steel (design examples will be available):
  - Based on the capacity of the principal elements;
  - Activation of spacers to enhance the bearing capacity;
  - Supplementary activation of a reinforcement mesh in a compression layer;
  - Exclusive activation of the reinforcement mesh in the compression layer.









Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus

KU LEUVEN

Technical regulation

New proposal upcoming Technical Regulation (TR), enhanced robustness:

- Sound engineering principles should be followed:
  - To promote the activation of ductile structural components in the structure and, accordingly, to avoid brittle failure modes, with a specific attention to be paid to the welds (the use of full-strength welds is recommended);
  - To ensure links between the elements using the tying approach according to the proposed Tying Force Strategy (TFS);
  - Optimise the design making use of strain-hardening and combined actions if this can be supported by tests or reliable data.

André et al., *Guidance on the design for structural robustness*, JRC-technical report, 2023?.

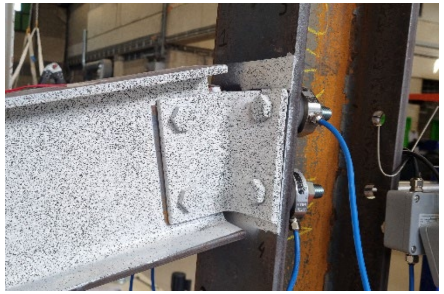
Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus

Recent research

Technical regulation

Ongoing research at KU Leuven in collaboration with Infosteel (BE):

- Reduction factor ρ, investigation on the interaction between tying and flexural action (not yet published). Dependency of the type of connection:
  - Hinge
  - Semi-rigid, flexible
  - Semi-rigid, stiff
  - Rigid

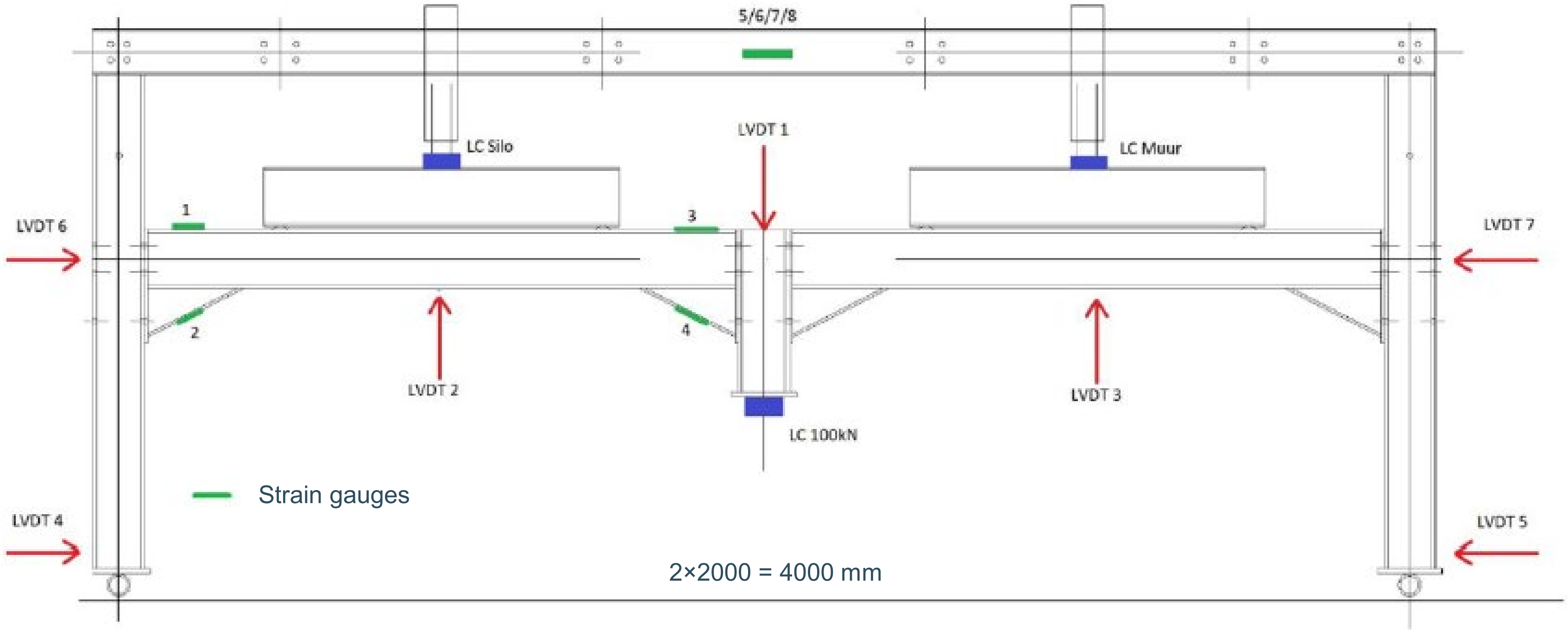


Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus

Technical regulation

Ongoing research at KU Leuven in collaboration with Infosteel (BE):

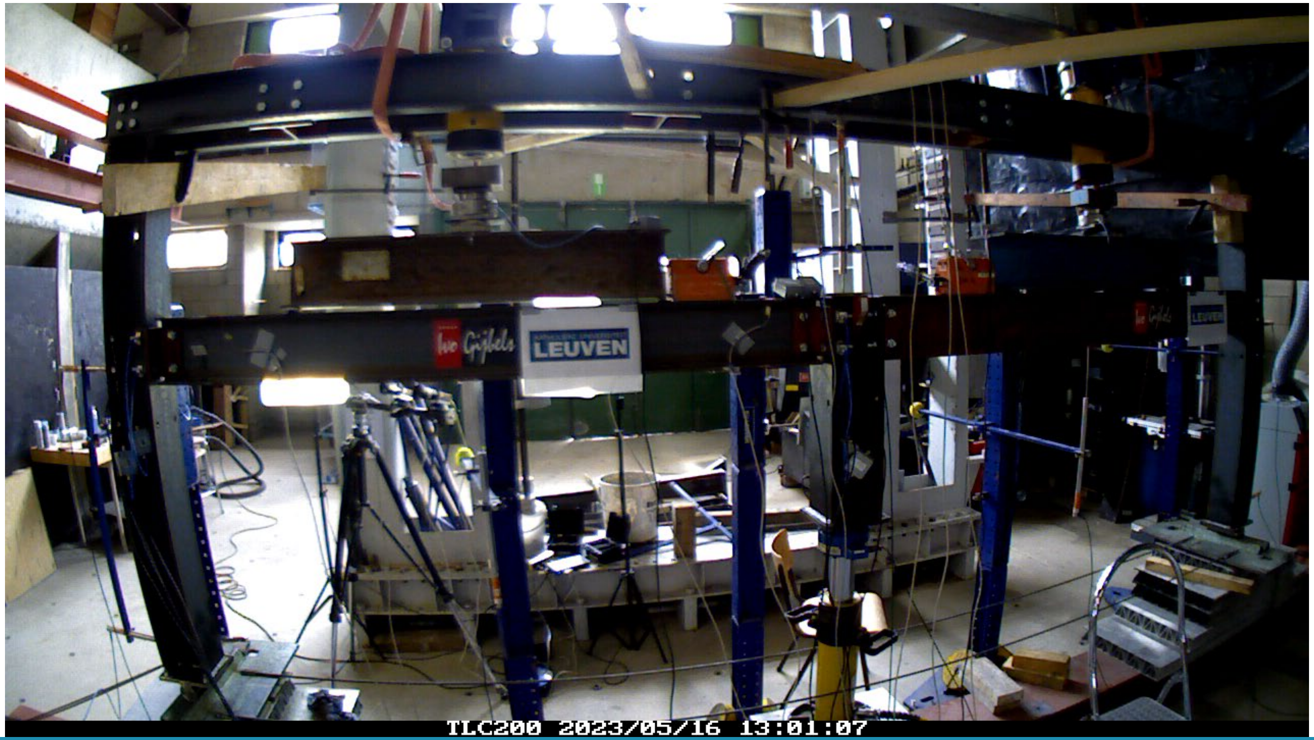
- Test set-up, quasi-static = 2 × accidental load (including DAF).



Technical regulation

Ongoing research at KU Leuven in collaboration with Infosteel (BE):

- Test impressions – hinge type connection:



Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus

Technical regulation

Ongoing research at KU Leuven in collaboration with Infosteel (BE):

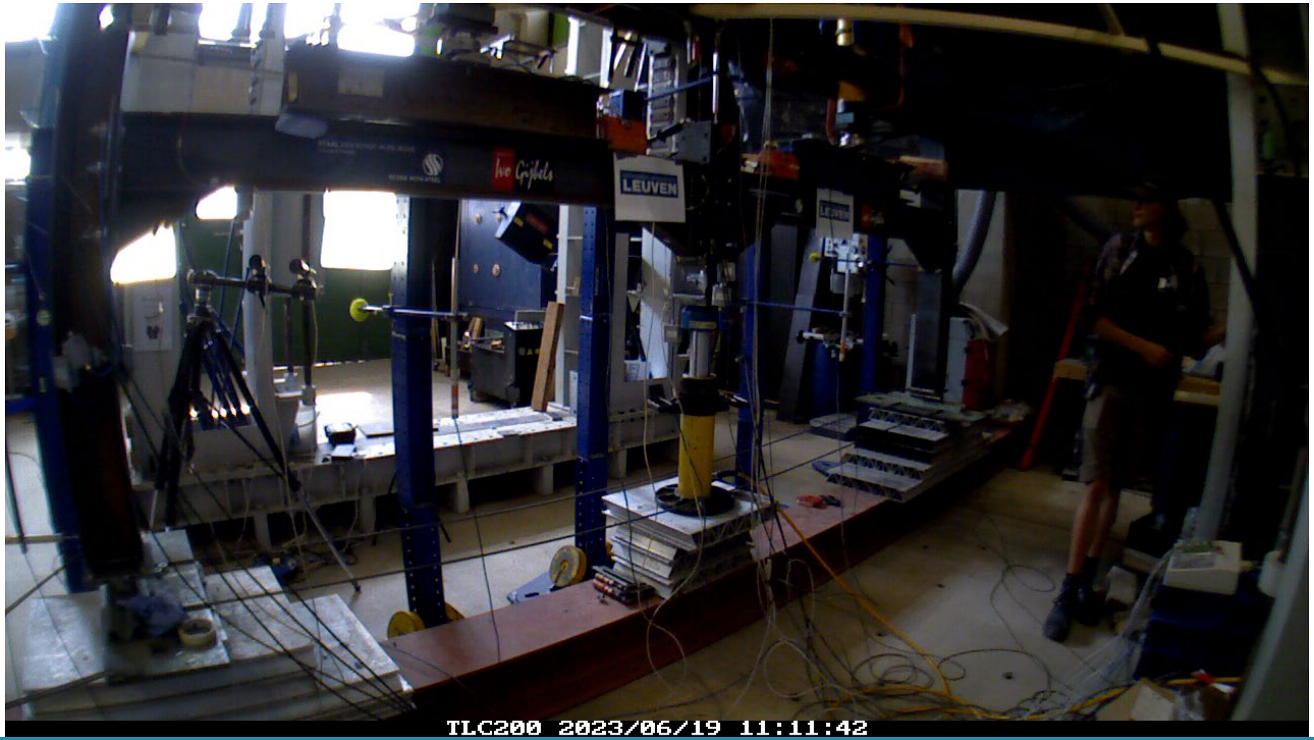
- Test impressions – semi-rigid (stiff) type connection:

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus

Technical regulation

Ongoing research at KU Leuven in collaboration with Infosteel (BE):

- Test impressions – rigid type connection:



Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus

Resilience capacity of steel to fire

Introduction

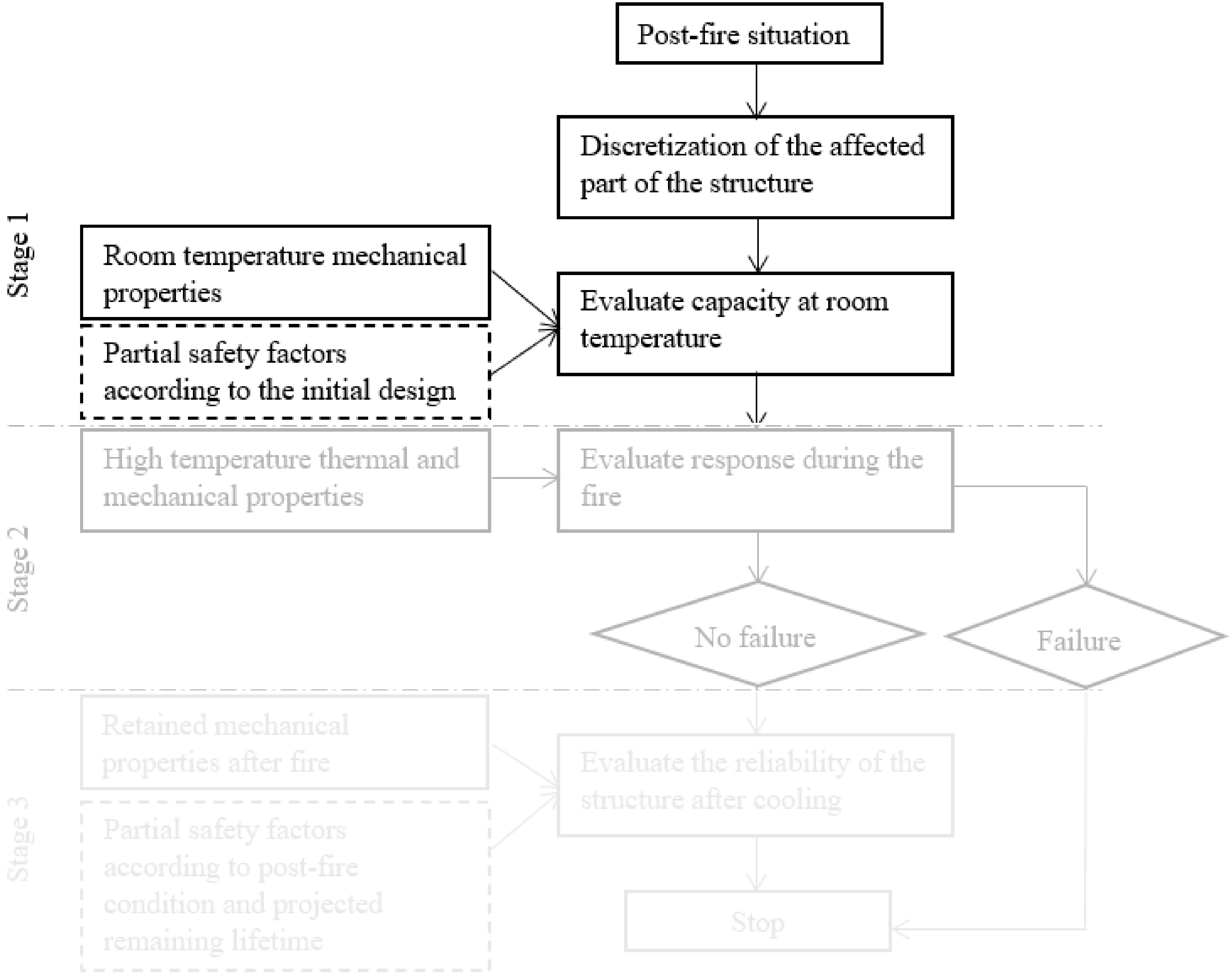
- If we are all talking about sustainability, this includes structural resilience to for example fire (and unforeseen events).
- Impact can be on:
  - Exploitation of a factory
  - Delivering of goods
  - Infrastructure
  - Social impact

- High need for scientific (reliability based) assessment tool

Methodology

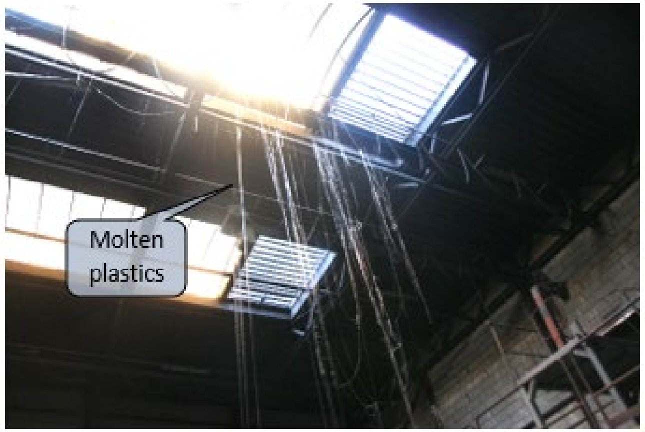
Flow chart

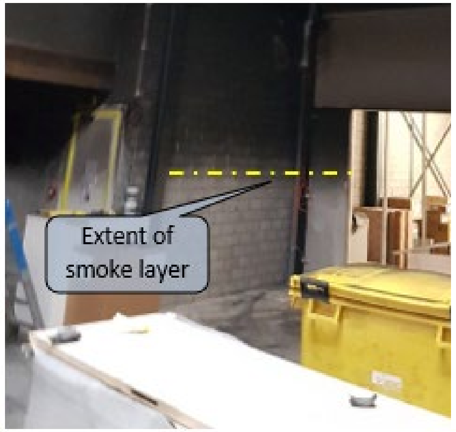
- Stage 1 = ambient
- Stage 2 = fire
- Stage 3 = post-fire



Fire severity

- In situ observations methods:
  - Melting temperatures of materials





100°C et >	: Les peintures se détériorent légèrement.
200°C environ	: Les câbles de P.V.C. brunissent, la laine brûle.
200°C et >	: Le bois s'enflamme dans certaines conditions (vitesse de combustion : 0.6 à 0.7 mm/min.).
230°C	: Les papiers, les journaux brûlent.
250°C environ	: Le coton s'enflamme et brûle, le PMMA fait des bulles.
250°C et >	: Les peintures sont nettement dégradées.
275, 300°C	: Modification de l'aspect des surfaces zinguées.
290°C et >	: Le PMMA brûle.
310°C	: La mousse de polyuréthane brûle.
327°C	: Fusion du plomb, formation de gouttes.
345°C	: Inflammation du polyéthylène.
346 à 399°C	: Le G.F.R.Polyester brûle.
350°C	: Le polystyrène brûle.
391°C	: Le polyvinyl chloride brûle.
416°C	: La mousse de polyuréthane s'enflamme.
419°C	: Fusion du zinc.
400 à 500°C	: Le P.V.C. noircit.
424°C	: Le nylon s'enflamme.
450°C environ	: Le PMMA s'enflamme.
454°C	: Le polyvinyl s'enflamme.
485°C	: Le G.F.R.Polyester s'enflamme.
490°C	: Le polystyrène s'enflamme.
660°C	: Fusion de l'aluminium, formation de gouttes.
700 à 800°C	: Ramollissement des plaques de verre.
950°C	: Fusion de l'argent, formation de gouttes.
1000°C	: Fusion du bronze.
1023°C	: Fusion du cuivre.
1100 à 1200°C	: Fusion de la fonte.

  - Straightness of elements, what is straight after a fire is safe (Tide, 1998).
  - Comparative methods based on measuring techniques like hardness of crystal structure.

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

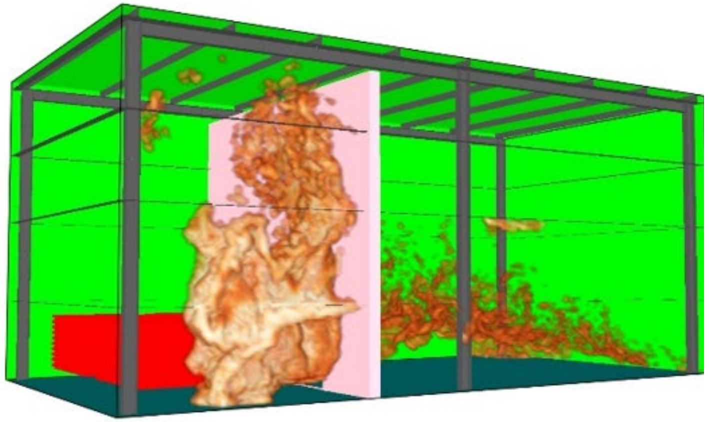
Fire severity

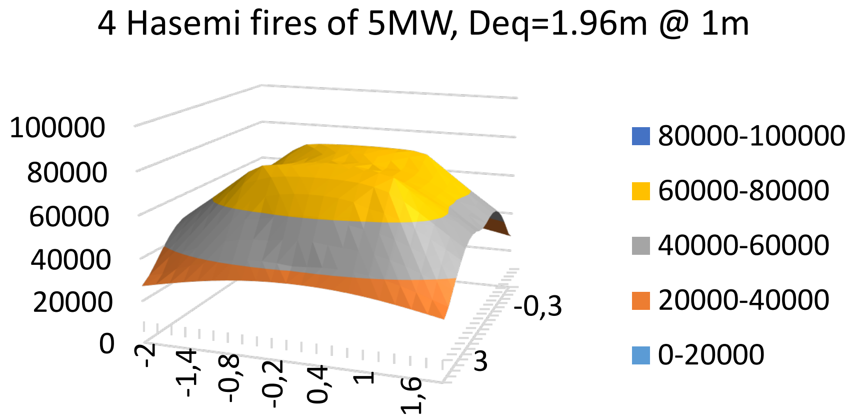
- Numerical models and simulations
  - Compartment fire including flash over like ISO834 → no sense: collapse.
  - Adjusted parametric fire (Reitgruber formulation, 2006) or BFD-fire curve (Barnett, 2002).
  - Combination of parametric and local fires like Hasemi or Heskestad.
    - Ozone
    - Locafi
    - Trafir
  - Computational fluid dynamics CFD (by FDS for example) → Speed ?

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

Fire severity

- Combination of methods and models:
  - On site investigation,
  - Simplified local fire models, if finding confirmed → stop,
  - Adjusted or advanced fire models with corresponding results.





Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

Post-fire material properties

- Uncertainties: basic material properties in ambient condition, quenched or not, fully exposed or shadow effect, exposure time, number of tests available for which grade and which exposure temperature, …
- Assumption 1: log-normal distribution:

$$\mu_x = exp\left(\frac{\sum_{i=0}^{n} \ln(X_{test,i})}{n}\right) = exp(\mu_y)$$

$$\sigma_y = \sqrt{ln(V_{test}^2 + 1)} \approx V_{test} = \frac{\sigma_x}{\mu_x} = \frac{1}{\mu_x(n-1)} \sum (X_{test,i} - \mu_x)^2$$

$$X_k = exp(\mu_y \pm k_n \sigma_y) \approx \mu_x \cdot exp\left(k_n \sqrt{ln(V_{test}^2 + 1)}\right) \approx \mu_x exp(k_n V_{test})$$

- Assumption 2: JCSS-values:

Property	Mean value μ	V_{amb}
f_y	$f_{y,n} \cdot \alpha' \cdot exp(-u \cdot V_{amb}) - C$	0.07
f_u	B·$f_{u,n}$	0.04
ε_u	$\varepsilon_{u,n}$	0.06
E	E_n=210 GPa	0.03

Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Post-fire material properties

- Assumption 3: Application of EN1990 for k_n-values, with V_x = known (JCCS).

n	1	2	3	4	5	6	8	10	20	30	∞
V_X bekend	2,31	2,01	1,89	1,83	1,80	1,77	1,74	1,72	1,68	1,67	1,64
V_X niet bekend		–	3,37	2,63	2,33	2,18	2,00	1,92	1,76	1,73	1,64

- Operator to flatten the effect of high k_n-values due to a limit set of tests for certain temperatures:

$$R_{\theta,i} = min\left(R_{k,\theta-1,i}; MAX\left(R_{\theta,k,i}; \frac{R_{k,\theta-1,i} + R_{k,\theta+1,i}}{2}\right)\right)$$

Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Post-fire material properties

- Carbon steel grades:

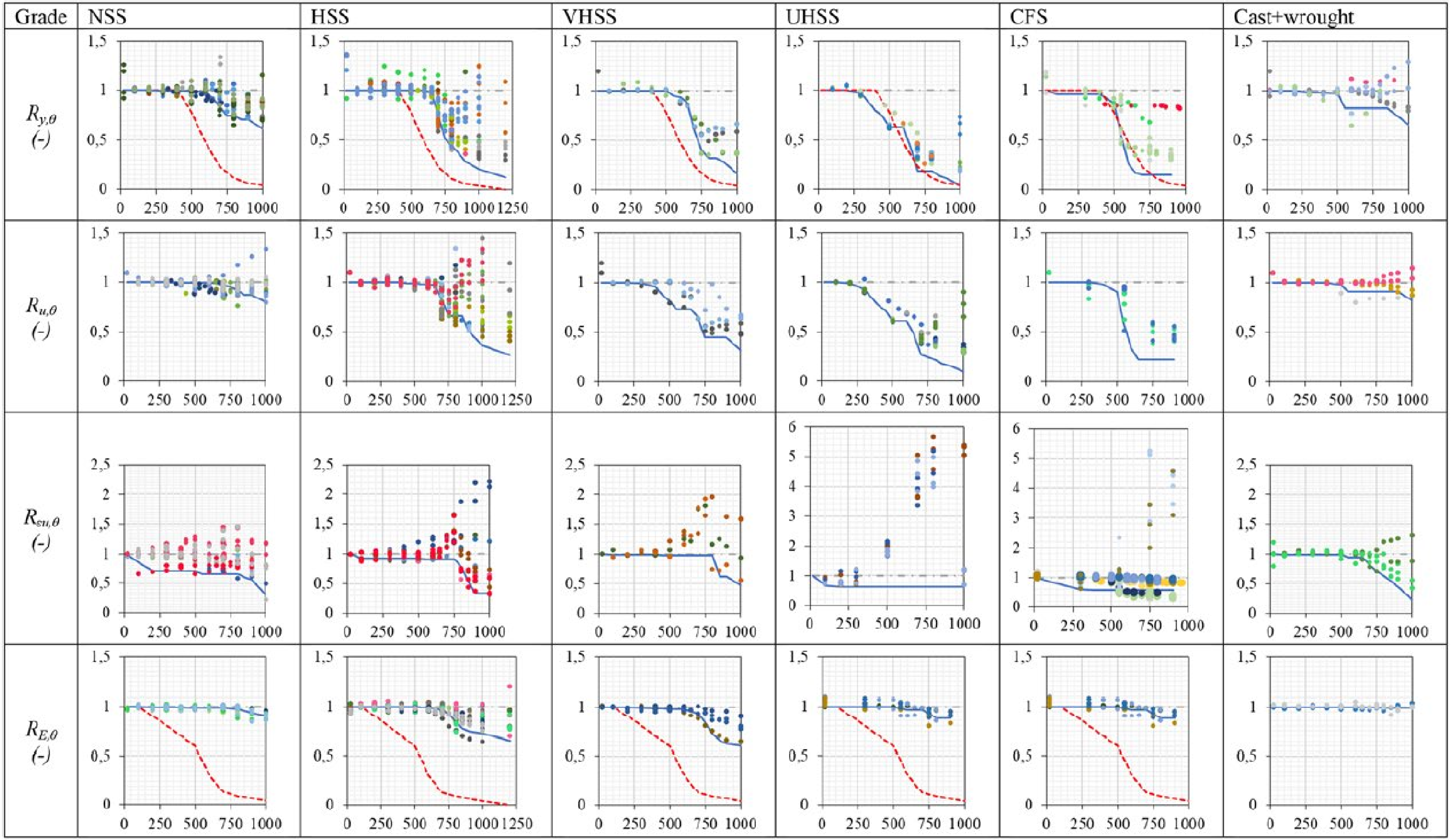
Name of subsets	Abbreviation	Yield strength (MPa)	European reference standards
Normal structural steel	NSS	≤ 420	EN 10025-2 to 5 EN 1993-1-1 Table 6.2
High strength structural steel	HSS	> 420 and ≤ 700	EN 10025-6 EN 1993-1-1 and -1-12
Very high strength structural steel	VHSS	> 700 and ≤ 960	EN 10025-6
Ultra high strength structural steel	UHSS	> 960 and ≤ 1200	VDA239-100:2016
Cold-formed steel	CFS	300 up to 550	EN 10149-2
Cast and wrought iron	Cast	≤ 385	EN 10293

- In total 719 test results out of peer reviewed references

Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Post-fire material properties

- Blue = retention or post-fire
- Red = fire
- Dots = experiments



Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

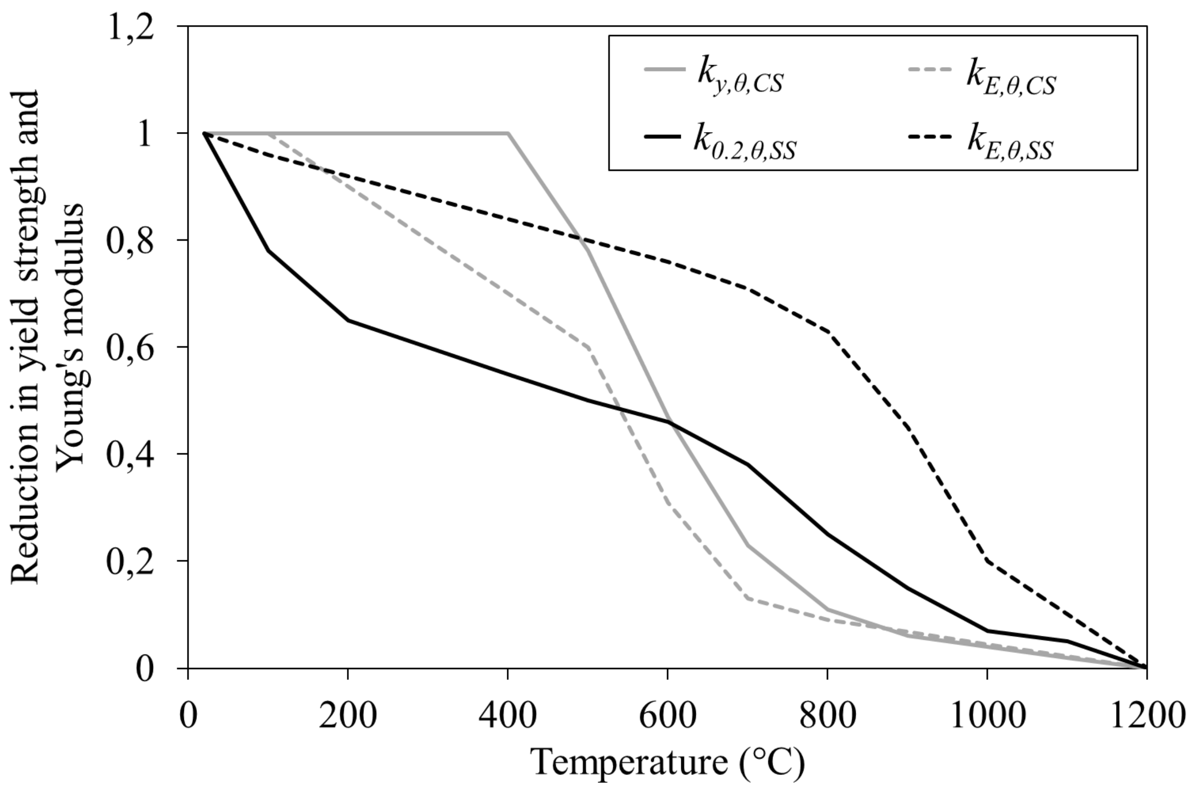
Post-fire material properties

Exposed steel temperature θ	Retention factor after exposure to a temperature θ relative to the value of $f_{y,n}$ or E_n at 20°C													
	All grades		**NSS; normal strength steel**		**HSS; high strength steel**		**VHSS; very high strength steel**		**UHSS; ultra high strength steel**		**CFS; cold-formed steel**		**Cast and wrought iron**	
	Retention factor for yield strength $R_{y,\theta,all}$	Retention factor for Young's modulus $R_{E,\theta,all}$	Retention factor for yield strength $R_{y,\theta,NSS}$	Retention factor for Young's modulus $R_{E,\theta,NSS}$	Retention factor for yield strength $R_{y,\theta,HSS}$	Retention factor for Young's modulus $R_{E,\theta,HSS}$	Retention factor for yield strength $R_{y,\theta,VHSS}$	Retention factor for Young's modulus $R_{E,\theta,VHSS}$	Retention factor for yield strength $R_{y,\theta,UHSS}$	Retention factor for Young's modulus $R_{E,\theta,UHSS}$	Retention factor for yield strength $R_{y,\theta,CFS}$	Retention factor for Young's modulus $R_{E,\theta,CFS}$	Retention factor for yield strength $R_{y,\theta,cast}$	Retention factor for Young's modulus $R_{E,\theta,cast}$
20°C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
100°C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.998	1.000	1.000	1.000	1.000	1.000	1.000
200°C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.995	1.000	1.000	1.000	1.000	1.000	1.000
300°C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.991	0.968	1.000	0.960	1.000	0.979	1.000
400°C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.986	0.875	1.000	0.960	1.000	0.979	1.000
500°C	0.809	1.000	1.000	1.000	1.000	0.998	1.000	0.980	0.633	1.000	0.867	1.000	0.970	1.000
600°C	0.809	1.000	1.000	1.000	1.000	0.994	0.935	0.976	0.633	0.986	0.263	0.971	0.824	1.000
700°C	0.591	0.966	0.830	0.986	0.745	0.968	0.583	0.933	0.187	0.973	0.150	0.970	0.824	0.997
800°C	0.351	0.846	0.746	0.973	0.446	0.835	0.317	0.725	0.187	0.926	0.150	0.874	0.824	0.992
900°C	0.351	0.767	0.708	0.939	0.290	0.746	0.283	0.624	0.114	0.801	0.150	0.874	0.769	0.992
1000°C	0.250	0.746	0.618	0.905	0.208	0.725	0.162	0.606	0.041	0.823			0.656	0.992
1200°C	0.126	0.655			0.126	0.655								
NOTE: For intermediate values of the steel temperature linear interpolation may be used. Values ≥ 0.999 are set equal to 1.000														

Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Post-fire material properties

- Stainless steel grades
  - Austenitic
  - Duplex
  - Ferritic
- Comparison with carbon steel in case of fire

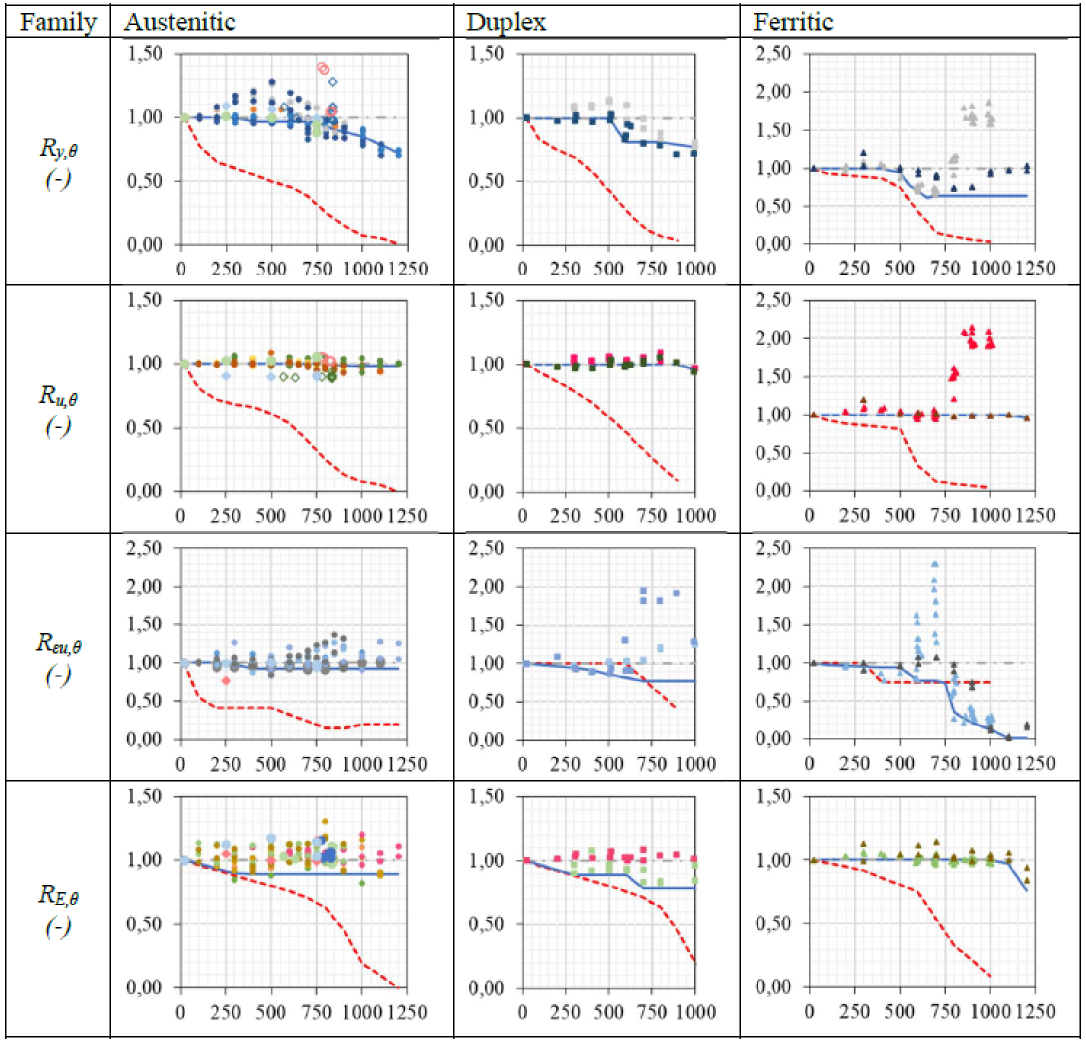


- In total 270 test results out of peer reviewed references

Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Post-fire material properties

- Blue = retention or post-fire
- Red = fire
- Dots = experiments



Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Post-fire material properties

Exposed steel temperature θ	Retention factor for proof strength $R_{0,2,\theta}$	Retention factor for the slope of the linear elastic range $R_{E,\theta}$	Retention factor for tensile strength $R_{u,\theta}$	Retention factor for the elongation at the tensile strength $R_{\varepsilon u,\theta}$
Austenitic stainless steels - Grades 1.4301, 1.4307, 1.4401, 1.4404				
20°C	1.000	1.000	1.000	1.000
100°C	1.000	0.976	1.000	1.000
200°C	1.000	0.935	1.000	1.000
300°C	1.000	0.896	1.000	0.978
400°C	0.971	0.890	1.000	0.928
500°C	0.971	0.890	1.000	0.928
600°C	0.971	0.890	1.000	0.928
700°C	0.971	0.890	0.999	0.928
800°C	0.932	0.890	0.999	0.927
900°C	0.890	0.890	0.987	0.927
1000°C	0.850	0.890	0.984	0.927
1100°C	0.786	0.890	0.984	0.927
1200°C	0.721	0.890	0.984	0.927

Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Post-fire material properties

Exposed steel temperature θ	Retention factor for proof strength $R_{0,2,\theta}$	Retention factor for the slope of the linear elastic range $R_{E,\theta}$	Retention factor for tensile strength $R_{u,\theta}$	Retention factor for the elongation at the tensile strength $R_{\varepsilon u,\theta}$
Duplex stainless steels - Grades 1.4162. 1.4362. 1.4462				
20°C	1.000	1.000	1.000	1.000
100°C	1.000	0.963	1.000	0.983
200°C	1.000	0.927	1.000	0.967
300°C	1.000	0.890	1.000	0.950
400°C	1.000	0.890	1.000	0.908
500°C	1.000	0.890	1.000	0.862
600°C	0.810	0.890	1.000	0.810
700°C	0.810	0.780	1.000	0.770
800°C	0.810	0.780	1.000	0.770
900°C	0.790	0.780	1.000	0.770
1000°C	0.770	0.780	0.960	0.770
1100°C	0.000	0.000	0.000	0.000
1200°C	0.000	0.000	0.000	0.000

Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus

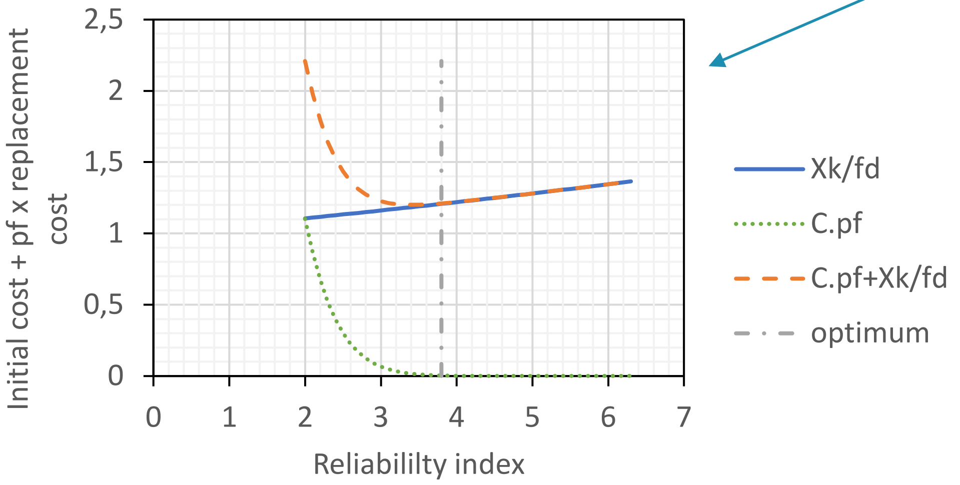
Post-fire material properties

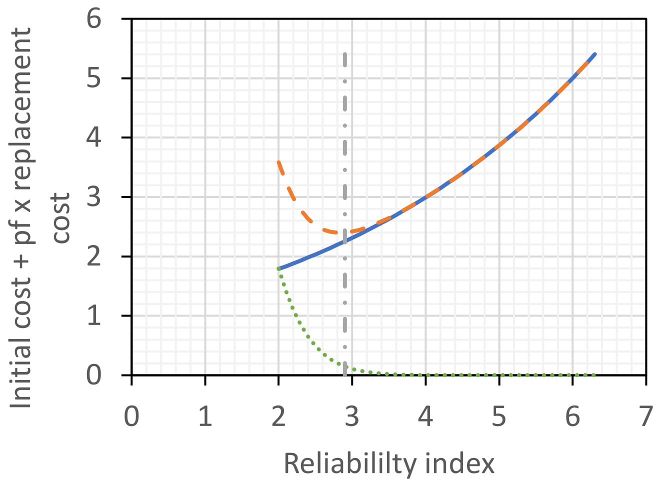
Exposed steel temperature θ	Retention factor for proof strength $R_{0,2,\theta}$	Retention factor for the slope of the linear elastic range $R_{E,\theta}$	Retention factor for tensile strength $R_{u,\theta}$	Retention factor for the elongation at the tensile strength $R_{\varepsilon u,\theta}$
Ferritic stainless steels - Grade 1.4003				
20°C	1.000	1.000	1.000	1.000
100°C	1.000	1.000	1.000	0.979
200°C	1.000	1.000	1.000	0.960
300°C	1.000	1.000	1.000	0.952
400°C	1.000	1.000	1.000	0.946
500°C	0.940	1.000	1.000	0.940
600°C	0.690	1.000	1.000	0.770
700°C	0.640	1.000	1.000	0.770
800°C	0.640	1.000	1.000	0.350
900°C	0.640	1.000	1.000	0.210
1000°C	0.640	1.000	1.000	0.140
1100°C	0.640	0.971	1.000	0.020
1200°C	0.640	0.760	0.964	0.020

Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Reliability aspects

- Reliability level is expressed as a failure probability or reliability index β.
- Partial safety factors are linked the desired reliability, coefficient of variation (considering the uncertainty) and the total economic cost.
- Differentiation will appear between the design of and an existing building!





Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus

Reliability aspects

- Out of codes maximum Δβ = -0.5 (ISO2394, 2015).
- Safety factor by reversed calculation, based on EN1990, annex D:

$$\gamma_{M0,\theta} = \frac{X_{k,\theta}}{X_{d,\theta}} = \frac{exp\left(-1.645\sqrt{ln\left({V_{test,\theta}}^2 + 1\right)}\right)}{exp\left(-\alpha\beta\sqrt{ln\left({V_{test,\theta}}^2 + 1\right)}\right)}$$

- Influence of the fire:

$$V_{test}^2 = V_{amb}^2 + V_{post}^2$$

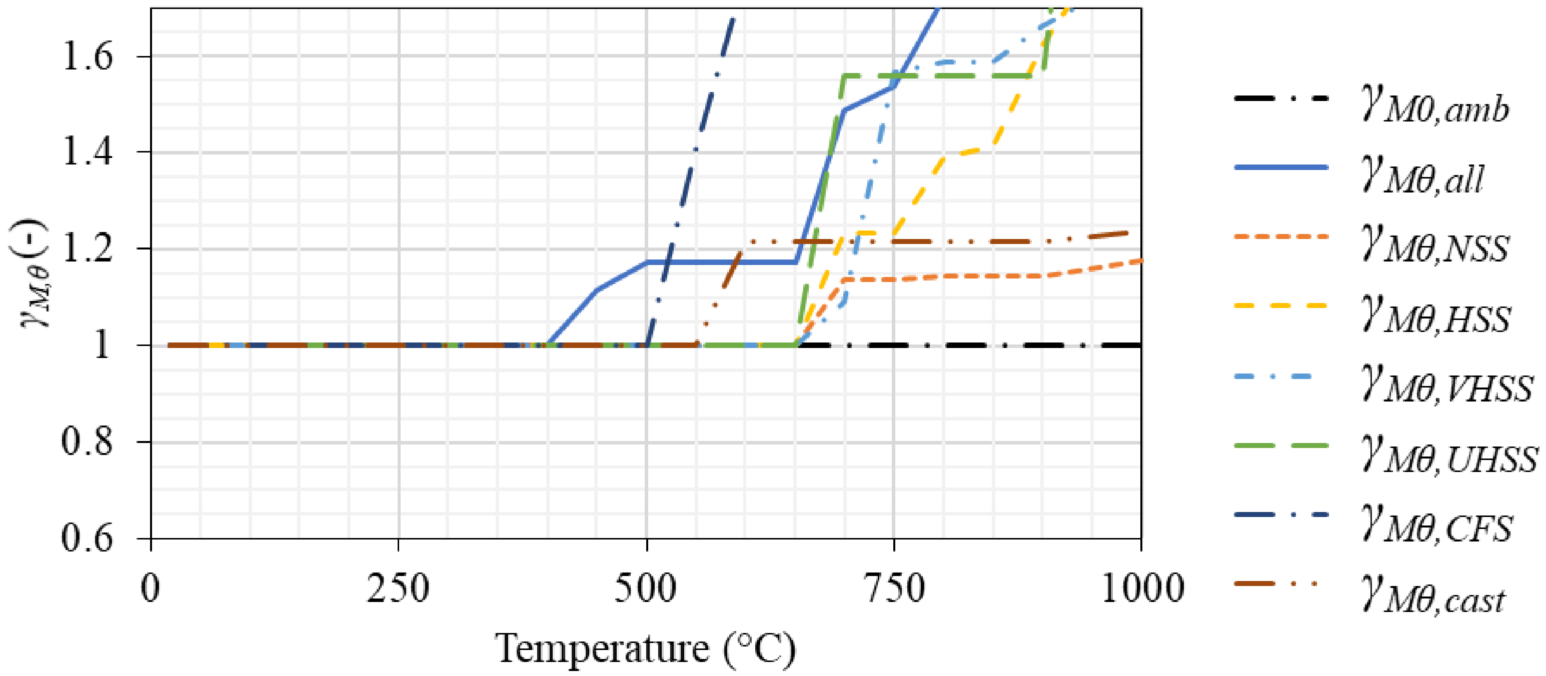
$$\gamma_{M0,test} = \gamma_{M0,amb} \times \gamma_{M0,post}$$

- For carbon steel $\gamma_{M0,amb}$ = 1.0 → makes life easy
- For stainless steel $\gamma_{M0,amb}$ = 1.1 → not really complicated

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

Reliability aspects

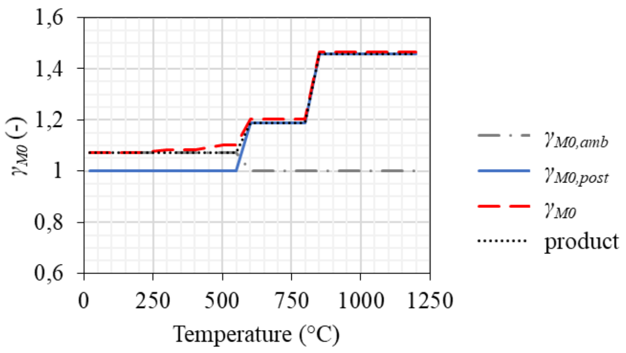
- Carbon steel



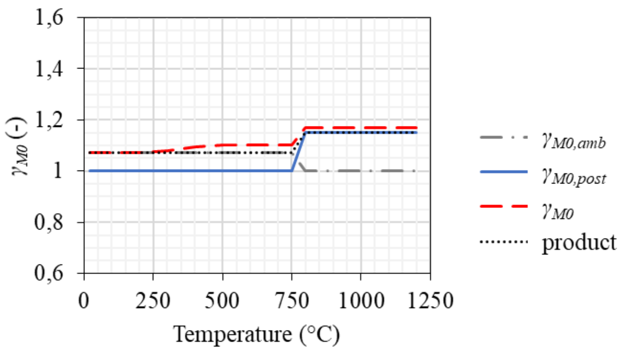
Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Reliability aspects

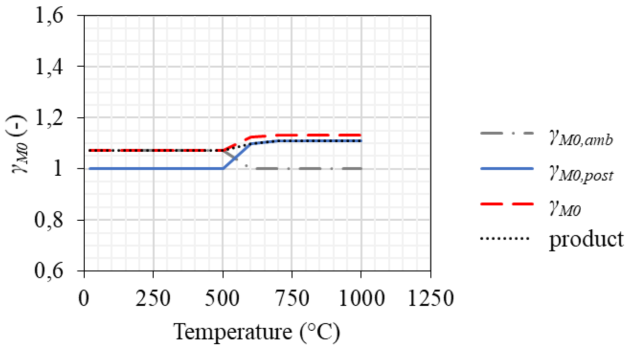
- Stainless steel, all grades, austenitic, duplex and ferritic



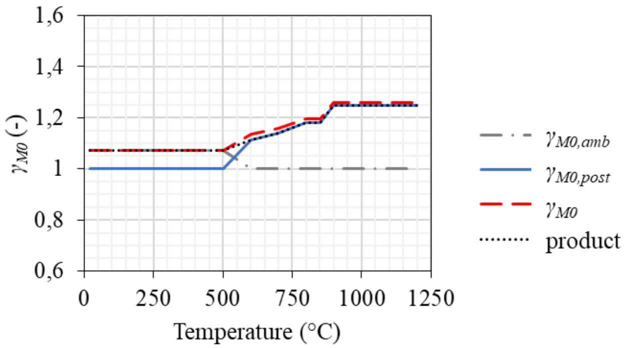
a



b



c



d

Molkens T., Rossi B., *The Post-fire Assessment of Steel Structures, a Reliability-Based Semi-probabilistic Approach*, Fire Technology, 12th of August 2022.

Application

- **Final assessment formula:**

$$f_{yd,post} = \frac{R_\theta \times f_{y,k}}{\gamma_{M0,post} \times \gamma_{M0,amb}}$$

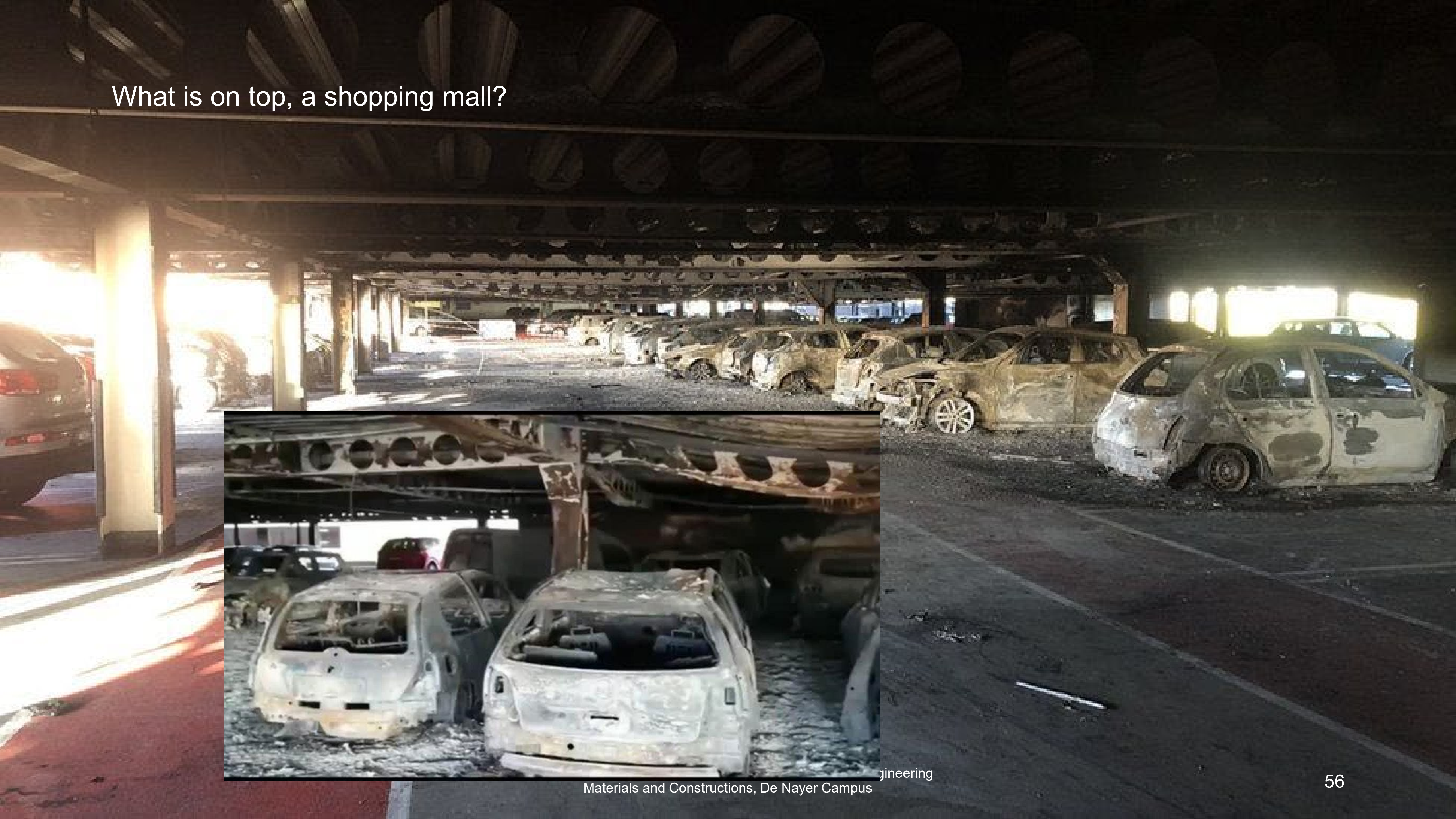
- Worked examples

Carbon steel S235	Austenitic stainless steel 1.4301
Column 550°C	Column 550°C
Slide 49 → $R_{y,\theta,NSS}$ = 1.00	Slide 52 → smallest $R_{y,\theta}$ = 0.97
Slide 57 → $\gamma_{M0,post}$ = 1.0	Slide 58 (a) → $\gamma_{M0,post}$ = 1.1
$f_{yd,\theta}$ = 1×235/(1.0×1.0) = 235 MPa	$f_{yd,\theta}$ = 0.97×210/(1.0×1.1) = 185 MPa
Roof beam 750°C	Roof beam 750°C
Slide 49 → $R_{y,\theta,NSS}$ = 0.79	Slide 52 → $R_{y,\theta}$ = 0.95
Slide 57 → $\gamma_{M0,post}$ = 1.15	Slide 58 (a) → $\gamma_{M0,post}$ = 1.00
$f_{yd,\theta}$ = 0.79×235/(1.15×1.0) = 161 MPa	$f_{yd,\theta}$ = 0.95×210/(1.0×1.1) = 181 MPa

Faculty of Engineering Technology, Department of Civil Engineering
Materials and Constructions, De Nayer Campus
KU LEUVEN

Conclusions

- A simple, but scientifically based, fast procedure is proposed. The assessment of a post-fire situation follows the same methodology as for the design for new buildings by the application of a combination of safety and reduction factors.
- Several outcomes are possible: the reliability is still ensured, or small modifications are needed either at the load level, either at the structural level, or only dismantling and recycling is the latest option.
- Stainless steel seems to perform better in post-fire situations at higher temperatures which makes the material better suitable for critical elements or elements which are difficult to replace.



What is on top, a shopping mall?

Q&A

- Thank you for your kind attention

- Further information: tom.molkens@kuleuven.be