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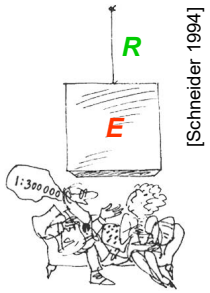
180th STUFIB LECTURE EVENING
Delft / Online. 11-10-2023

ASSESSMENT OF CONCRETE STRUCTURES – EXPERIENCES AND OUTLOOK

Peter Tanner



[Schneider 1994]

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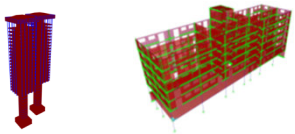
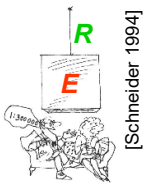
ANALYSIS AND VERIFICATIONS

– Design and assessment: determination of action *E*ffects and structural *R*esponse based on established engineering theory and practice

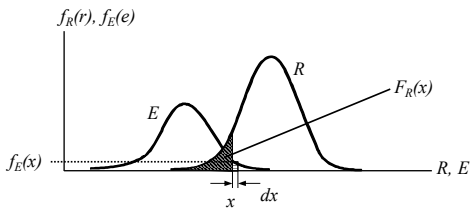


Who is who?

– General principles of structural reliability are also the same for design and assessment



[Schneider 1994]



$$ER = \int_{g(x)<0} C(x) \cdot f_X(x) \cdot dx \le ER_t$$

$$p_f = \int_{-\infty}^{\infty} f_E(x) \cdot F_R(x) dx \le p_{ft}$$

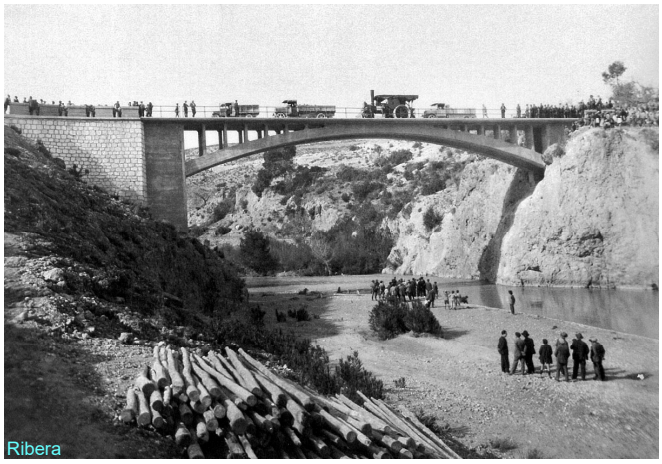
$$p_f = \Phi(-\beta) \rightarrow \beta \ge \beta_t$$

$$\gamma_E \cdot E_k \le \frac{R_k}{\gamma_R}$$

2

UNIQUE PROPERTIES OF ENGINEERING STRUCTURES

- Often, prototypes
- Typically, differences in environment, exposure conditions, …



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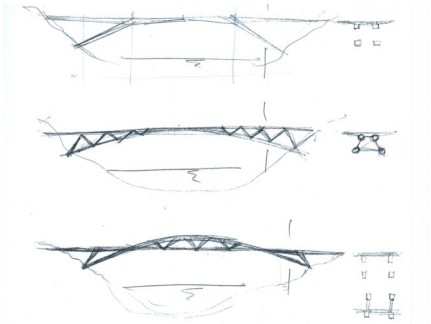
STRUCTURAL AND GEOTECHNICAL ENGINEERING

- Determination of ***E*** and ***R*** based on the same principles, both in design and assessment
- **Structural reliability** principles are of general validity
- **Case-specific conditions** for each individual structure



→ New or existing, does it matter from a technical perspective?

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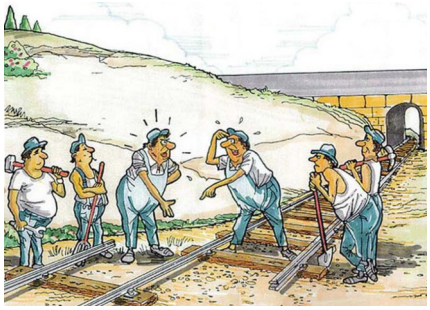
MOTIVATION

- General principles of structural engineering and reliability, usually specified in design standards, also apply to the assessment
- But important differences exist between design and assessment
- Design-oriented rules are conservative for assessment
  - Ecological
  - Economic
  - Socio-political consequences

→ Divergent approaches exist to deal with those differences depending on
  - National choices
  - Type of engineering work
  - Constitutive material

→ Harmonization needed



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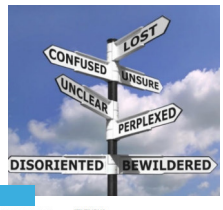
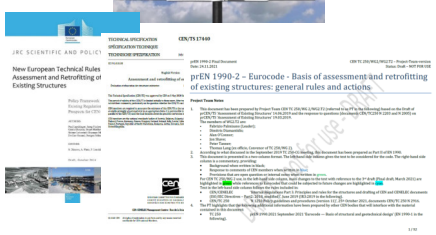
ASSESSMENT OF CONCRETE STRUCTURES – EXPERIENCES AND OUTLOOK

- Introduction
- Design, assessment and the Eurocodes
- Stadium refurbishment and extension
- Conclusions and discussion





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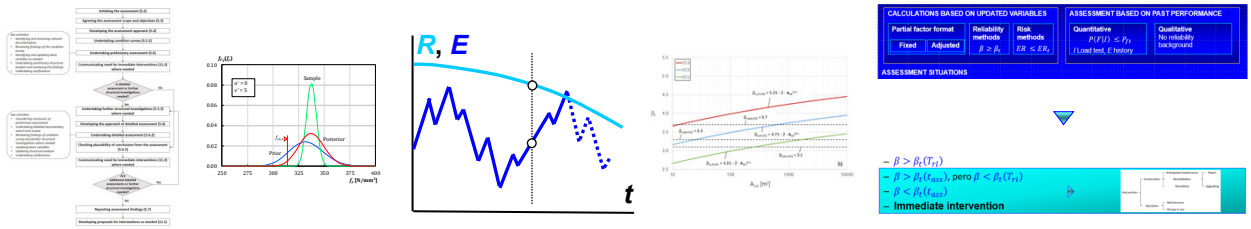
MAIN DIFFERENCES

- Focusing on reliability issues, both activities differ with regard to
  - State of information and its updating through distinct types of information
  - Structural condition, in particular concerning possible deterioration
  - Reliability requirements
  - Verification methods and formats
  - Multiple outcomes and decision options



- No general agreement on all aspects

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EVOLUTION

- First generation of Eurocodes, 2002 – 2007, intended for design
- Additional provisions required to allow assessment
- European technical rules for assessment and retrofitting planned for
  - All types of existing structures, including geotechnical aspects
  - All sorts of actions
- Priority: material independent rules on basis of assessment and actions
- Two exceptions
  - Rules for seismic assessment and retrofitting, already in first generation
  - Annex on assessment of concrete structures, prior to general rules
- CEN's work programme follows a step-by-step approach



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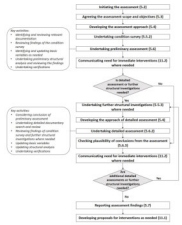
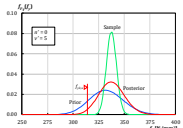
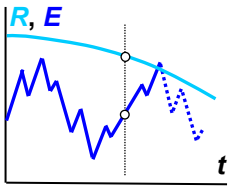
Technical Specification

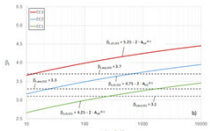
MILESTONES

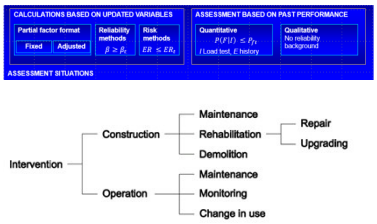
- **2015 JRC Science and Policy Report**
  - Policy framework
  - Existing regulations and standards
  - Prospect for CEN guidance
- **2020 Technical Specification**
  - Complements EN 1990
  - General rules and actions











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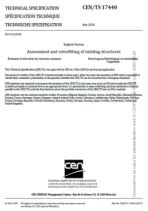
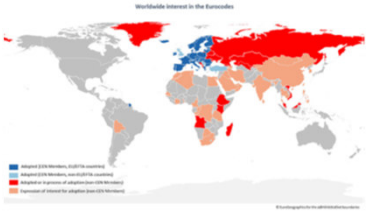
Technical Specification

STATUS

- **DAV** Date of availability **July 2020**
- **DOP** Date of publication **DAV + 6 months**
- **DOW** Date of withdrawal **DAV + 6 months**

  But: contradictory national rules may remain in force
- **National Annex allows for national choices, where indicated**
  - National Annexes are not mandatory for Technical Specifications
  - In this case, most countries chose not to prepare any NA at this stage
  - Only F and GB prepared NA





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Eurocode on basis of assessment and retrofitting of existing structures

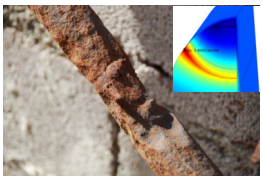
CURRENT STATE

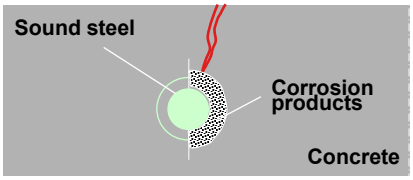
- **Decision 15 of CEN/TC250/SC10, 2019 → prEN 1990-2**

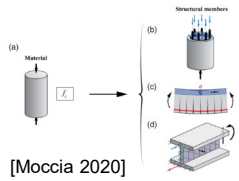
SC 10 (...) Agrees that the provisions developed by CEN/TC 250/WG 2 will be incorporated in EN 1990 and that WG 2 proceeds on the assumption that WG 2 will develop a Part 2 of EN 1990, on the condition that:

- *TC 250 and SC 10 national delegations decide their preferred way on the basis of the work of WG2.PT2,*
- *SC 10 Management Group in conjunction with CEN/TC 250/WG 2 completes the steps necessary to fulfill this plan.*

- **Development of 3 subtasks by specific Project Team**
  - **Conversion of CEN TS 17440:2020 into EN for Existing structures – General rules**
  - **Conversion of CEN TS 17440:2020 into EN for Existing structures – Actions**
  - **Report on requirements for the development of material-specific provisions**







[Moccia 2020]

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Eurocode on basis of assessment and retrofitting of existing structures

CURRENT STATE

- **prEN 1990-2 Project Team version available since November 2021**
- **Scope**
  - **Additional provisions to EN 1990-1 for assessment**
  - **Provisions for using updated information for basic variables, structural models and failure probabilities**
  - **Principles for assessment of structures in case of retrofitting**
- **Content limited to basic, assessment-specific reliability issues**

- **Decision 21 of CEN/TC250/SC10, April 2023 → prEN 1990-2**

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Eurocode on basis of assessment and retrofitting of existing structures

GUIDANCE FOR THE DEVELOPMENT OF MATERIAL-SPECIFIC PROVISIONS

- Project Team version available since November 2021
- Contents

INTRODUCTION
1 Scope of the document
2 Assumptions
3 References
PART A
A.1 General rules for drafting
A.2 Assessment of structural resistance
A.3 Establishment of default probabilistic models (and characteristic values) for resistance variables
A.4 Information update related with resistance variables
A.5 Testing of material properties and specification of material partial factors
A.6 Partial factors associated with the uncertainty of resistance models
A.7 Deterioration
A.8 Rehabilitation
A.9 Structural analysis for assessment

PART B

Sections and sub-sections of the document on existing structures	Reference to sections/clauses of part A[a)]
1 Scope	
1.1 Scope of the document	
1.2 Assumptions	
2 Normative references	
3 Terms, definitions and symbols	
3.1 Terms and definitions	
3.2 Symbols and abbreviations	
4 Basis of assessment and retrofitting design	
4.1 Requirements	
4.2 Basic variables	A.3, A.4.2, A.6.2, A.6.3, A.7.2, A.7.3, A.8
4.3 Verification by the partial factor method	A.5.1, A.5.4, A.6.1, A.6.2, A.6.3, A.7.2, A.7.3, A.8
5 Material and product properties	A.3, A.4.2
5.1 Materials and products covered by the Eurocodes	A.3, A.4.2, A.4.3, A.5.1, A.5.2, A.5.3, A.8
5.2 Materials and products not covered by the Eurocodes	A.3, A.4.2, A.4.3, A.5.1, A.5.2, A.5.3, A.8
6 Deterioration models	A.3, A.4.1, A.7
7 Structural Analysis	
7.1 Structural analysis for assessment	A.9
7.2 Structural analysis for retrofitting	A.8, A.9
7.3 Assessment and design assisted by testing	A.6.3
8 Ultimate Limit States	
8.1 Resistance models for assessment	A.2, A.3, A.4.2, A.4.3, A.7.1, A.7.2
8.2 Resistance models for retrofitting	A.2, A.3, A.4.2, A.4.3, A.7.1, A.7.2, A.8
9 Serviceability Limit States	A.8
10 Fatigue	A.5.1, A.7.3, A.8
11 Detailing	
11.1 Assessment of detailing	A.2
11.2 Detailing for retrofitting	A.2, A.8

[a)] Section A.1 applies to the entire document on existing structures.

Common structure of Annexes / Parts

Reference to Part A

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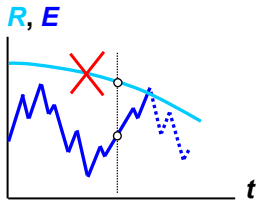
Concrete structures

EXISTING STRUCTURES IN EUROCODE 2

- FprEN 1992-1-1:2023 Annex I *Assessment of existing structures*
- Scope
  - Additional rules for aspects not covered in the design part: materials, detailing, bond of plain bars
  - Generic considerations for deterioration
- In case of deterioration, assessment should consider
  - Reduced concrete section
  - Reduced area and ductility of reinforcement
  - Stress concentration due to corrosion and stress corrosion
  - Reduced concrete – steel bond
  - Loss of mechanical properties of concrete
  - Cracking or expansion of concrete

→ No prediction rules for deterioration rates



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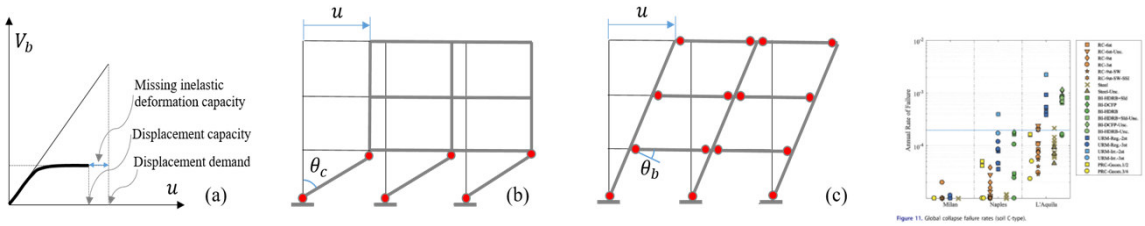
EXISTING STRUCTURES IN EUROCODE 8

- Seismic assessment and retrofitting are outside the scope of Eurocode prEN 1990-2
- Topic already covered in the first generation of Eurocode 8
- Evolution within the framework of the second generation, prEN 1998-3
  - Rules on updating information
  - Non-linear methods as default
  - Partial factors based on knowledge levels



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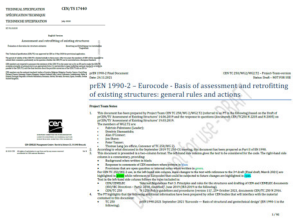
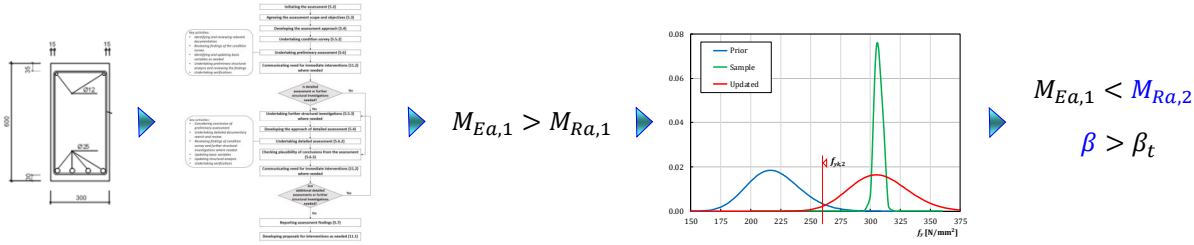
SUMMARY OF THE CURRENT SITUATION

- Scope and contents of TS 17440 and prEN 1990-2 limited to reliability aspects specific to assessment and retrofitting
- Few operational rules, but sufficient in many cases
- Examples in the Background Document to prEN 1990-2





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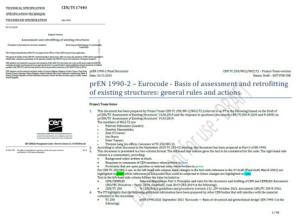
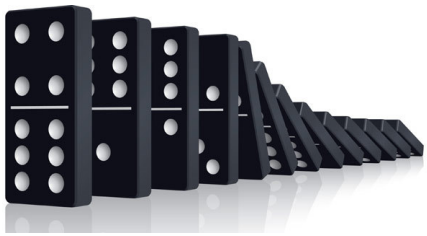
SUMMARY OF THE CURRENT SITUATION

- In other cases, the consistent application of such generic rules requires
  - Assumptions
  - Case-specific developments
- → Example from practice





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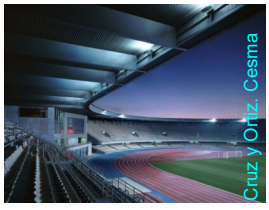

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Context

RELIABILITY OF STRUCTURAL SYSTEMS

– Redistributions due to local failure may lead to successive collapse of other components

→ Structures should not only meet specified safety, serviceability and durability requirements, but should also be robust

– To avoid progressive collapse, codes require that consequences of damage should not be disproportionate to original cause

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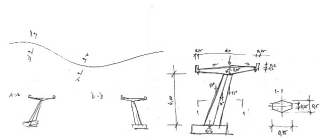
Context

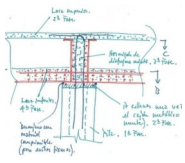
ROBUSTNESS

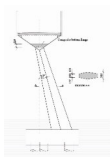
– Generic robustness requirements not further developed in codes

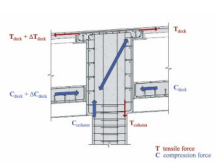
– Lack of operational rules related with
  – Absence of practical metric for robustness quantification
  – Complexity of the problem at hand

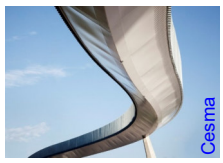
– Conceptual design is most important
  – Choice of type, layout, main dimensions of system, individual members, details and selection of materials
  – Identification of members influencing system stability
  – Choice of resistance mechanism after failure of those members











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Context

ROBUSTNESS

- Any conceptual solution for increased robustness may worsen performance for other hazard scenarios



- Conceptual changes difficult or impossible in existing structures
- Therefore
  - Unequivocal identification and consideration of all relevant hazards and hazard scenarios is of paramount importance, especially in existing structures
  - Operational rules needed, beyond general strategies, for providing or verifying structural robustness
  - Quantitative criteria needed for decision making
- → Case study for illustration

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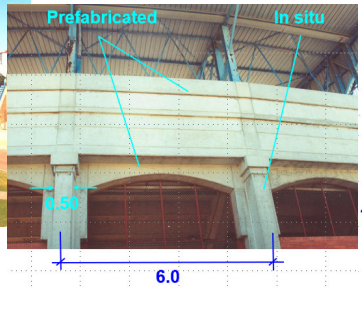
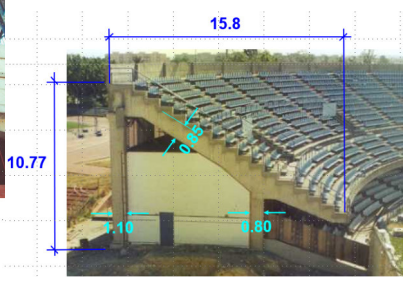
Chapin stadium

EXISTING STRUCTURE

- Completed in 1988
- Only main grandstand covered with a roof
- In situ concrete frames at 6 m centres
- Precast concrete elements as platforms for spectator seats



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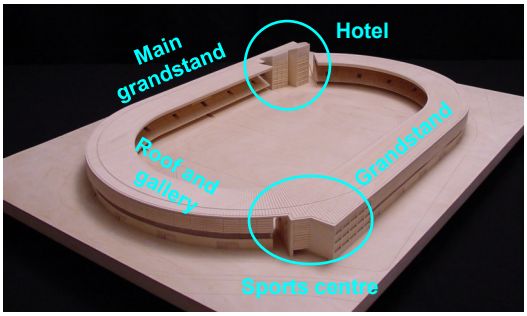
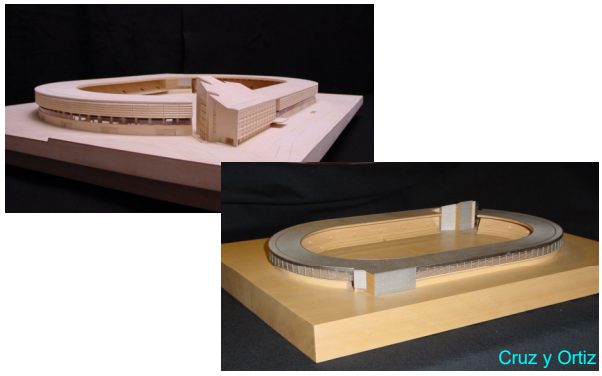
Chapin stadium

PLANNED INTERVENTION

- New roof and gallery
- Reorganization of the access for the public
- Integration of sports centre and hotel
- New office area for sports officials





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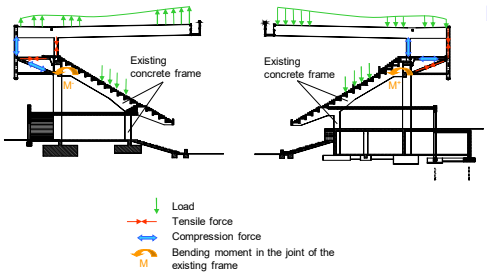
Chapin stadium

CONCEPTUAL DESIGN

- Steel frames added to existing concrete frames
- Roof panels span 6 m between main beams
- Load transfer mechanism
  - Gravity loads and positive wind pressure
  - Inversion of action effects due to negative wind pressure

Grandstand



Main grandstand

→ Change of internal forces and moments in existing frames

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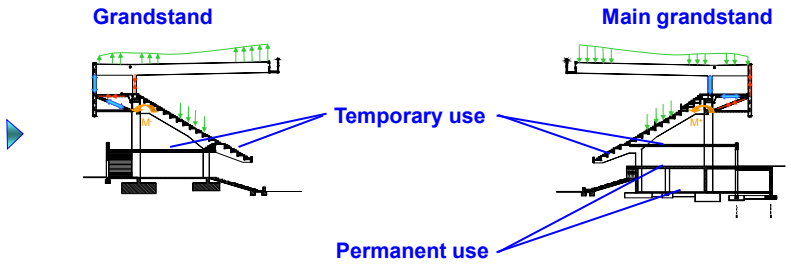
Chapin stadium

USE CONDITIONS

- Areas on grandstands and walkways
  - Persons are present during events
  - → Consideration of reduced risk exposure times
- Office areas
  - Persons are permanently present
  - → Risks associated with existing frames still acceptable after the intervention?
  - → Insufficient robustness through stadium transformation?



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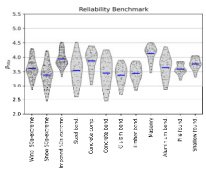
Operational procedure

GENERAL

- Aspects to be considered when establishing reliability requirements
  - Acceptable life safety risk
  - Economic criteria, including the consequences of unsustainable development
  - Heritage values
- Code requirements often pursue economic optimisation
- LSR can be dominant for members that can trigger system collapse
- Reminder
  - Lack of harmonised metric for robustness quantification
  - Large scatter in implicitly accepted risk levels

→ Inference of reliability requirements based on implicitly accepted LSR associated with BCP

$$ICAF = \frac{g \cdot e}{4} \cdot \frac{1-w}{w}$$



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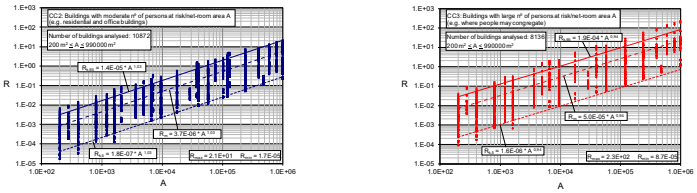
Operational procedure

INFERENCE OF RELIABILITY REQUIREMENTS

– Implicitly accepted notional risks versus total net room area



→ Individual risk: $r_{t,LR} \approx 10^{-6}$ to 10^{-5} [y^{-1}]

→ Comparison: overall individual lethal accident rate $\approx 10^{-4}$ [y^{-1}]

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Operational procedure

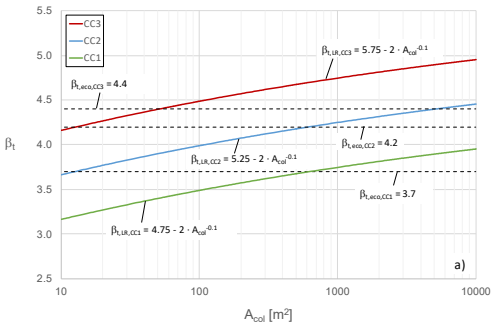
INFERENCE OF RELIABILITY REQUIREMENTS

– Conversion of acceptable risks into $p_{ft,LR,1y}$

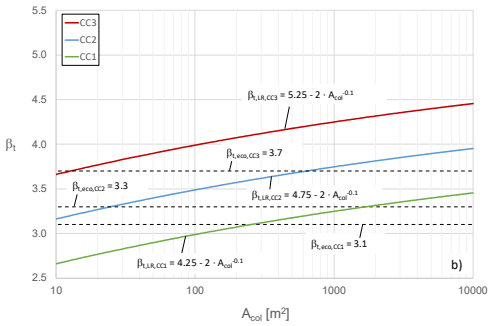
– Transformation of $p_{ft,LR,1y}$ into $\beta_{t,LR,1y}$ and representation $\beta_{t,LR,1y}(A_{col}; CC)$

– Differentiation between design and assessment

Design



Assessment



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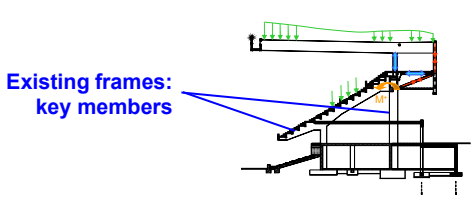
Operational procedure

ASSESSMENT OF ROBUSTNESS

– **Expected consequences** and relative cost of safety measures depend on **failure mode**

→ Identifying members decisive to system or subsystem strength and stability: **key members**



→ Different reliability requirements for

- Structural members in identified assessment situations: $\beta_{t,code} \approx \beta_{t,eco}$
- Key members in identified assessment situations: $\beta_{t,km} = \max(\beta_{t,eco}; \beta_{t,LR})$
- Remaining system still standing during and after key member failure due to unidentified situations: conditional $\beta_{t,rs}$

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Robustness of existing frames

PERSISTENT SITUATIONS

– Assume frame failure, e.g. due to wind acting on new roof

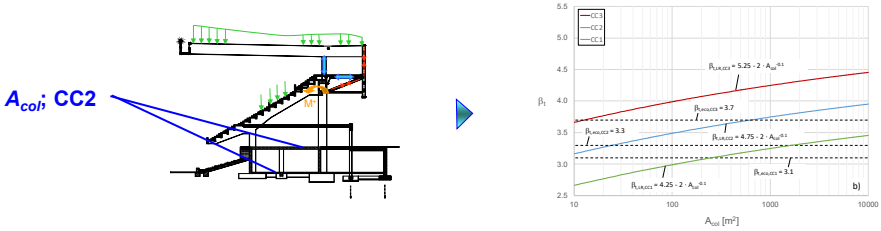
– Estimation of collapse area

- Statically determinate, prefabricated transverse elements
- Continuous transverse steel structure with large deformation capacity

→ Collapse stop leading to $A_{col} \approx 24 \cdot 6 \cdot 2 \cdot 2 \approx 580$ m²

– Consequence class CC2: buildings where people normally enter

→ For identified situations: $\beta_{t,LR,1y}(A_{col}; \text{CC2}) = 3{,}7 > \beta_{t,eco,1y}(\text{CC2}) = 3{,}3$



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Refurbished and extended

Photo: Duccio Malagamba

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Refurbished and extended

Photo: Duccio Malagamba

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Refurbished and extended

Photo: Duccio Malagamba

33

Refurbished and extended

Photo: Duccio Malagamba

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Stufib
Studievereniging fib-Nederland

ASSESSMENT OF CONCRETE STRUCTURES – EXPERIENCES AND OUTLOOK

- Introduction
- Design, assessment and the Eurocodes
- Stadium refurbishment and extension
- Conclusions and discussion

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CESMA ingenieros

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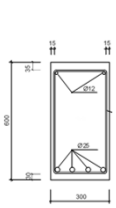
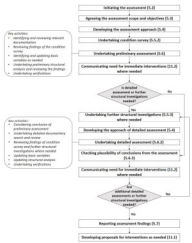
Conclusions

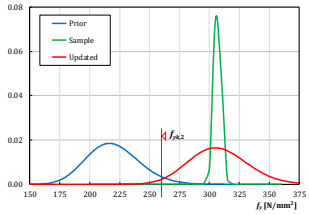
CURRENT SITUATION

- General reliability principles apply to design and assessment
- Important differences exist between both activities
- In most cases, design-oriented rules are conservative for assessment
- More advanced methods exist that are advantageous





$M_{Ea,1} > M_{Ra,1}$



$M_{Ea,1} < M_{Ra,2}$

$\beta > \beta_t$

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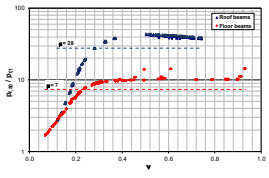
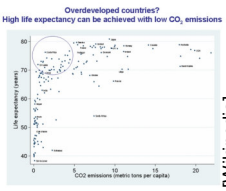
NEEDS FOR FURTHER DEVELOPMENT

- **Target and minimum reliability levels**
  - Lifetime versus annual requirements
  - Requirements based on explicit risk analysis: maximize progress for minimal resource consumption and emissions
  - Indicative values for SLS





[Wikipedia]

- **Resistance models based on mechanical principles**
  - Explicit consideration of the effects of deterioration
  - Description of the propagation of deterioration
  - Load-bearing capacity after intervention

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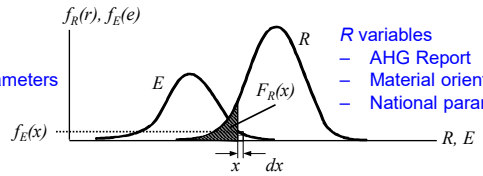
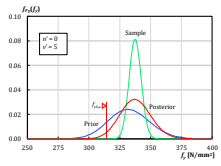
NEEDS FOR FURTHER DEVELOPMENT

- **Prior information including model uncertainties**

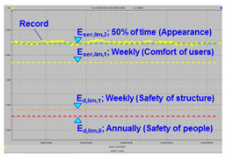
E variables
- AHG Report
- National parameters



R variables
- AHG Report
- Material oriented Eurocodes
- National parameters



- **Operating rules for robustness including quantitative decision criteria**
- **Guidelines for monitoring**
  - Choice of adequate strategies
  - Definition of performance indicators and establishment of threshold values



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… and discussion

STUBBORN REALITY

- No reason to wait for such developments
- More advanced methods can be used
- Rare applications in practice

versus

- Why?

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