AALBORG UNIVERSITY

Robustness of structures – Danish approach

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- Introduction
- Robustness – stochastic model
- Robustness – Danish code DS409 / DK EN 1990 national annex
- Key elements
- Conclusions

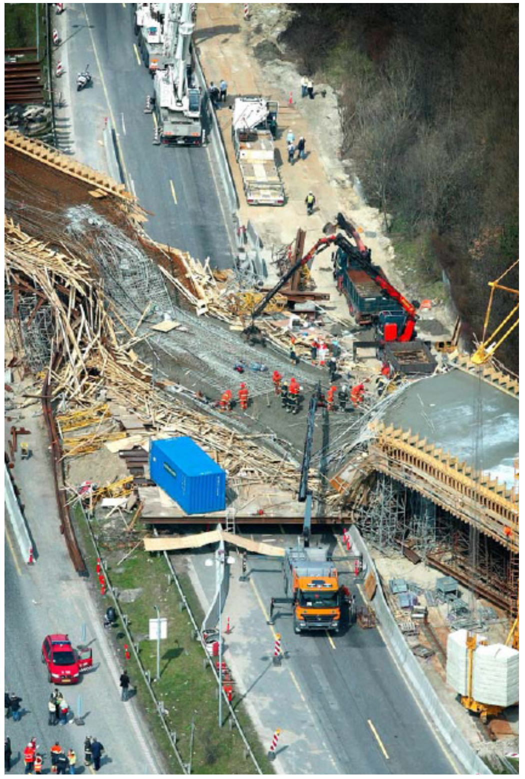
Introduction

Reasons to failures:

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

- Other reasons / aspects:
  - Unexpected hazards
  - Design errors
  - Execution errors
  - Deterioration of critical structural elements
  - System effects

→Robustness requirements



Nørresundby, Denmark
April 2006

Introduction - robustness

Siemens superarena Copenhagen,
Januar, 2003

Robustness - Eurocodes

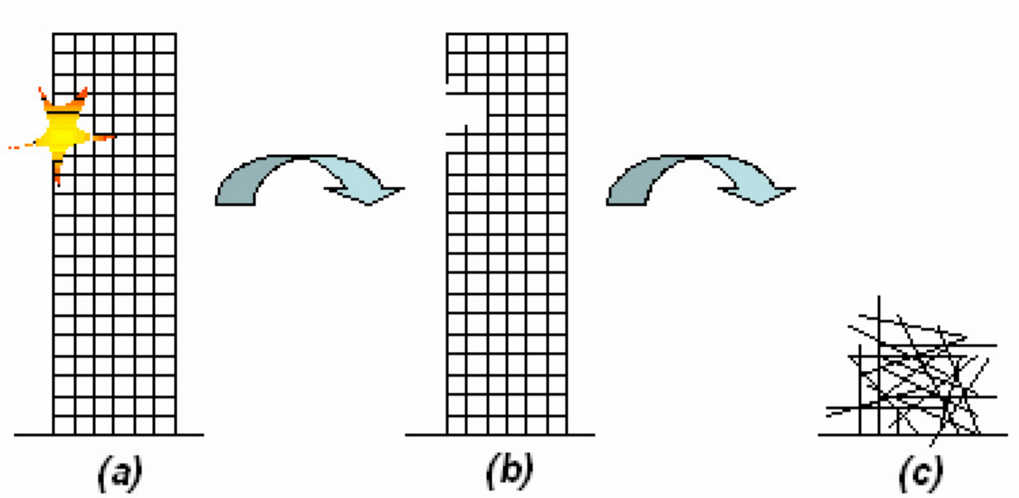
EN1990 and EN1991-1-7

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

- explosion,
- impact, and

accidental actions

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



Robustness – Danish code DS 409 / DK EN 1990 national annex

Definition of robustness and key elements

- A structure is robust:
  - when those parts of the structure essential for the safety only have little sensitivity with respect to unintentional loads and defects,

    or
  - when extensive failure of the structure will not occur if a limited part of the structure fails.
- Key element:
  - limited part of structure, which has an essential importance for the robustness of the structure in the way that a possible failure of the key element implies a failure of the entire structure or significant parts of it.

Robustness – probabilistic model

- Exposure - unintentional loads or defects - E_i :
  - Examples: unforeseen load effects, unforeseen settlements; incorrect structural modelling; incorrect computational model; error related to material
  - Probability: $P(E_i)$ ← Difficult to identify/quantify
- Damage due to exposure - D_j :
  - Examples: loss of column; failure of part of storey area
  - Probability of damage no *j* given exposure no *i*: $P(D_j | E_i)$
- Consequence – Collapse - C
  - Example: collapse of major part of structural system (building, bridge,…)
  - Probability of collapse given exposure no *i* and damage no *j*: $P(C | E_i \cap D_j)$

Robustness – probabilistic model

Total probability of collapse:

$$P(C) = \sum_i \sum_j P(C | E_i \cap D_j) P(D_j | E_i) P(E_i)$$

Probability of collapse can be reduced (and robustness increased) by:

- Reduce probabilities of exposures $P(E_1)$, $P(E_2)$,…
- Reduce probabilities of damages $P(D_1 | E_1)$,… or reduce extent of damages
  - Example: strengthen vital structural elements - key elements (e.g. column): $P(D_j | E_i)$ is reduced
  - Example: strengthen/redesign reinforced concrete slab in order to reduce extent of storey damage
- Reduce probabilities $P(C | E_1 \cap D_1)$,…
  - Example: increase redundancy of structure

Robustness – probabilistic model

Key Element:

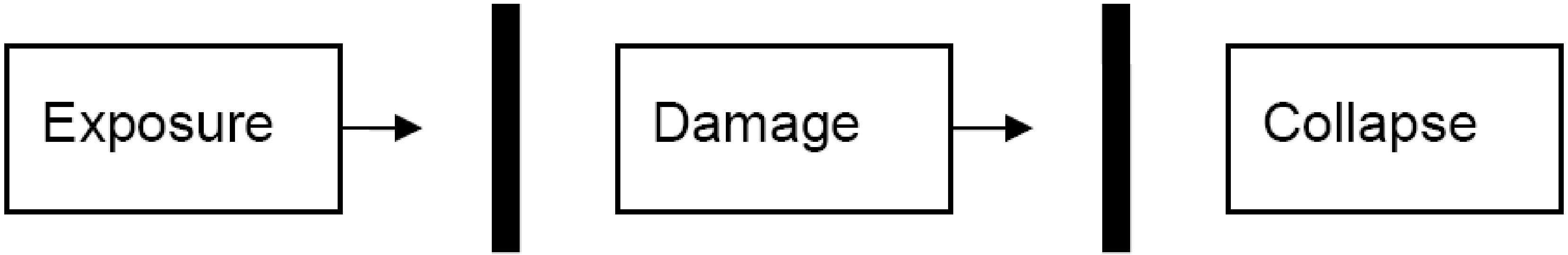
$$P(C | E_i \cap D_j) \cong 1$$

Increasing the robustness at the design stage will in many cases only increase the cost of the structural system marginally

The key point is often to use a reasonable combination of suitable structural system and materials with ductile behaviour

Alternatives to increase the robustness: choose alternative *k* with smallest expected total costs

Robustness – Barrier model



Barrier:
Prevent undefined/unknown "exposure" from damaging the structural system

Barrier:
Prevent that damage results in collapse

Robustness – probabilistic model

Total Risk:

$$P(D_j) = \sum_i P(D_j | E_i) P(E_i)$$

$$\underbrace{\sum_j C_j \cdot P(D_j)}_{\text{consequence of local damages}} + \underbrace{C_F \cdot P(C)}_{\text{consequence of collapse}}$$

consequence of local damages | consequence of collapse

robustness requirements

↓

Consequence Class 1: no
Consequence Class 2: 'evaluation' of robustness
Consequence Class 3: document robustness

Robustness – Danish code DS 409

- Requirements to robustness of a structure is related to the consequences of failure of the structure.

  Documentation of robustness is only required for structures in **high consequence class, CC3**.

Robustness – Danish code DS 409

Robustness: documented by a technical review where at least one of the following criteria is fulfilled:

a) demonstrate that those **parts of the structure essential for the safety only have little sensitivity** with respect to unintentional loads and defects

or

a) demonstrate a load case with '**removal of a limited part of the structure**' in order to document that an extensive failure of the structure will not occur if a limited part of the structure fails

or

a) demonstrate sufficient safety of **key elements**, such that the entire structure with one or more key elements has the same reliability as a structure where robustness is documented by b).

Robustness – Danish code DS 409

The **technical review should include**:

1) **Report on load determination** for permanents, imposed, environmental and accidental loads, including thoughts about possible failure scenario; determination of acceptable collapse extent by removal of a limited part of the structure

2) **Report on the structural composition** including identification of possible key elements

3) **Assessment of safety of essential parts of the structure** with respect to sensitivity regarding unintentional loads and defects

4) **Demonstration of robustness** by the load case '**removal of a limited part of the structure**' if point 3 does not document sufficient robustness

5) **Design of key elements** with extra safety, if point 4 does not document sufficient robustness

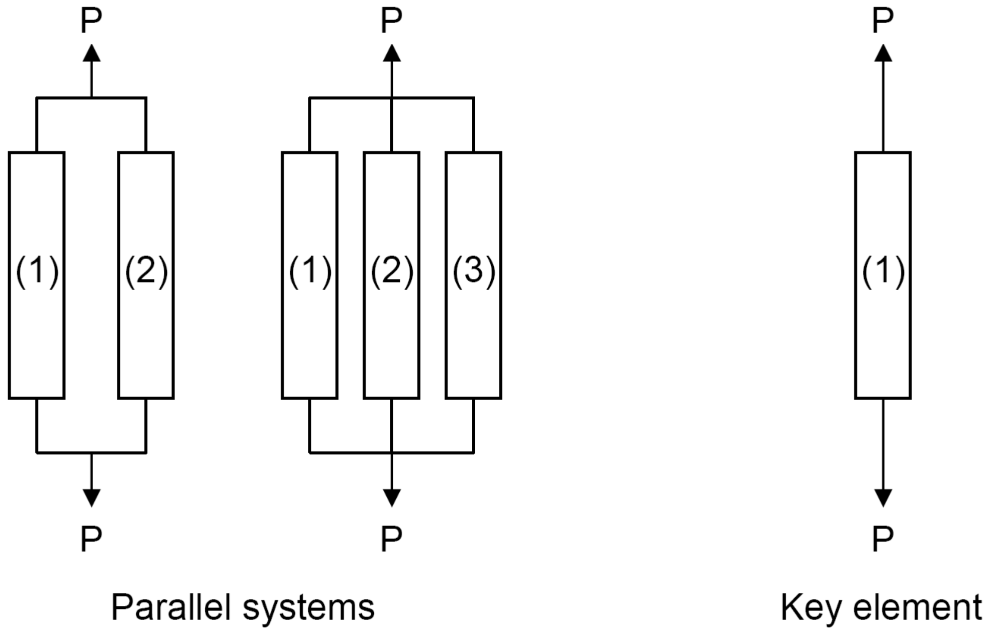
Robustness – Danish code DS 409

Note: robustness should be **distinguished from accidental loads** although some of the design procedures and measures are similar.

If robustness is documented by extra safety of key elements this can be achieved by increasing the material partial safety factor by a factor 1.2.

It should be verified that the resistance against unintentional loads and defects is really improved.

Key element - designed with extra safety



Same reliability of:

- Structure modelled by 2 or more parallel failure elements *and*
- key element

→ Key elements designed with material safety factor increased by a factor 1.2

Robustness – Danish code DS 409

Table 1. Examples of unintentional loads and defects

Load / defect	**Example**
Changed load situations	Permanent loads (ex: change of permanent load in connection with replacement of roofing)
	Imposed loads (ex: other use of building)
	Accidental loads (ex: Buildings can be exposed to intentional collision by heavy vehicles in connection with burglary; or Explosion or other damage of primary building parts by vandalism or terror acts)
Erroneous/insufficient structural system	Fully or partly moveable systems (ex: insufficient support of system with respect to horizontal movements)
	Change of system compared to original design (ex: removal of existing primary building parts)
Erroneous/insufficient calculation models	Overlooked failure modes (ex: tilting risk of beam flanges in compression)
	Erroneous assumptions on statically system (ex. multi-storey frame structure without stabilizing staircase/elevator core, which erroneously is assumed fixed)
	Unnoticed fatigue cracks due to unintentional combined load effects especially for inaccessible and hidden details which cannot be inspected

Robustness – Danish code DS 409

Load / defect	Example
Erroneous/insufficient calculations	Calculation errors and defective calculations
	Erroneous computer programs, and erroneous use of calculations programs
Material errors	Errors in material production (ex: error in mixing composition for concrete)
	Errors in material grading (ex: defective visual or machine grading of timber)
Project errors	Erroneous and/or defective project material (ex: errors in transfer of calculation results to drawings)
Execution errors	Misunderstanding of project material
	Use of incorrect materials (ex: incorrect dimensions or quality of reinforcement steel)
	Shoddy construction work
Unforeseen geometrical imperfections	Imperfect elements or assembly of elements
Unforeseen settlements	Uneven settlements of foundations
Unforeseen deteriora-tion	Steel structures: corrosion – inappropriate connections; concrete: delamination due to e.g. frost; reinforcement: corrosion due to chlo-ride attack; masonry: corrosion of masonry header; timber: rot

Robustness – Danish code DS 409

Table 2. Conditions that can increase robustness

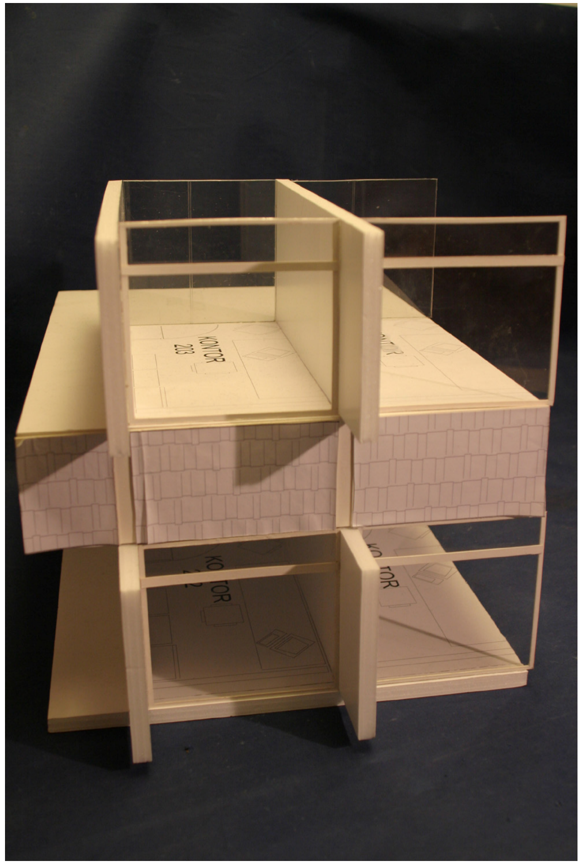
Condition	**Example**
Load determination	Imposed load (ex: operation instructions should specify allowable loads); accidental loads (ex: all imaginable accident scenarios should be considered)
System configuration	Use of parallel systems; Non-sensitive systems with respect to settlements of supports (ex: statically determinate systems are normally not sensitive with respect to settlements)
Statically indeterminate systems	Redistribution of internal sectional forces and/or internal stresses (ex: structures, members and connections)
Ductility	Ductile materials and connections
Solidity	Large dimensions and masses; Reduced slenderness; Oversizing (ex: key elements are given larger dimensions than required by the code; connections are given a capacity similar to the capacities of the adjacent elements although not required)
Coherency	In-situ cast concrete structures (normally high degree of coherency in horizontal and vertical direction)
Investigation and control	Critical investigations during design in order to identify details and elements important/vital for the reliability and robustness of the system, ensuring accessibility during operation for inspection; Quality control during execution; Control during operation (inspection procedures etc.)

Relation to: COST E55 – WG3
– System effects & Robustness of timber structures

- Robustness
  - Key elements
  - Redundancy
  - Ductility
  - Solidity
  - Prescriptive design rules
- System effects in timber structures
  - Unlikely that maximum load effects occur at cross-sections with very low strength
  - Load sharing
  - Redistribution of load effects
  - Non-linear material behaviour

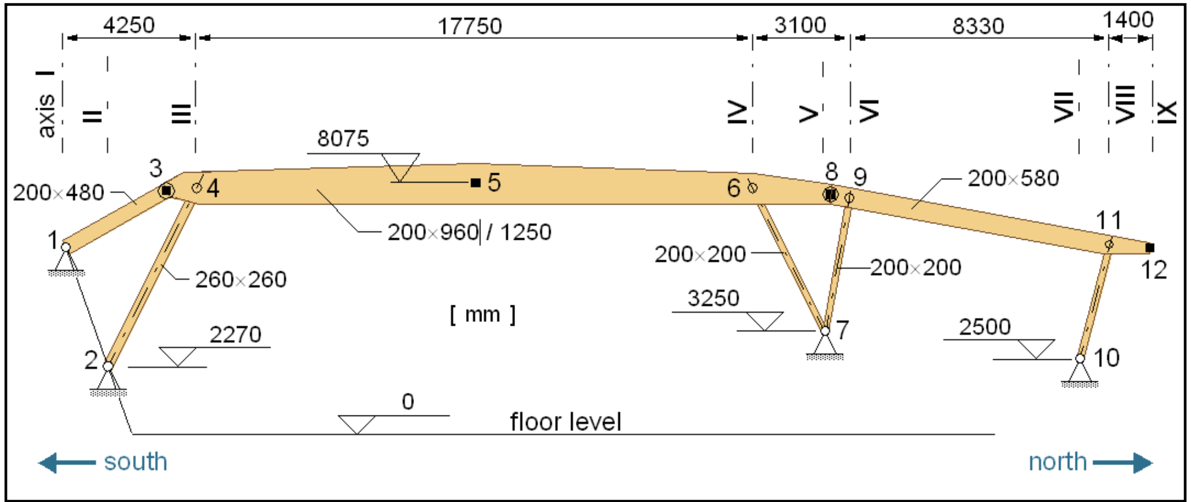
Robustness of timber structural systems

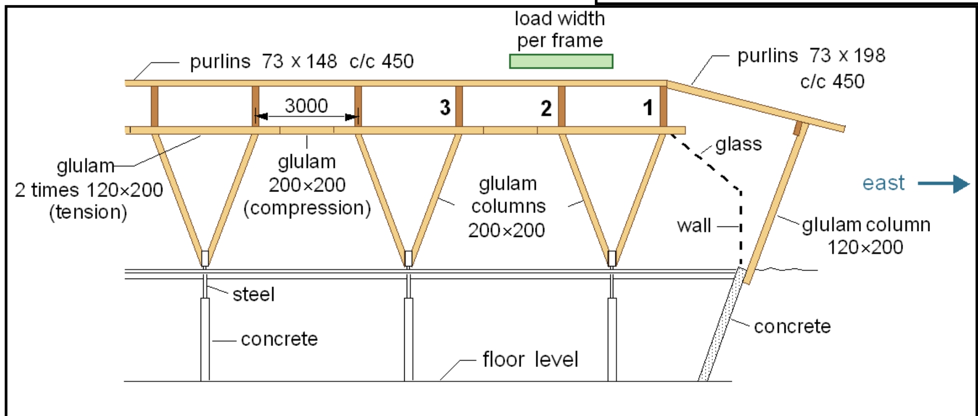
Examples: Solid timber structures – robustness problems?



Robustness of timber structural systems

Examples: Sport centre – robustness problems?

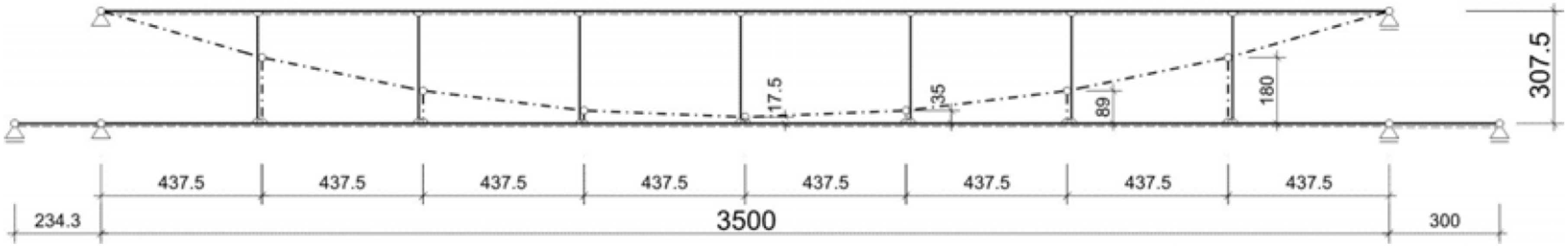




SECTION Y - Y

Robustness of timber structural systems

Examples: pedestrian bridge – robustness problems?



Conclusions

- Robustness is introduced in the Danish Code of Practice for Safety of Structures as a general requirement to all structures in order to reduce the sensitivity of the structure with respect to unintentional loads and defects
- For structures in high safety class robustness shall be documented:
  a) by demonstrating that those parts of the structure essential for the safety only have **little sensitivity with respect to unintentional loads and defects**, *or*
  b) by demonstrating a load case with '**removal of a limited part of the structure**' *or*
  c) by demonstrating **sufficient safety of key elements**