Framework for robustness assessment of timber structures

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- Introduction
- WG 3 focus area and results
- Framework for robustness assessment of timber structures
    - Reliability-based approach
    - Risk-based approach
    - Robustness indicators
- Concluding remarks

WG3 ‘Robustness of systems’

Focus areas:

- Reliability of timber systems
- Robustness of timber structures

Activities / results:

- Presentations and papers from COST E55 workshops
- Presentations and papers at conferences
- Fact Sheets
- Guideline - Design for robustness of timber structures
- Papers in ‘Engineering Structures’

- Close cooperation with COST TU601 ‘Robustness of structures’

Guideline - Design for Robustness of Timber Structures

1. Introduction
2. Definition of robustness and related terms
3. Framework for structural robustness
4. System reliability of timber structures, ductility and redundancy
5. Robustness in large-span timber structures – structural aspects and lessons learned
6. Earthquakes and robustness
7. Effect of quality control
8. Recommendations

Annex A. Robustness requirements in codes

Annex B. Examples / Case studies

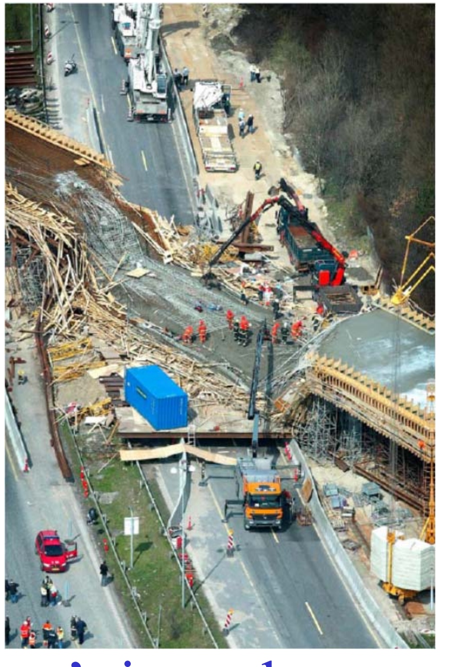
Framework for robustness assessment of timber structures

Reasons to failures:

- Extreme high load / extreme low strength: very unlikely (probability of failure per year ~ 10^{-5} - 10^{-6})

  covered by 'component-based' design rules and psf in codes

- Other reasons:
  - Design errors
  - Execution errors
  - Deterioration of critical structural elements / lack of maintenance
  - Unexpected hazards - unforeseeable incidents
  - System effects



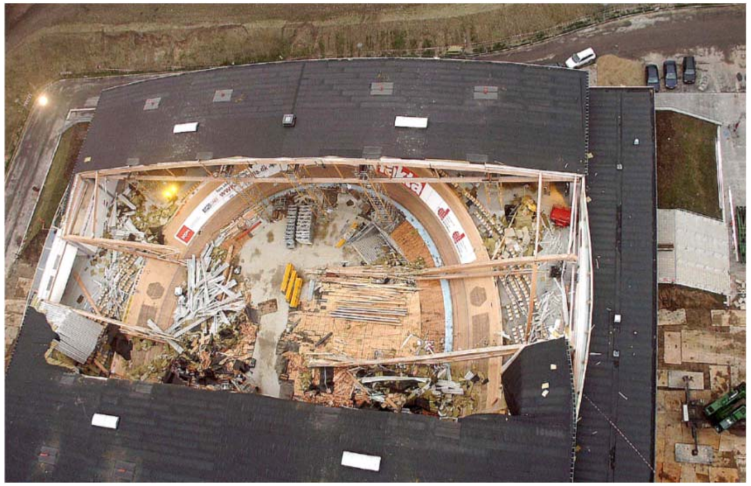
→(to be) covered (partly) by 'Robustness requirements' in codes

Robustness – Theoretical framework

Ballerup arena - 2003

Copenhagen, Denmark

2 out of 12 main trusses collapsed



Ice skating arena - 2006

Bad Reichenhall, Germany

Total collapse

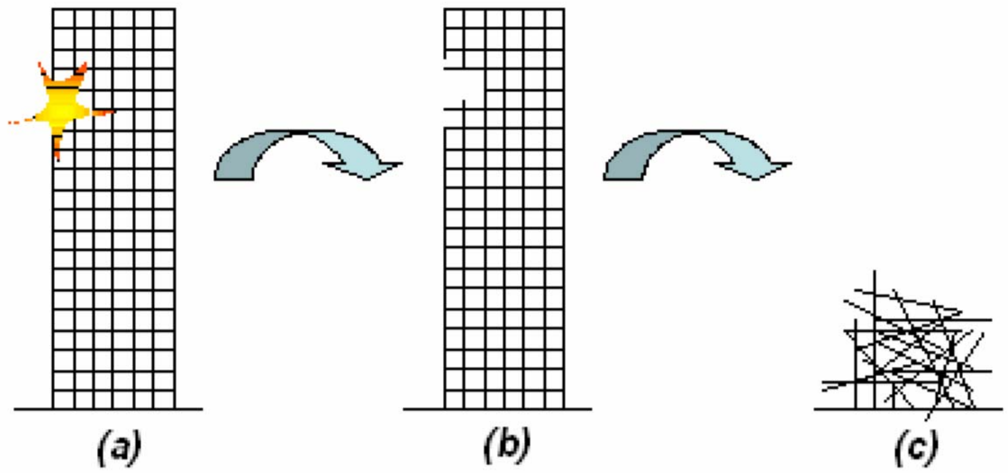
- Hazards: design error, unforeseen incidents, …
  - Correlated / uncorrelated for different elements?
  - New / conventional system?
- Connection between main trusses/beams: strong / weak?
  - Series / parallel (redundant) system?
- Brittle / ductile failure type?

Robustness - Eurocodes

EN1990 and EN1991-1-7

A structure shall be designed and executed in such a way that it will not be damaged by events such as :

- explosion,
- impact, and
- the consequences of human errors, to an extent disproportionate to the original cause.

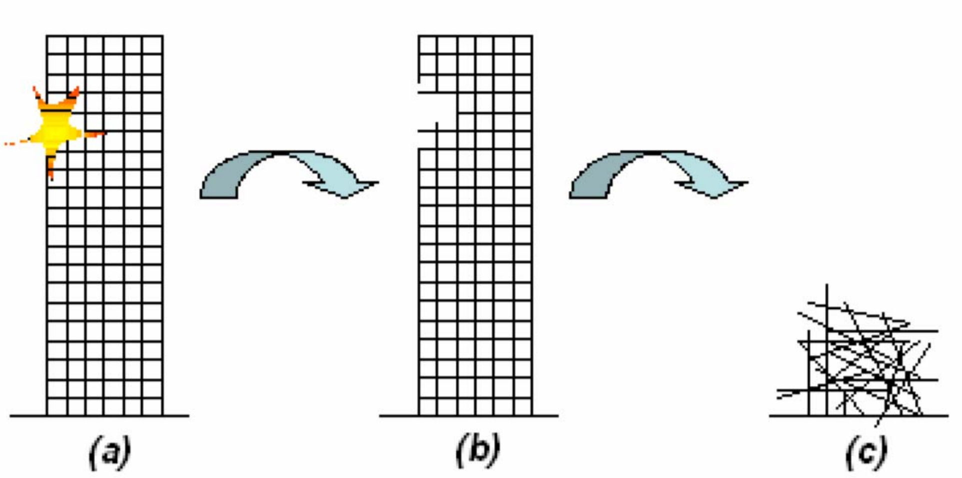


Robustness - Eurocodes

Potential damage shall be avoided or limited by:

- avoiding, eliminating or reducing the hazards to which the structure can be subjected
- selecting a structural form which has low sensitivity to the hazards considered
- selecting a structural form and design that can survive adequately the accidental removal of an individual member or a limited part of the structure, or the occurrence of acceptable localised damage
- avoiding as far as possible structural systems that can collapse without warning → *(ductility)*
- tying the structural members together

Robustness – probabilistic model



- Exposure - EX_i: $\quad P(EX_i)$
- Damage due to exposure - D_j : $\quad P(D_j | EX_i)$
- Consequence – Collapse: $\quad P(\text{Collapse} | EX_i \cap D_j)$

Total probability of collapse:

$$P(\text{Collapse}) = \sum_i \sum_j P(\text{Collapse} | EX_i \cap D_j) P(D_j | EX_i) P(EX_i)$$

Robustness – probabilistic model

$$P(\text{Collapse}) = \sum_i \sum_j P(\text{Collapse} \mid EX_i \cap D_j) P(D_j \mid EX_i) P(EX_i)$$

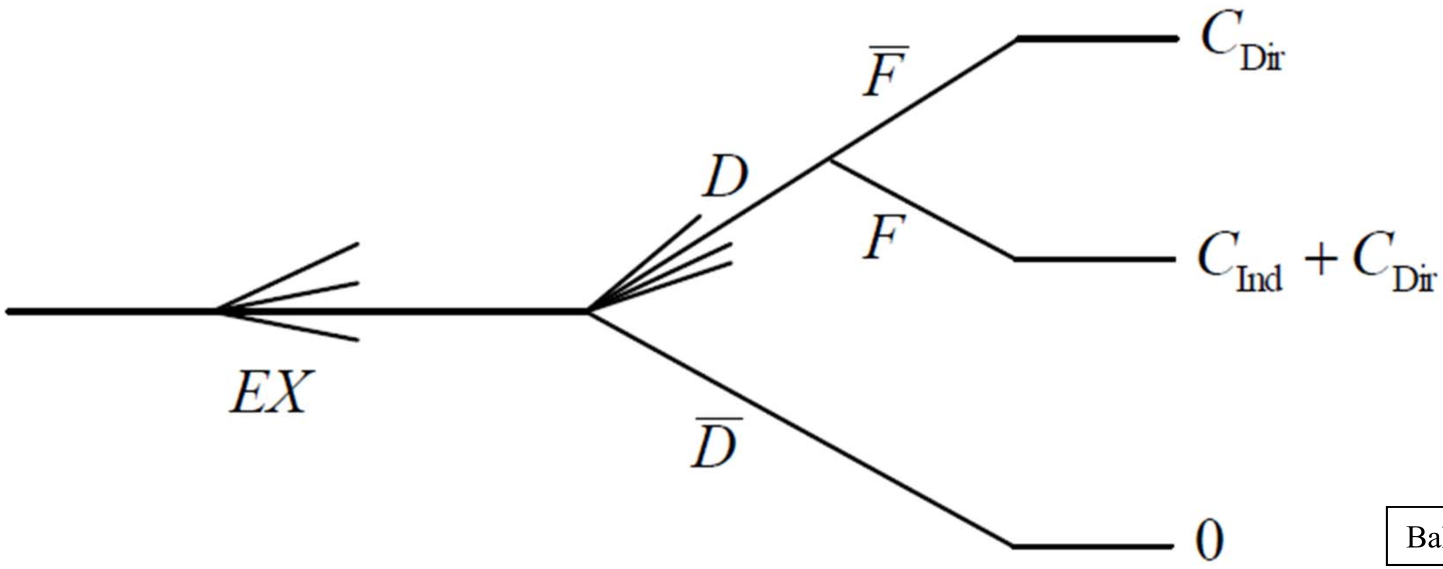
Post failure models

Member models

Exposure Action/hazard models

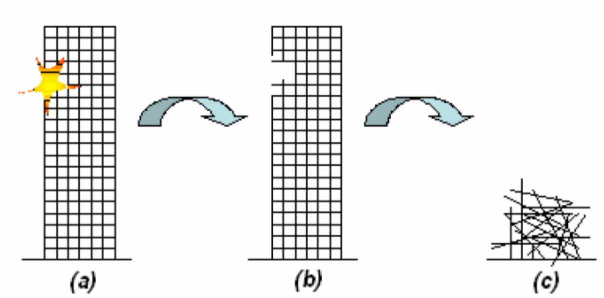
Model = physics + statistics

Robustness – risk-based model



Baker et al. 2008

Total Risk = Direct Risk + Indirect Risk:



$$R = \sum_{i}\sum_{j} C_{\mathrm{dir},ij} P\left(D_j \middle| EX_i\right) P\left(EX_i\right) +$$

$$\sum_{k}\sum_{i}\sum_{j} C_{\mathrm{ind},ijk} P\left(S_k \middle| D_j \cap EX_i\right) P\left(D_j \middle| EX_i\right) P\left(EX_i\right)$$

Robustness - Indicators

- Risk-based robustness index

$$I_{rob} = \frac{R_{Dir}}{R_{Dir} + R_{Ind}}$$

high robustness : $I_{rob} \rightarrow 1$

low robustness : $I_{rob} \rightarrow 0$

- Reliability-based robustness indices

$$\beta_R = \frac{\beta_{\text{intact}}}{\beta_{\text{intact}} - \beta_{\text{damaged}}}$$

high robustness : $\beta_R \rightarrow \infty$

low robustness : $\beta_R \rightarrow 0$

$$RI = \frac{P_{f\,(\text{damaged})} - P_{f\,(\text{intact})}}{P_{f\,(\text{intact})}}$$

high robustness : $RI \rightarrow 0$

low robustness : $RI \rightarrow \infty$

- Deterministic robustness index, e.g. based on a pushover analysis

$$RIF_i = \frac{RSR_{\text{damaged}}}{RSR_{\text{intact}}}$$

high robustness : $R_i \rightarrow 1$

low robustness : $R_i \rightarrow 0$

Robustness - Indicators

Conditional risk-based robustness indicator:

$$I_{rob|\text{exposure/damage}} = \frac{R_{Dir|\text{exposure/damage}}}{R_{Dir|\text{exposure/damage}} + R_{Ind|\text{exposure/damage}}}$$

- conditional on given exposure and/or damage

Robustness

$$\text{Risk} = \sum_i \sum_j C_{\text{dir},ij} \qquad P(D_j|EX_i)P(EX_i)$$

$$+\sum_k \sum_i \sum_j C_{\text{ind},ijk} P(S_k|D_j \cap EX_i)P(D_j|EX_i)P(EX_i)$$

Collapse

Removed column

Explosion
Fire
Human error

	$P(EX)$ [50 year]	$P(D|EX)$)
explosion	2x10^{-3}	0.10
fire	20x10^{-3}	0.01
human error	2x10^{-3}	0.10

Robustness

How to decrease risk / increase robustness?

$$\text{Risk} = \sum_i \sum_j C_{\text{dir},ij} P\left(D_j \middle| EX_i\right) P\left(EX_i\right) + \sum_k \sum_i \sum_j C_{\text{ind},ijk} P\left(S_k \middle| D_j \cap EX_i\right) P\left(D_j \middle| EX_i\right) P\left(EX_i\right)$$

Reduce exposures
- Action / hazard models

Limit local damages
-Component models

Reduce extensive damages / collapse
-Post failure models
-Redundancy, ductility, …
-Reduce / strengthen key elements

Reduce direct / indirect consequences

Robustness

Potential damage shall be avoided or limited by:

- Avoiding, eliminating or reducing hazards
- Structural design with low sensitivity to hazards
- Structural design that can survive adequately the accidental removal of an individual member or limited part of the structure
- Avoiding structural systems that can collapse without warning → (ductility)
- Tying structural members together

- Requirements depend on consequence class (CC1, CC2 or CC3)

Robustness

- Not always a good idea to use redundant systems / tie elements together – use of statically determinate (series) systems can be better than a redundant system → compartmentalization

Robustness strategy depend on

- Exposure type: design error, unforeseen incidents, …
- Correlation of exposure between elements
- New / conventional structural system
- Load bearing capacity: time dependency
- Load type: permanent / variable load dominating

Robustness - Codes

Code based design

Standard Code Format – Component based

- Safety format
- Design equations
- Enveloping loads
- Load combinations
- Material characteristics
- Characteristic values / partial safety factors / load combination factors
- etc.

Robustness requirements – system based

Quality control requirements - human errors
Inspection & maintenance - deterioration

Concluding remarks

- Reliability- and risk-based basis for assessment of robustness is available

Next steps

- Dissimilation to ‘code committees’ and ‘practicing engineers’
  – Guideline - Design for Robustness of Timber Structures
- Implementation
  – in updating of Eurocodes (TC250 - WG6 Robustness and EN 1990 Expert group)
  – JCSS Probabilistic Model Code