Reliability and probability of failure in structural fire safety engineering

An introduction

Ruben Van Coile

UNIVERSITEIT GENT

WSP | PARSONS BRINCKERHOFF

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I. Why use probabilistic calculations?

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Perfect safety does not exist

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It’s the basis of the Eurocodes and BS

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1990:2002+A1

December 2005

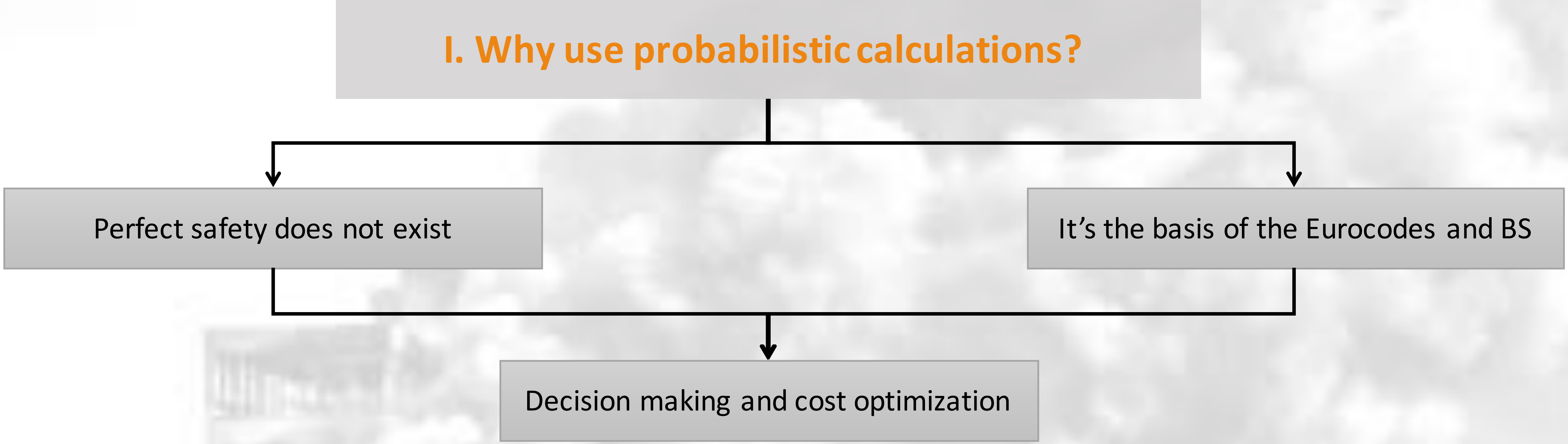
Supersedes ENV 1991-1:1994
Incorporating corrigenda December 2008
and April 2010

English version

Eurocode - Basis of structural design

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

I. Why use probabilistic calculations?

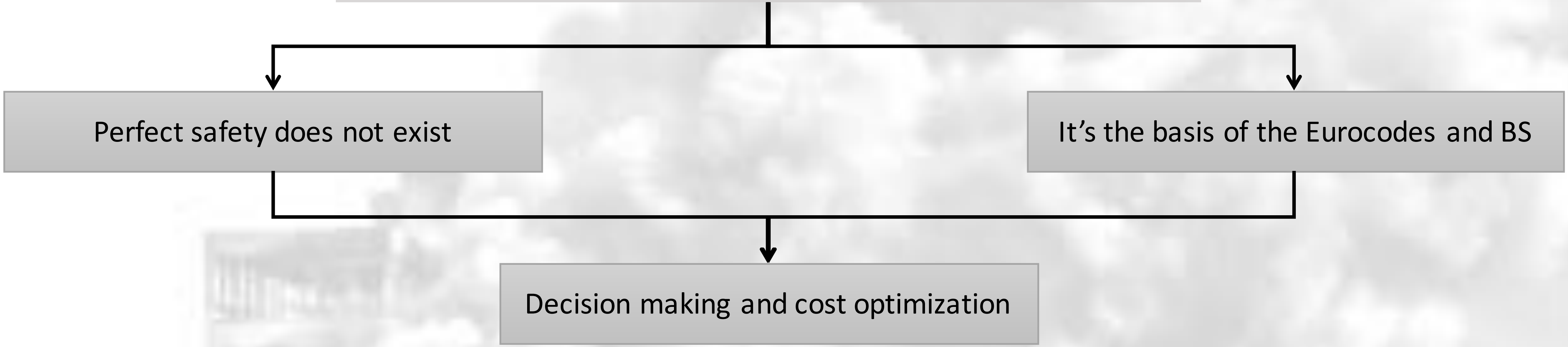


Perfect safety does not exist

It’s the basis of the Eurocodes and BS

Decision making and cost optimization

I. Why use probabilistic calculations?



Perfect safety does not exist

It’s the basis of the Eurocodes and BS

Decision making and cost optimization

II. Basic concepts for calculating failure probabilities

III. Discussion

Perfect safety does not exist

Every structure or structural element
has a probability of failure

The load effect exhibits random variations

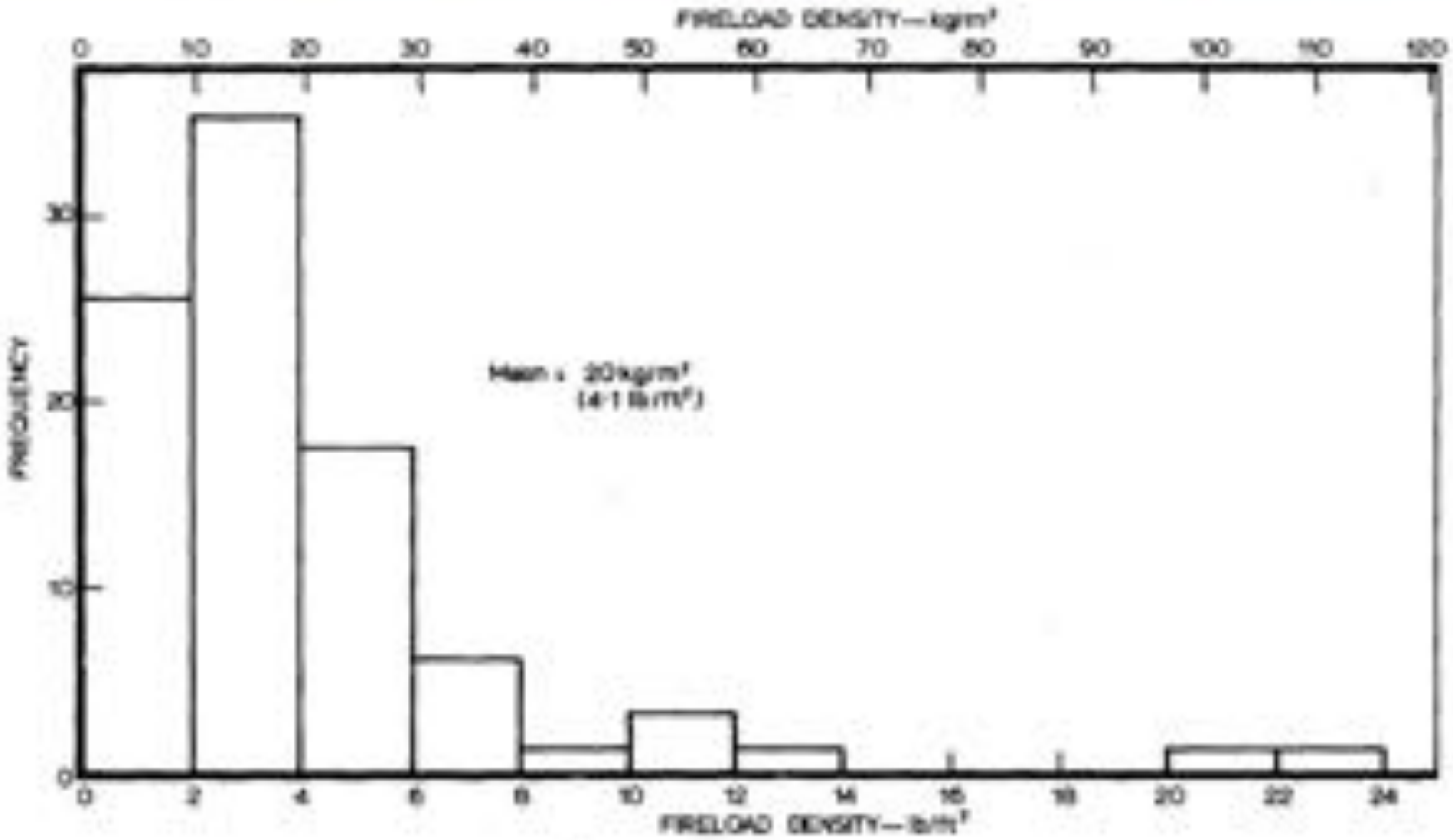


FIG. 5. FREQUENCY DISTRIBUTION OF FIRELOAD DENSITY—FIRELOAD PER UNIT FLOOR AREA

(Baldwin et al., 1970)

Material properties exhibit random variations

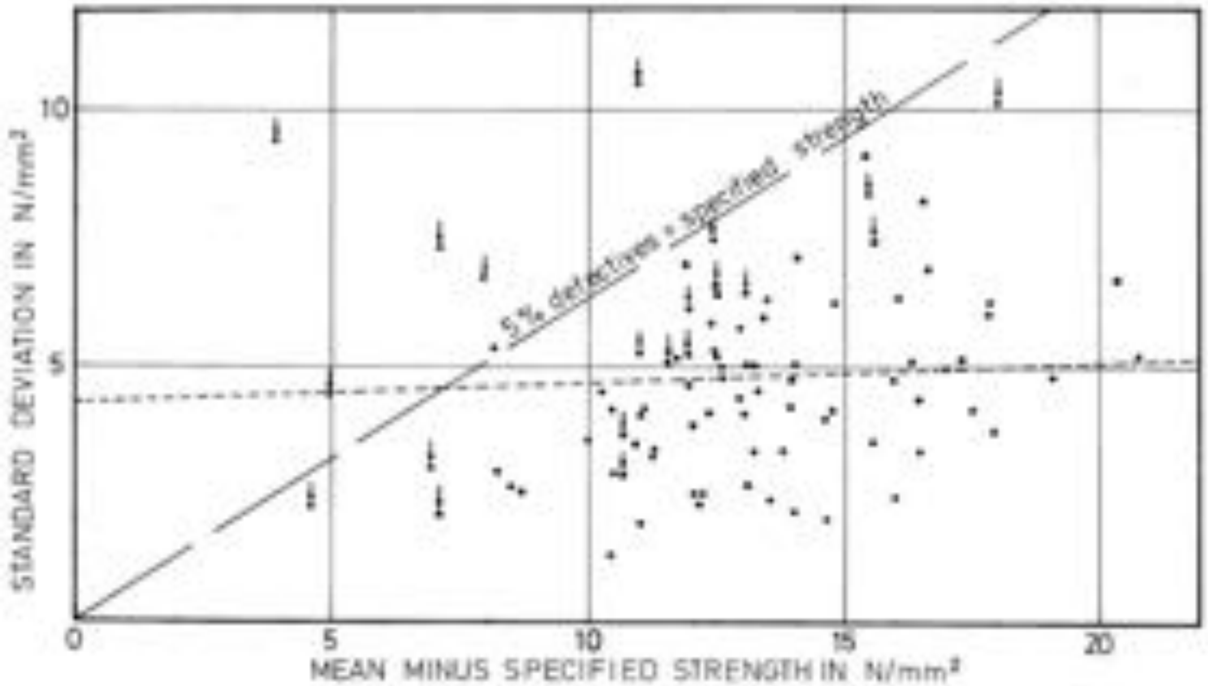
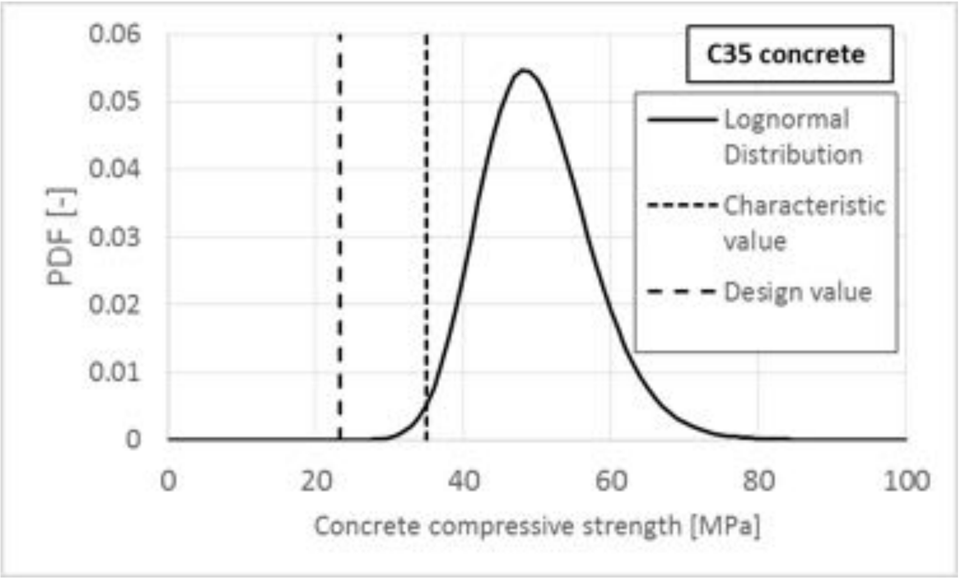


Figure II.2: Observed mean minus specified strength and standard deviation of standard cube strength of 88 production units of concrete grade C35 (Rackwitz 1983)

(Caspeele, 2010)



Engineering models and calculation tools are imperfect

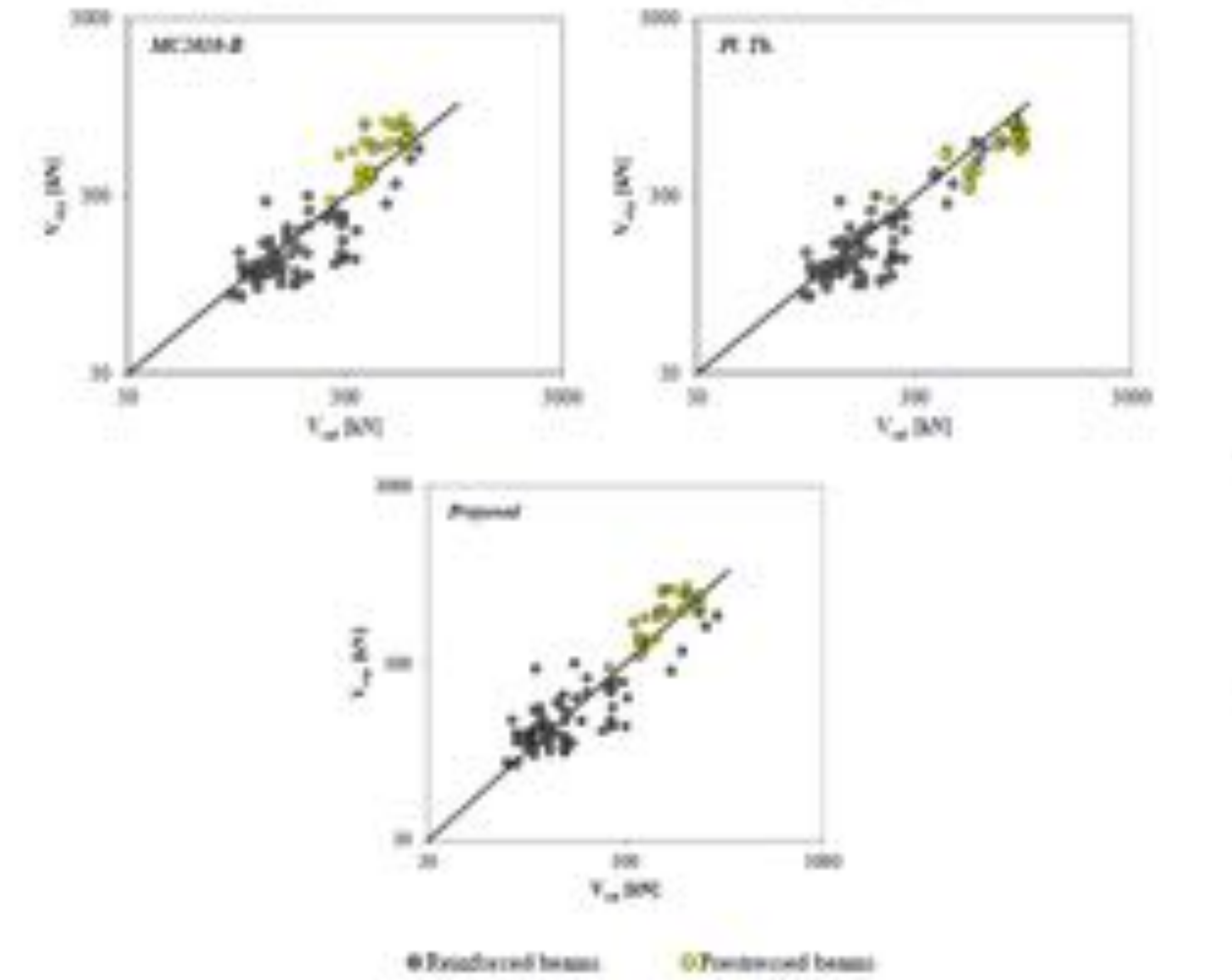
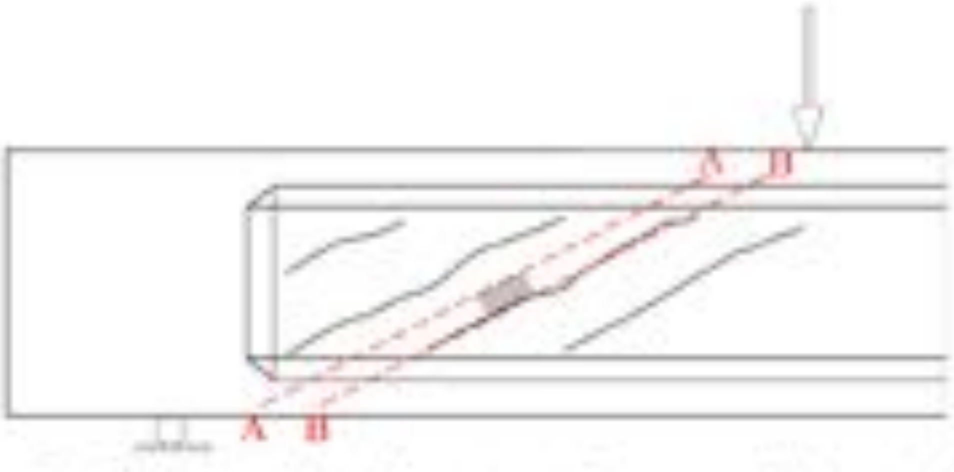


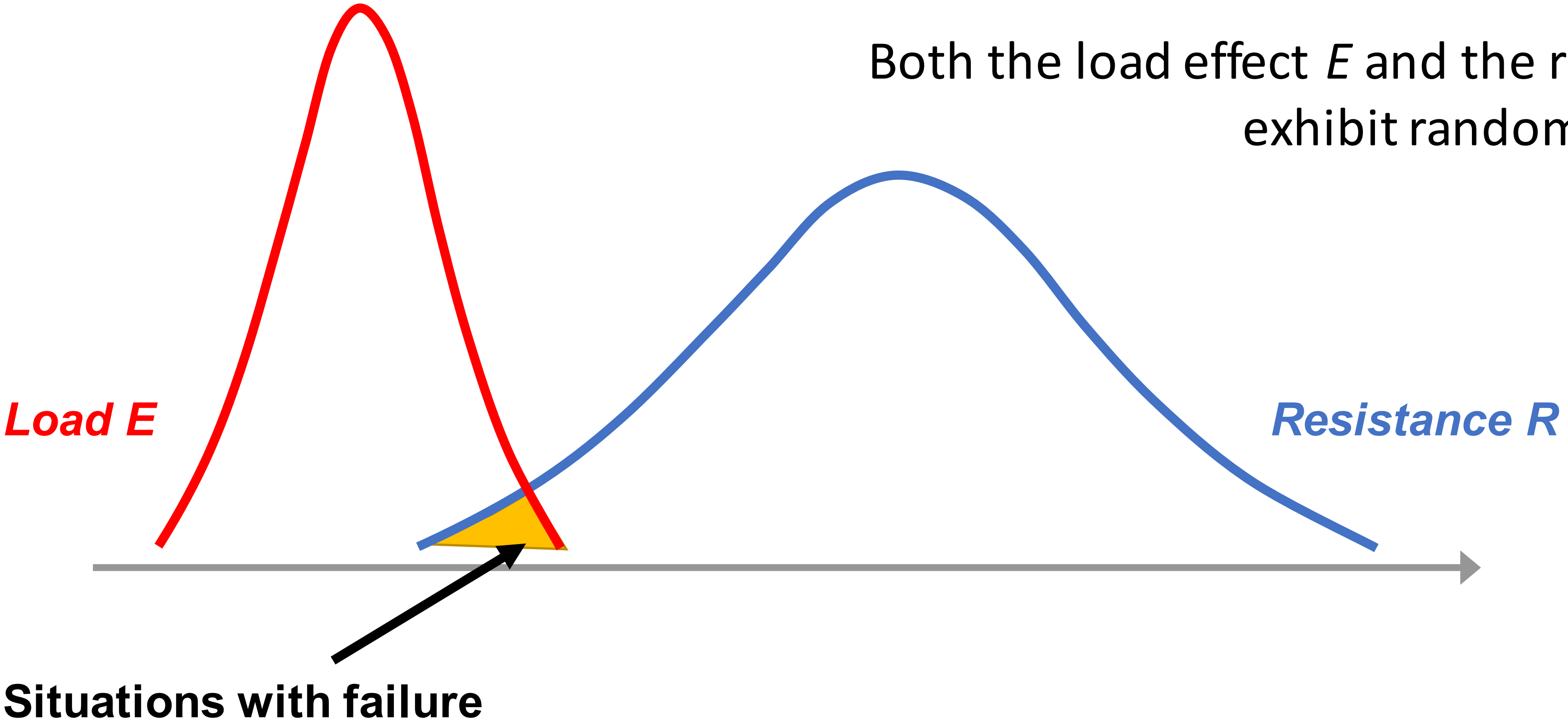
Fig. 7.2 – Comparison between experimentally obtained (V_{exp}) and calculated shear capacity (V_{cal}) of FRC beams



(Soetens, 2015)

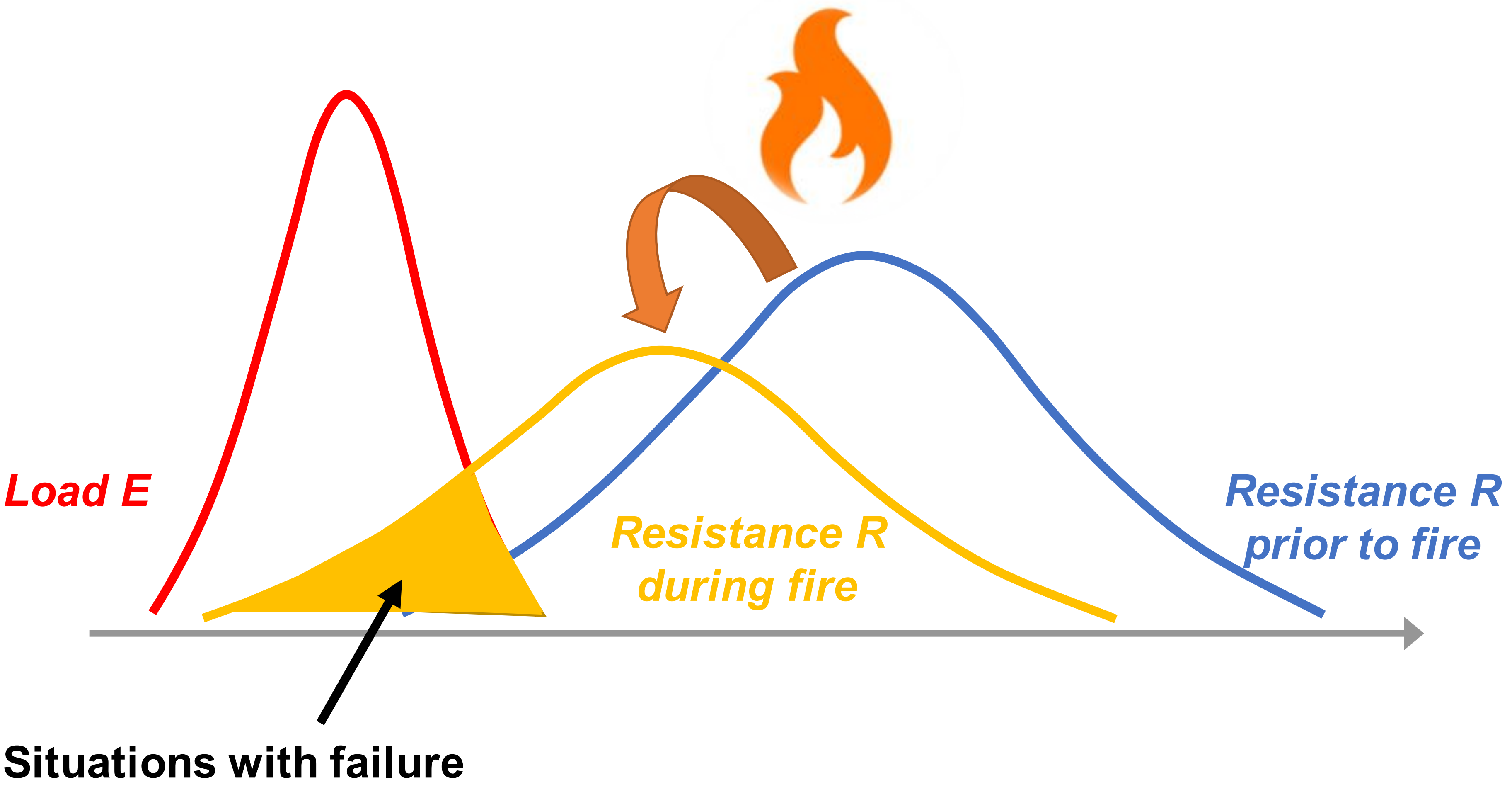
Thus:
Even for a good design, the load E may be larger than the resistance R

Both the load effect *E* and the resistance *R* exhibit random variations



Thus:

Even for a good design, the load E may be larger than the resistance R



Limiting the probability of failure by design

The basis of the Eurocodes

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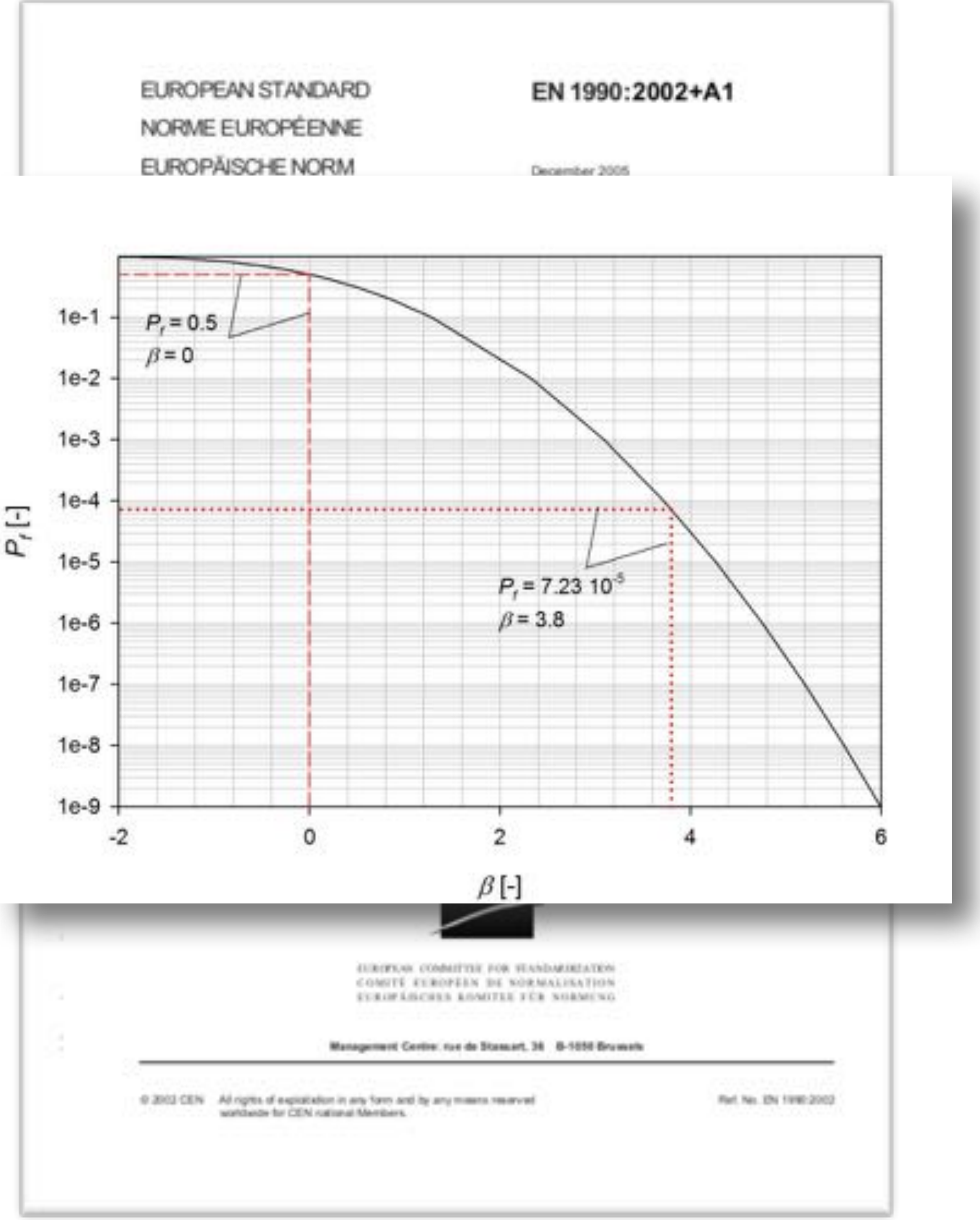
Eurocode - Basis of structural design

The Eurocode specifies a target safety level / failure probability



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Target reliability index in function of the consequences of structural failure (normal design conditions)

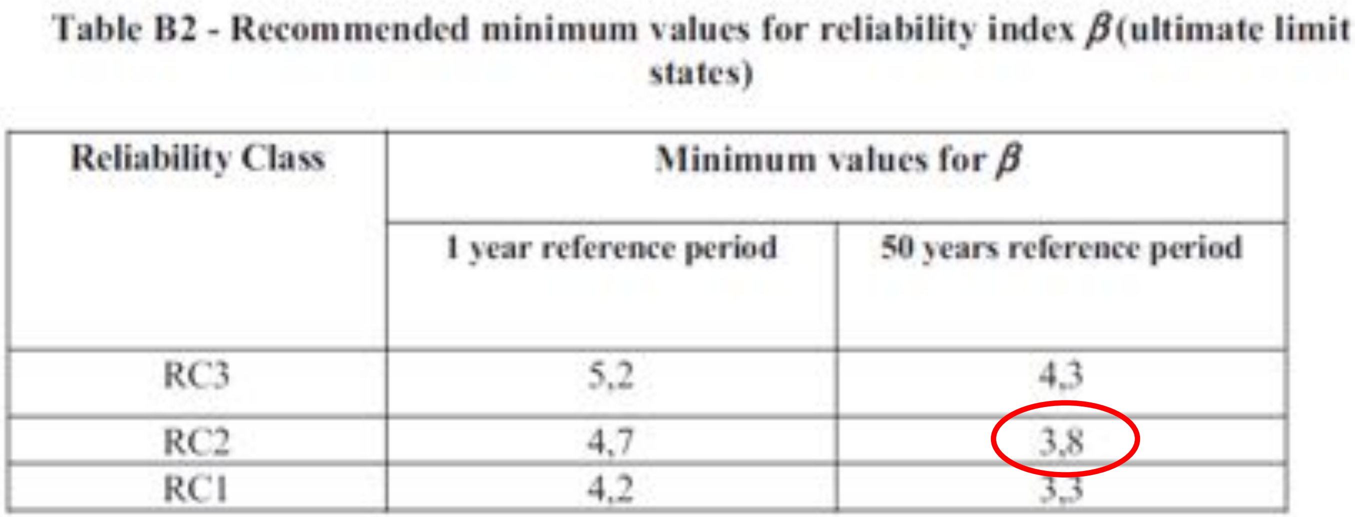


Table B2 - Recommended minimum values for reliability index β (ultimate limit states)

Reliability Class	Minimum values for β	
	1 year reference period	50 years reference period
RC3	5,2	4,3
RC2	4,7	3,8
RC1	4,2	3,3

- Eurocode partial safety factors derived from the target safety level
- Application of Eurocode design rules results in a safety level of 3.8
  (generally slightly higher because of conservatism)

Unfortunately, no target is specified for structural fire safety

But options do exist

- Target reliabilities in the European Natural Fire Safety Concept (background documents)
- Back-calculating the BS target reliability index for specific cases
- Cost-optimization:
  What is the optimum level of structural fire resistance?

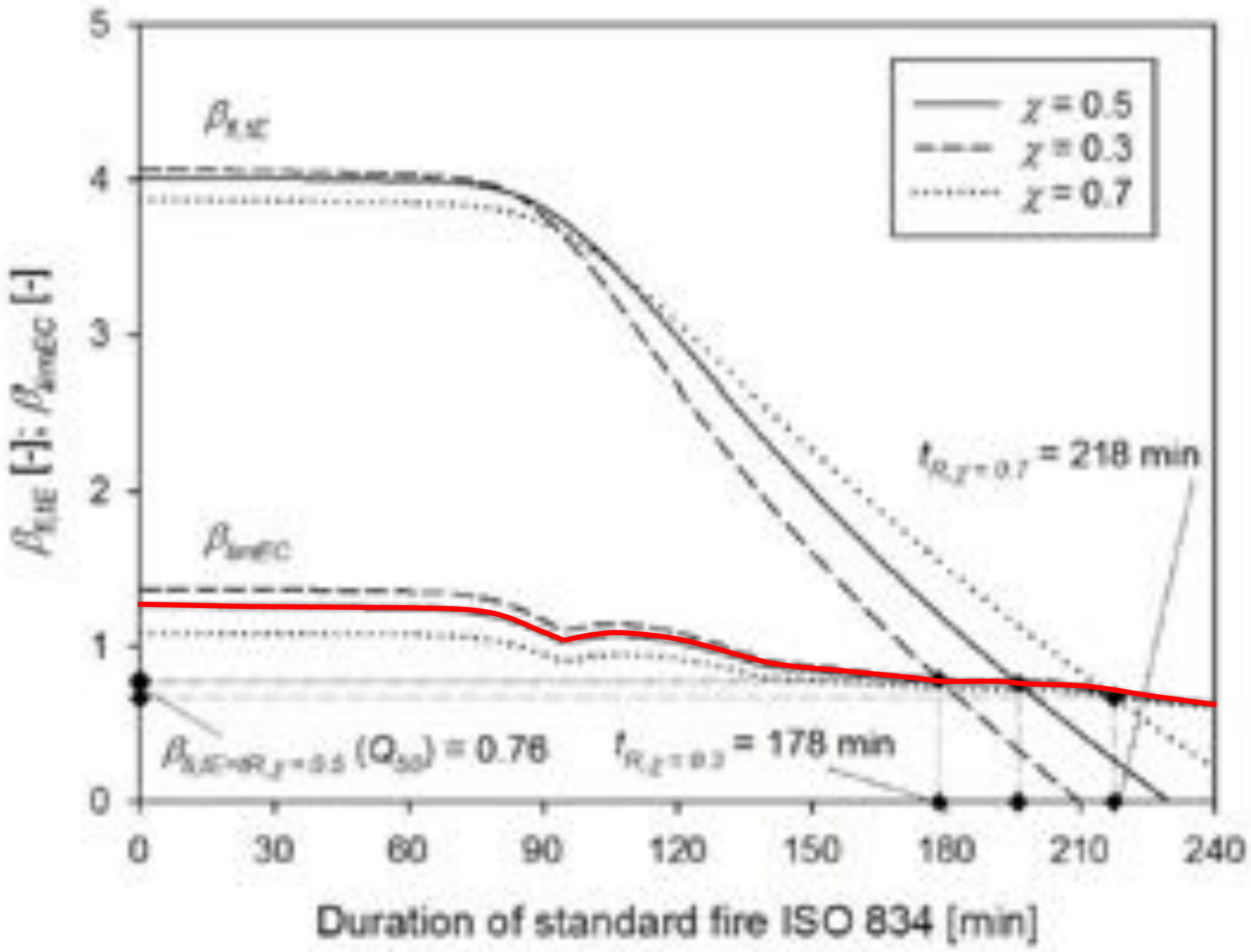


Figure V.25: β_{limEC} and $\beta_{fi,tE}$ for slab type A. 50 year reference period for Q, indication of t_R and $\beta_{fi,tR}$. (Van Coile, 2015)

Is there an optimum level of investment in structural fire safety?

Decision making and cost optimization

Is there an optimum level of investment in structural fire safety?

Utility function: $Y(p) = B(p) - C(p) - D(p)$ p = the optimization parameter

Benefit function

Initial construction cost

Expected costs due to failure and partial damage

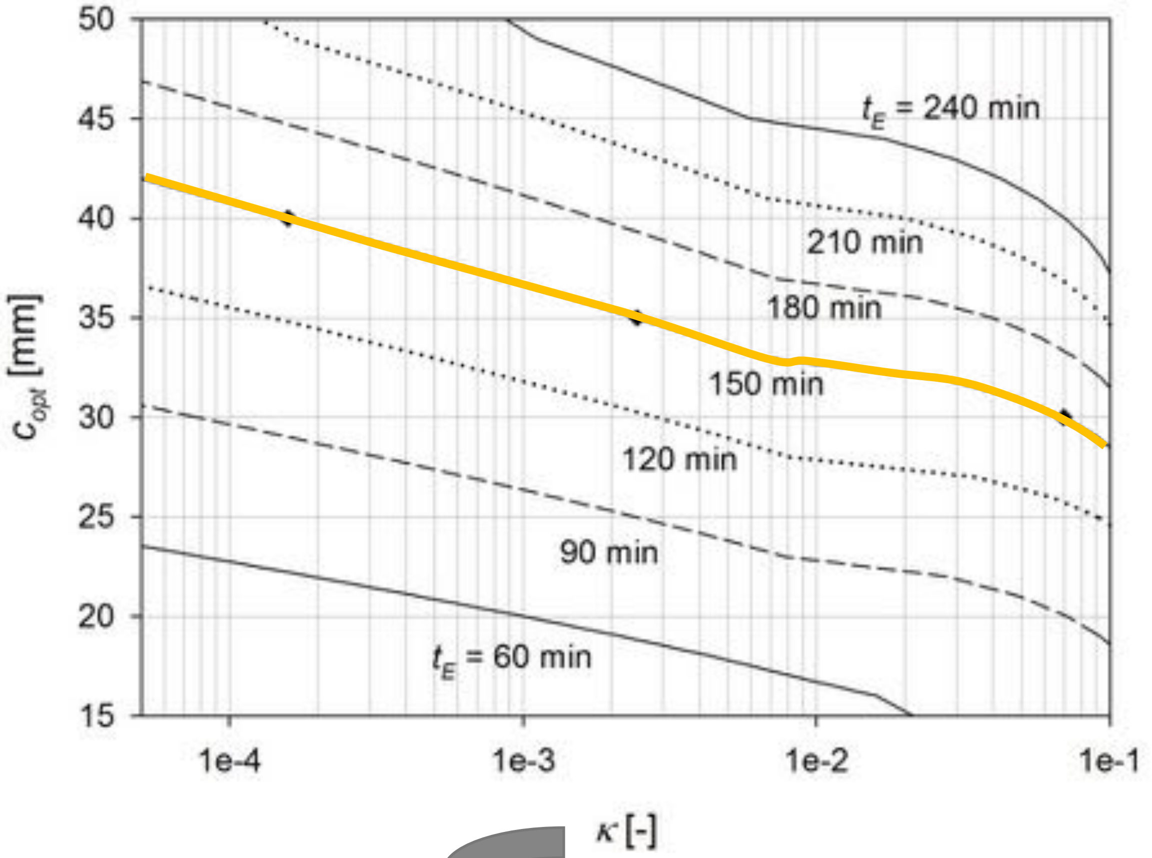
Includes

- [Annual] Probability of a fully developed fire (λ^*)
- **Probability of failure** given a fully developed fire ($P_{f,fi}$)
- Failure costs and repair/reconstruction costs in case of partial damage (ξ)

Optimization criterion: Maximize Y

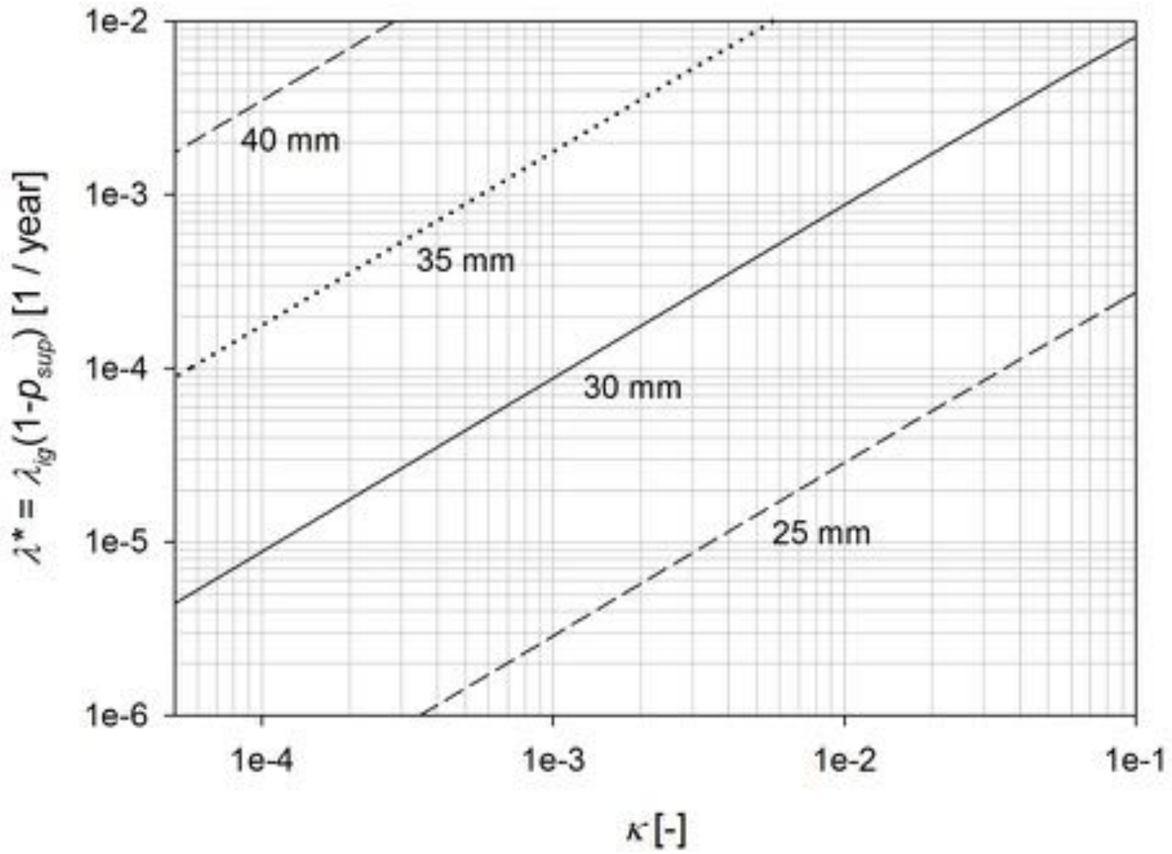
Is there an optimum level of investment in structural fire safety?

ISO 834 fire exposure, given λ*



Safety investment cost factor

120 min ISO 834 fire exposure



But cost-optimization is no silver bullet

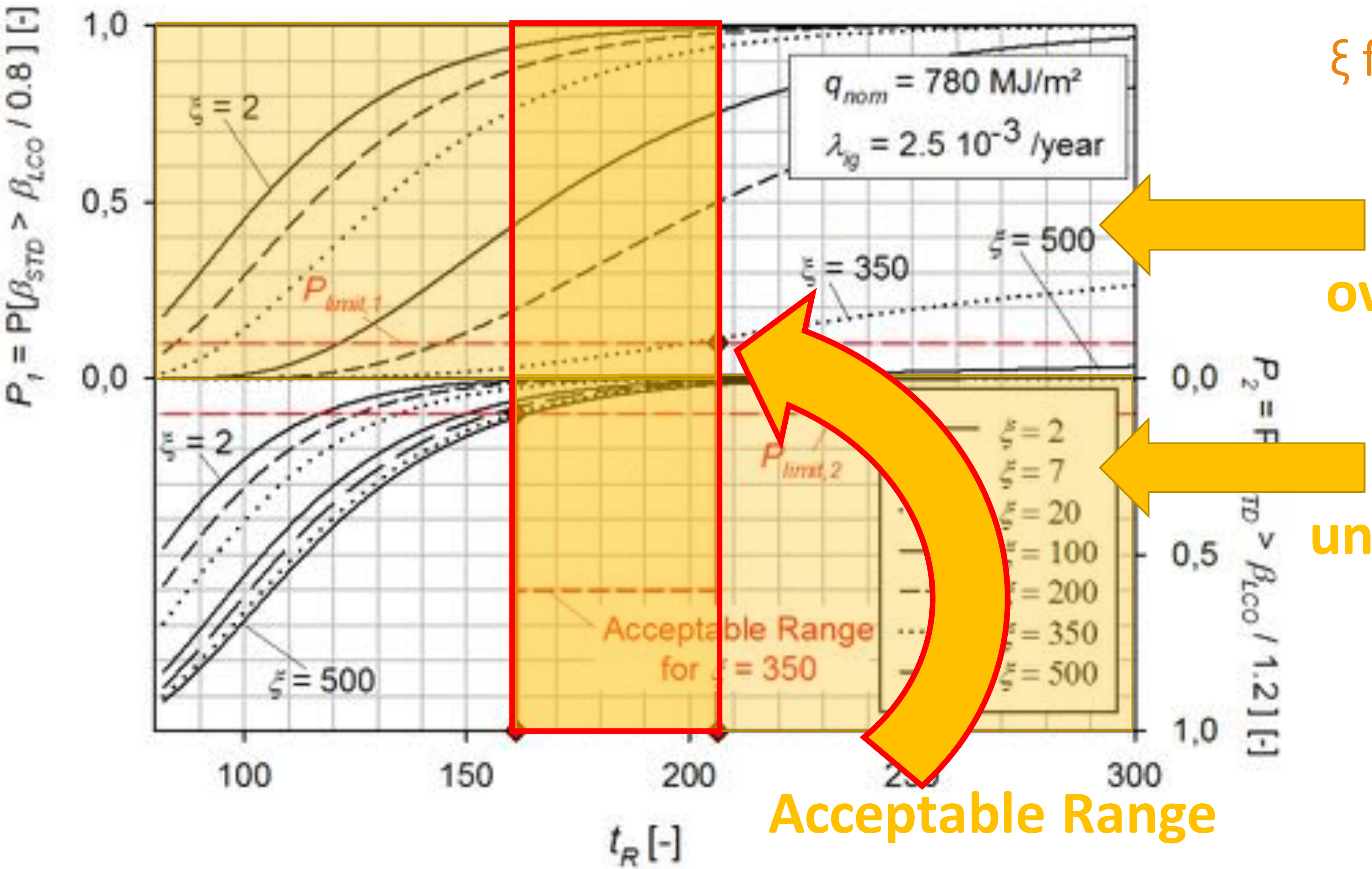
- Parameters of cost-optimization are uncertain
- Stakeholders may not all agree on each input parameter
- Case specific evaluations are not always feasible → need for general rules

→ Determine an Acceptable Range for the structural fire resistance time

Based on results of cost-optimization, i.e.

- **failure probabilities**
- fire ignition frequencies
- failure costs…

An acceptable range for the structural fire resistance time



ξ failure cost ratio

ξ = 350

Avoiding overinvestment

Avoiding underinvestment

Acceptable Range

Basic concepts for calculating failure probabilities

A conceptual introduction

The limit state function Z

How do you define failure?

<u>General formula</u>

$$Z = R - E$$

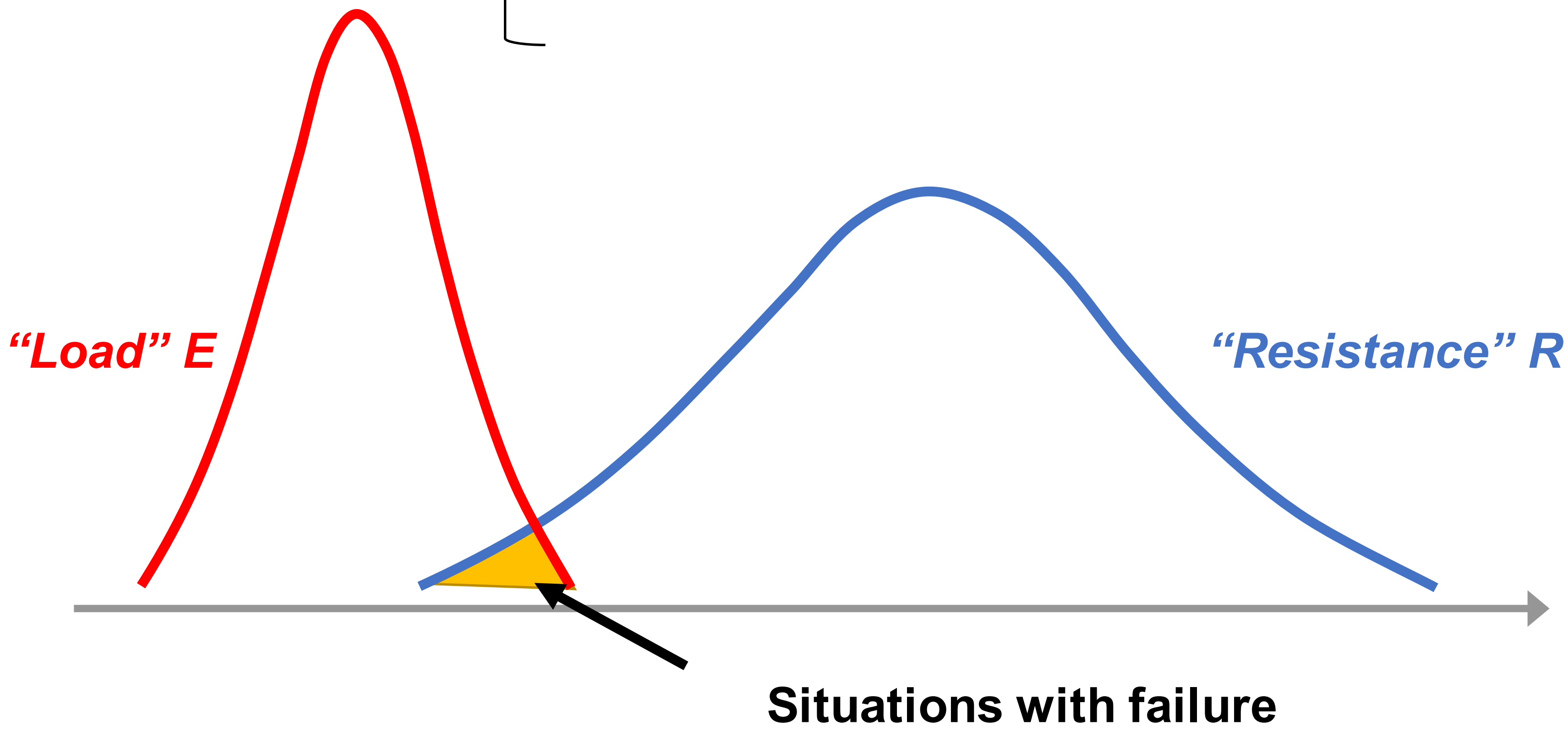
Failure $Z = R - E < 0$

Safe/Success $Z = R - E \geq 0$

Use Monte Carlo methods

$$P_f = I[Z = R - E < 0]$$

Or evaluate/know the PDF



The limit state function Z

Application to fire-exposed structural members: cross-section based

General formula

$$Z = R - E$$

Pure Bending

$$Z = K_R \underline{M_{R,fi,t}} - K_E\left(M_G + M_Q\right)$$

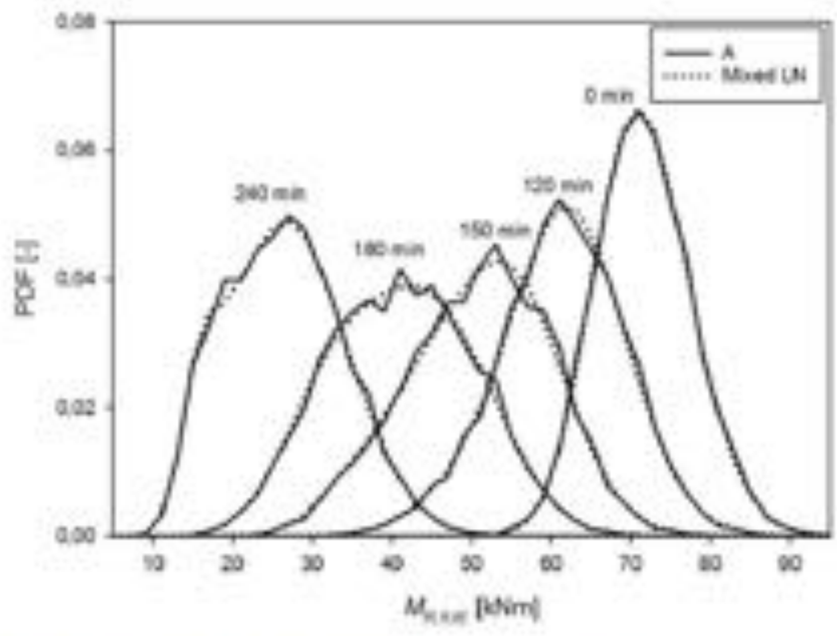


Figure III.6: Observed histogram 'A' of $M_{R,fi,t,pos}$ for different ISO 834 durations t_E and mixed-lognormal approximation 'Mixed LN' according to (III.10), slab type A.

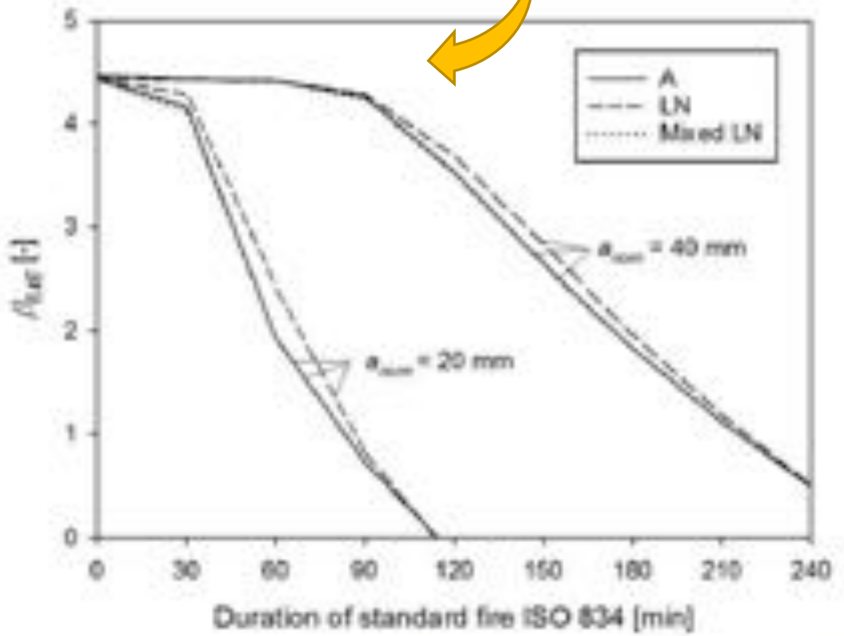


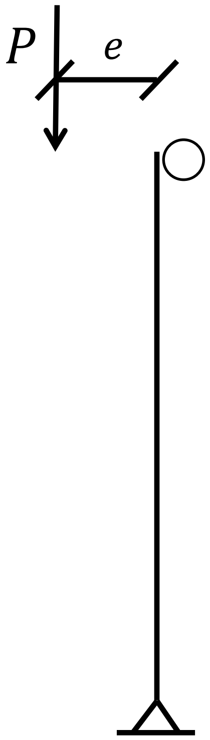
Figure III.17: $\beta_{fi,t}$ for slab type A with μ_c = 15 mm (a_{nom} = 20 mm) and μ_c = 35 mm (a_{nom} = 40 mm), σ_c = 5 mm, calculated with the histogram 'A', the lognormal 'LN' and mixed-lognormal approximation 'Mixed LN', $\chi = 0.5$.

The limit state function Z

Application to fire-exposed structural members: advanced models (2nd order effects)

General formula

$$Z = R - E$$



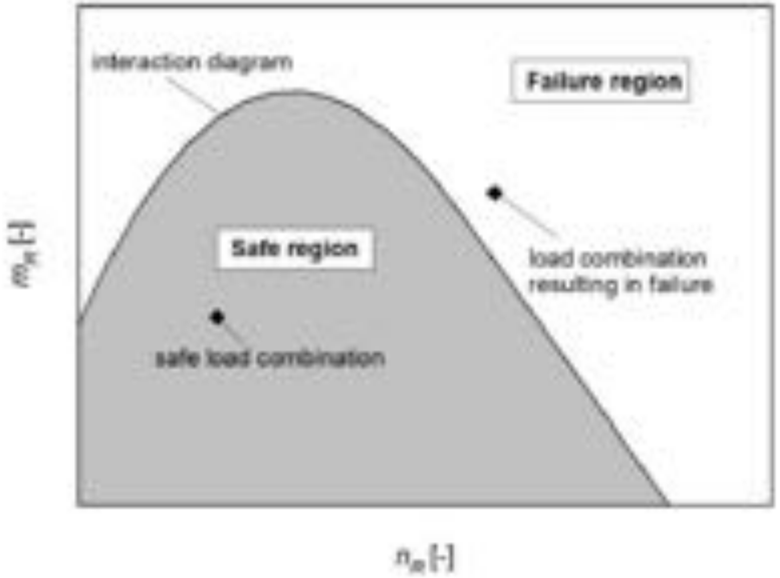


Figure III.54: Conceptual visualization of the failure region and the safe region for a single realization of the interaction diagram.

But the moment m_E depends on the deflection…

Doomed to computationally expensive Monte Carlo?

A detour to a feasible calculation method…

*Even for very complex models, the PDF of a **scalar model output Y** can be approximated "quickly"*

<u>Simple example</u>

$$Y = 2\frac{X_1 X_2}{X_3}$$

With:
X_1 : LN(3; 0.3)
X_2 : LN(4; 0.5)
X_3 : LN(2; 0.2)

Y: LN(12.48; 0.646)

10000 MCS

Analytical result

PDF approximation from 13 model realizations

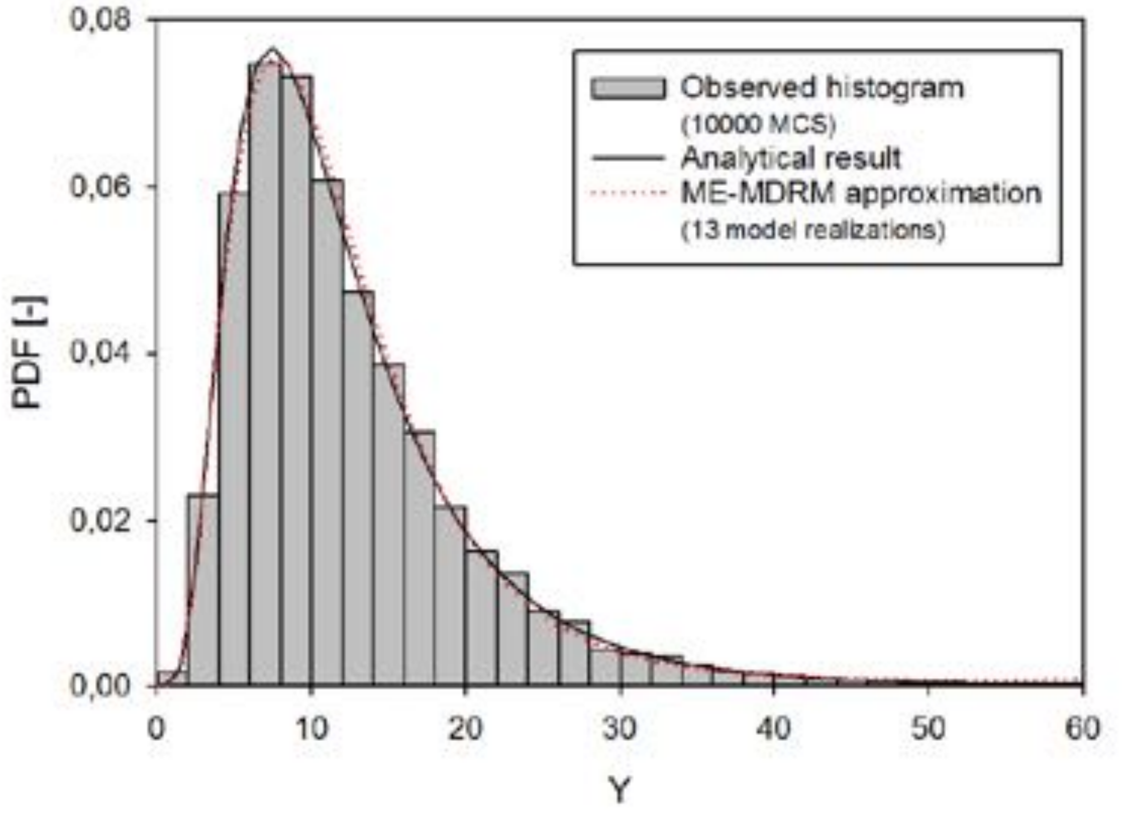


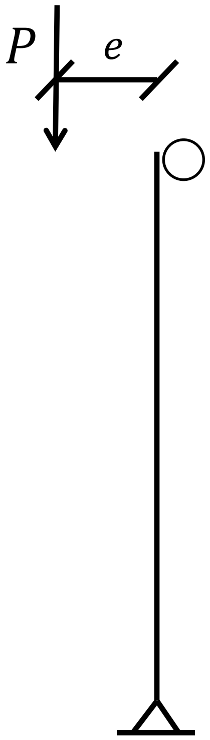
Figure 2. CDF for Y: Analytical result and ME-MDRM result. Comparison with observed cumulative frequency of 10000 MCS.

The limit state function Z

Application to fire-exposed structural members: advanced models (2^{nd} order effects)

General formula

$$Z = R - E$$



As there a scalar model output which is representative for the resistance R ?

For every column realization there is a maximum load P_{max}
(taking into account 2^{nd} order effects)
= run model to failure

10000 MCS

PDF approximation from 25 model realizations

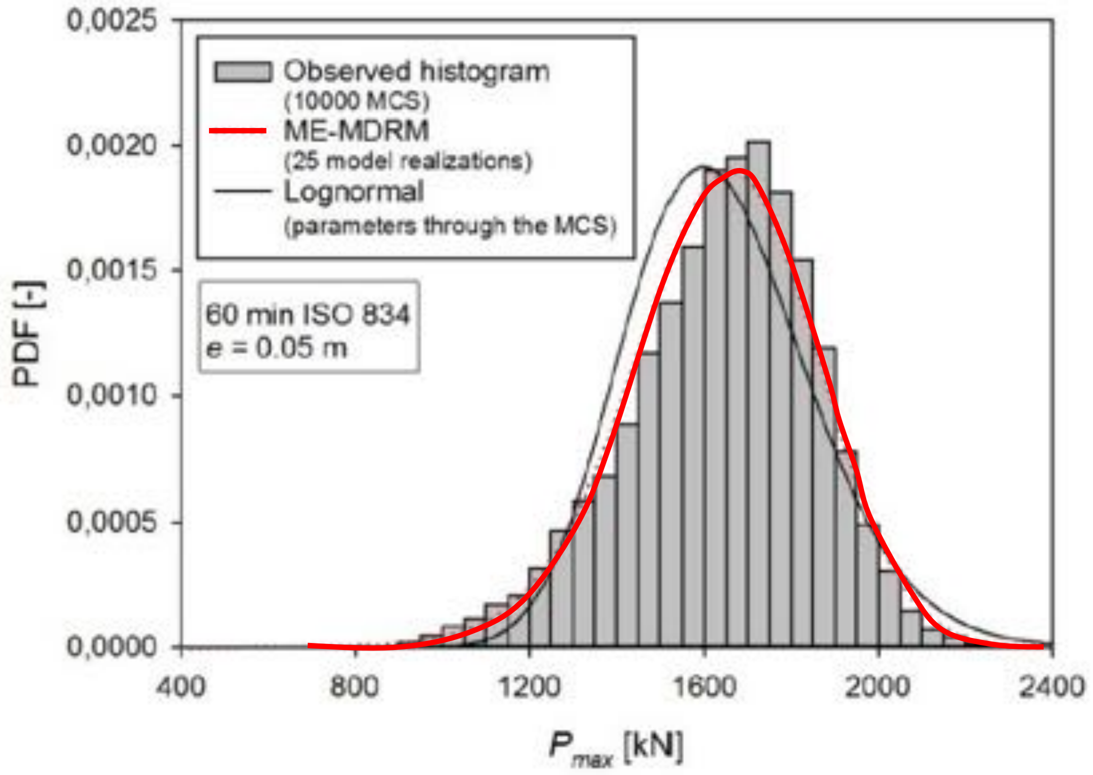


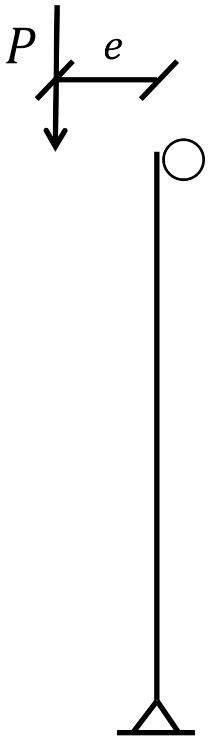
Figure 4. ME-MDRM result for CDF describing P_{max} at 60 minutes ISO834 for $e = 0.05$ m, and comparison with histogram of 10000 MCS, and a lognormal approximation (with parameters based on the MCS).

The limit state function Z

Application to fire-exposed structural members: advanced models (2nd order effects)

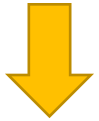
General formula

$$Z = R - E$$



Eccentric loading incl. 2nd order

$$Z = K_R P_{max,fi,t} - K_E \left(P_G + P_Q\right)$$



Failure probability evaluation feasible
with PDF of P_{max} approximated

Discussion

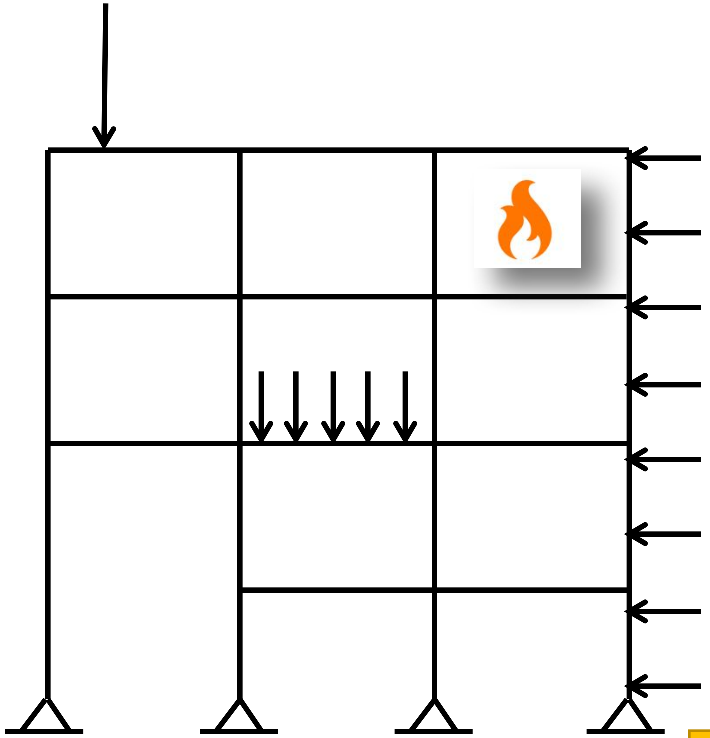
How to define “failure” for structural systems exposed to fire?

Need to define a limit state function Z

And determine a representative scalar model output Y

<u>General formula</u>

$$Z = R - E$$



<u>Options</u>

1. Run the model for **ISO 834 exposure** till failure → t_R

$$Z = K_R t_R - K_E t_E$$

2. Run the model for increasing **fire load** till failure → q_{max}

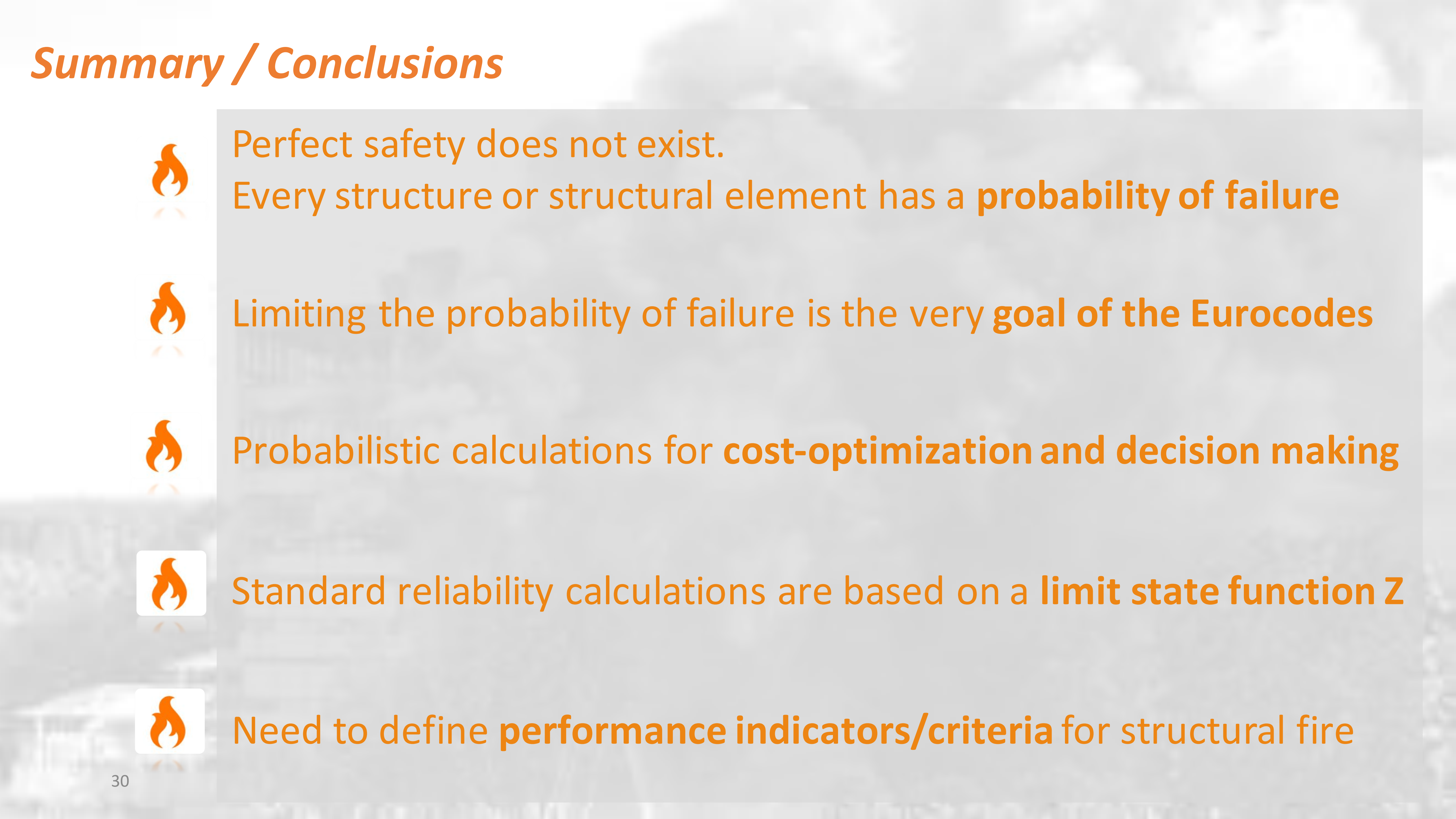
$$Z = K_R q_{max} - K_E q_E$$

3. Determine a **representative failure indicator** → e.g v_{max}

$$Z = K_R v_{max} - K_E v_{limit}$$

→ To apply reliability concepts to structural systems exposed to fire, we need a "performance indicator/criterion"

Summary / Conclusions



- Perfect safety does not exist.
  Every structure or structural element has a **probability of failure**
- Limiting the probability of failure is the very **goal of the Eurocodes**
- Probabilistic calculations for **cost-optimization and decision making**
- Standard reliability calculations are based on a **limit state function Z**
- Need to define **performance indicators/criteria** for structural fire

Thank you for your attention !