Implementation of robustness in codes & System effects in timber structures

John Dalsgaard Sørensen
Aalborg University, Aalborg, Denmark

- Introduction
- Robustness – Eurocodes
- Robustness – Danish code
- System effects in timber structures - examples
- Summary

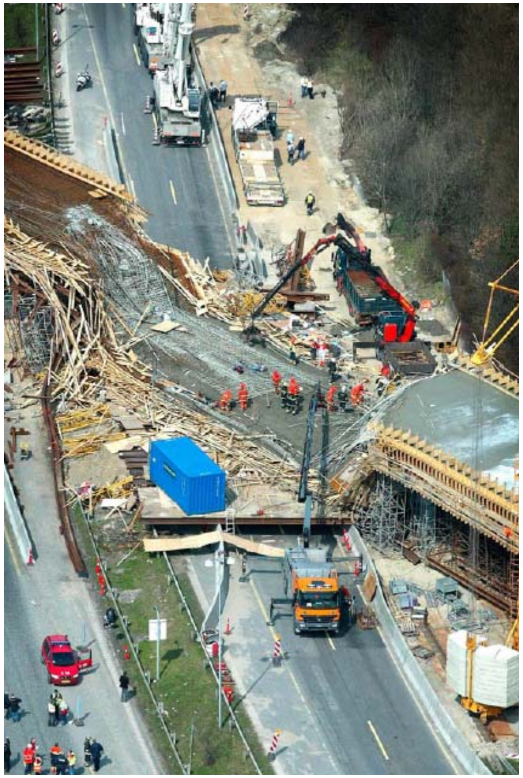
Introduction

Reasons to failures:

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

- Other reasons:
  - Unexpected hazards
  - Design errors
  - Execution errors
  - Deterioration of critical structural elements

→Robustness requirements



Nørresundby, Denmark
April 2006

Introduction - robustness

Transvaal Park, Moscow
Februar 2004

Introduction - robustness

Bad Reichenhalle
Germany, 2006

Introduction - robustness

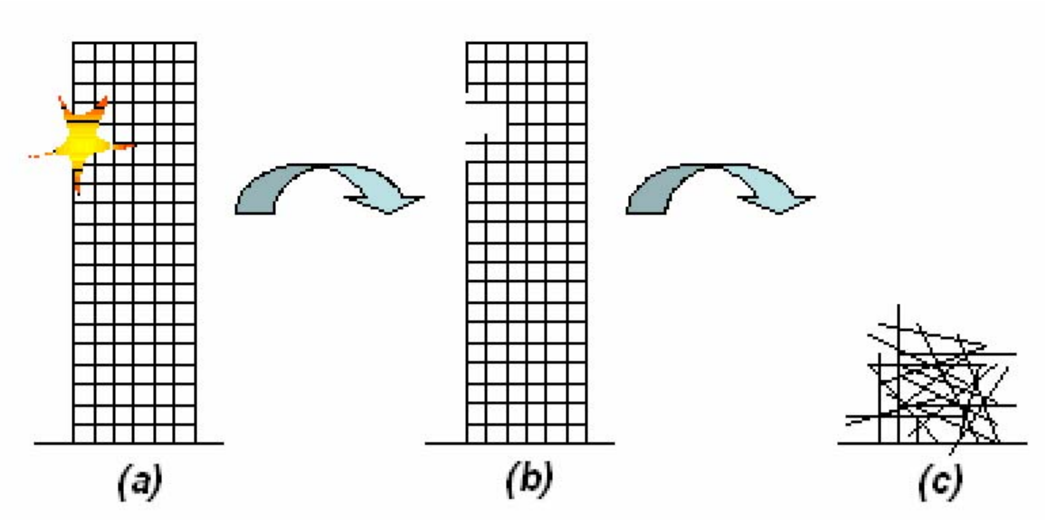
Siemens superarena København,
Januar, 2003

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
- 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
- tying the structural members together

Robustness - Eurocodes

The basic requirements should be met:

- by the choice of suitable materials
- by appropriate design and detailing
- by specifying control procedures for design, production, execution, and use relevant to the particular project

Robustness - Eurocodes

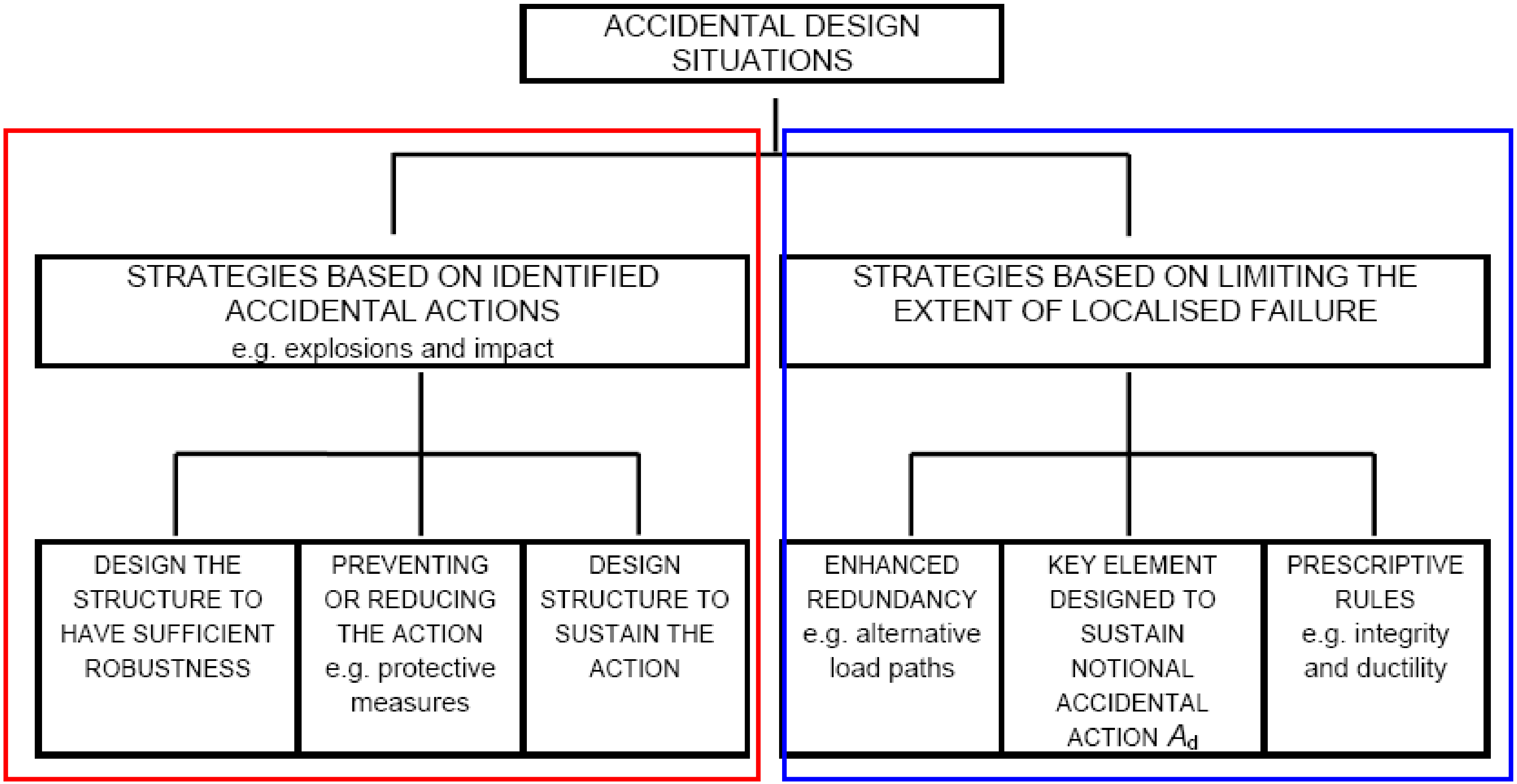


Figure 3.1 - Strategies for Accidental Design Situations

Design situations
- identified accidental action

Mitigation of the risk of accidental actions - strategies:

a) **Preventing the action from occurring** or reducing the probability and/or magnitude of the action

b) **Protecting the structure**

c) Ensuring that the structure has **sufficient robustness**
   1) designing **key elements**
   2) designing structural members, and selecting materials, to have sufficient **ductility**
   3) incorporating sufficient **redundancy** in the structure

Design situations - limiting extent of localised failure

Potential failure arising from an unspecified cause shall be mitigated

a) **Designing key elements**, on which the stability of the structure depends, to sustain the effects of a model of accidental action $A_d = 34$ kN/m^2

b) Designing the structure so that in the **event of a localised failure** (e.g. failure of a single member) the **stability of the whole structure** or of a significant part of it **would not be endangered**

c) Applying **prescriptive design/detailing rules**

Actions due to accidental actions from unidentified causes

Buildings in Consequences Class 1:

- No specific consideration is necessary

Buildings in Consequences Class 2a (Lower Group):

- **Effective horizontal ties**

Buildings in Consequences Class 2b (Upper Group):

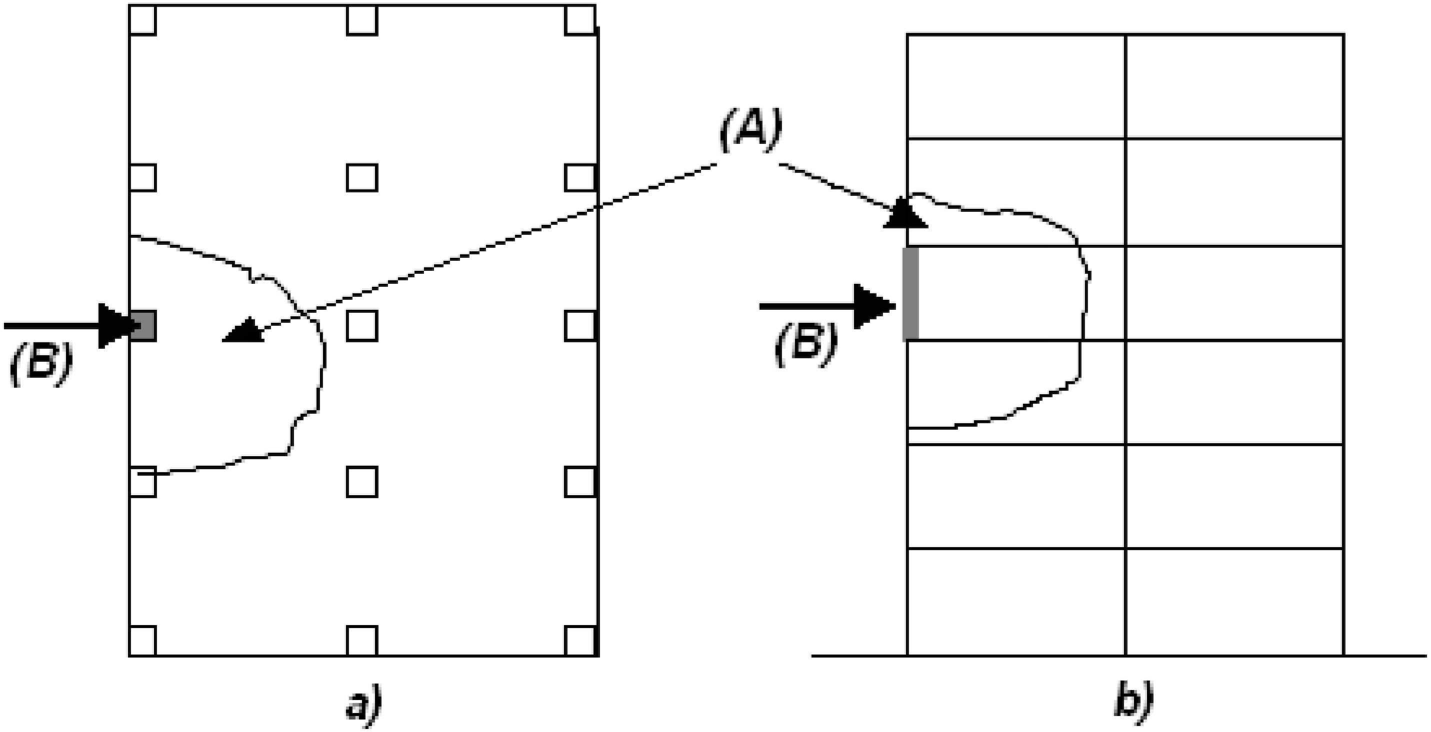
- **Effective horizontal ties** for wall construction, together with **effective vertical ties** in all supporting columns and walls

or

- Check notional **removal** of each supporting column, … building remains stable
- Design of "**key elements**"

Buildings in Consequences Class 3:

- Systematic **risk assessment** of the building



Key

(A) Local damage not exceeding 15 % of floor area in each of two adjacent storeys

(B) Notional column to be removed

a) Plan   b) Section

Figure A.1 – Recommended limit of admissible damage.

Robustness – Danish code DS 409

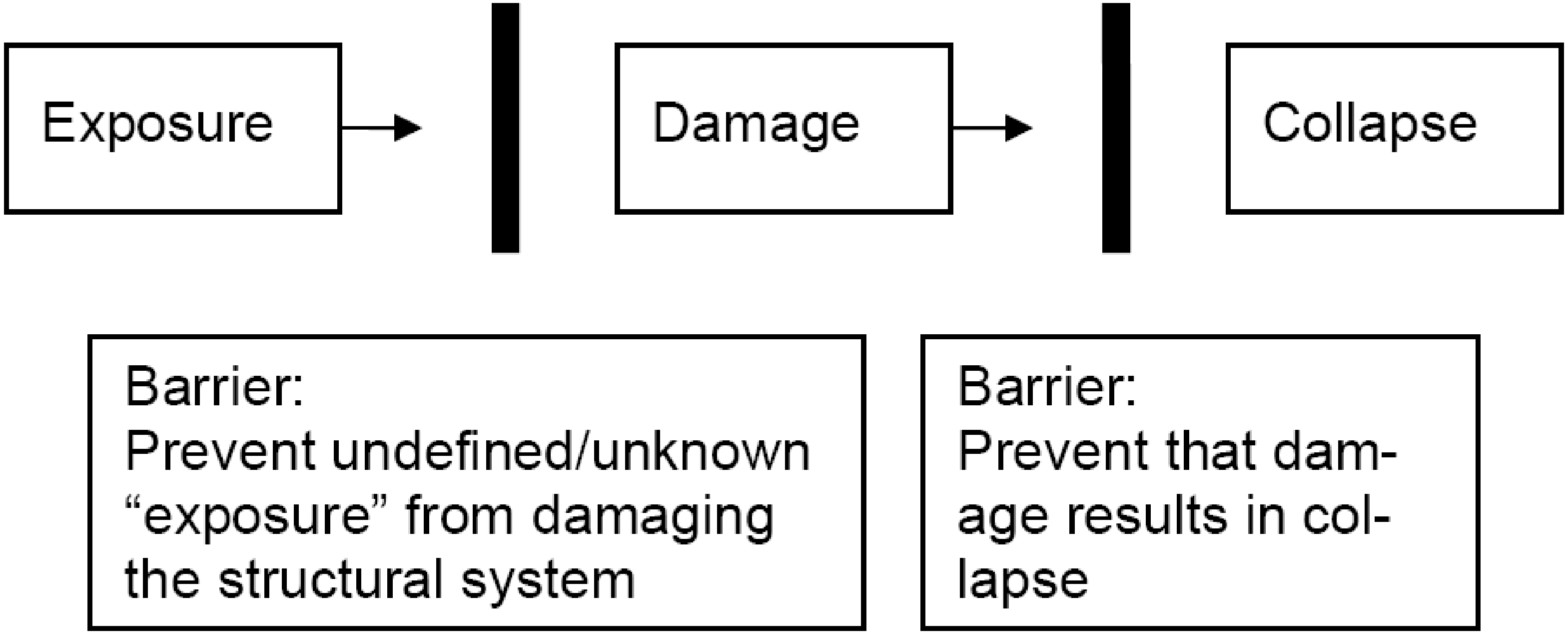
A structure is robust:

- 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.

Robustness – Barrier model



Robustness – probabilistic model

- Exposure - unintentional loads and defects - $E_i : P(E_i)$
  - Examples: unforeseen load effects, unforeseen settlements; incorrect structural modelling; incorrect computational model
- Damage due to exposure - D_j : $P(D_j | E_i)$
  - Examples: loss of column; failure of part of storey area
- Consequence – Collapse - C $P(C | E_i \cap D_j)$
  - Example: collapse of major part of structural system (building, bridge,…)

Total probability of collapse:

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

Robustness – probabilistic model

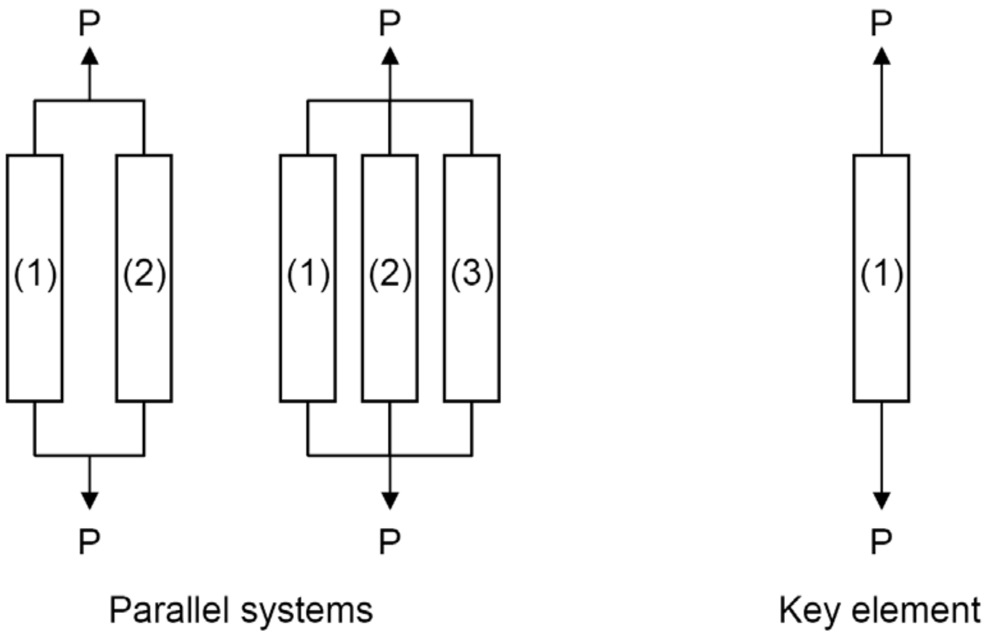
Key Element:

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

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

Key element - designed with extra safety



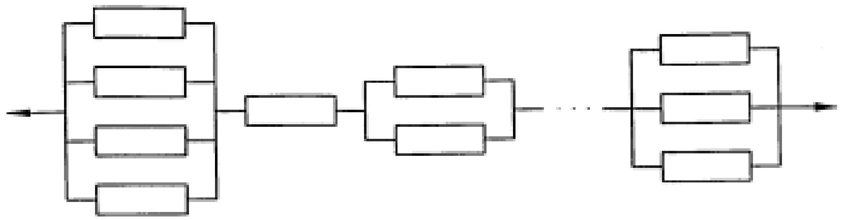
Same reliability of:

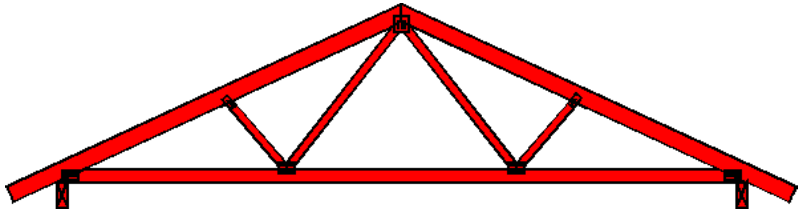
- Structure modelled by 2 or more parallel failure elements *and*
- key element

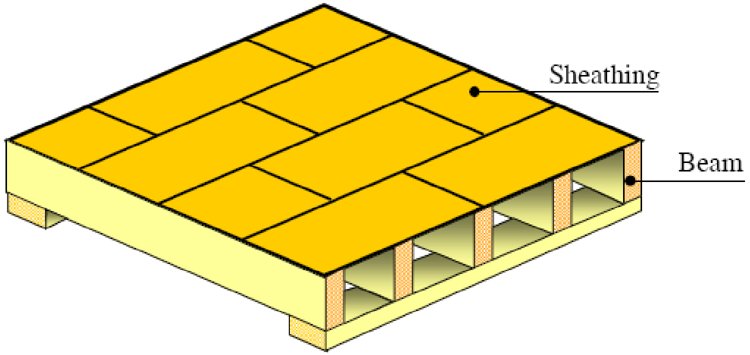
→ Key elements designed with material safety factor increased by a factor 1.2

Systems

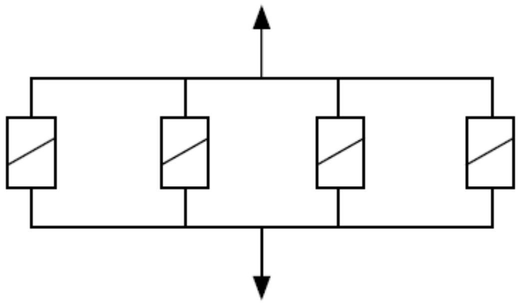
- General systems
- Roof elements
- Roof trusses

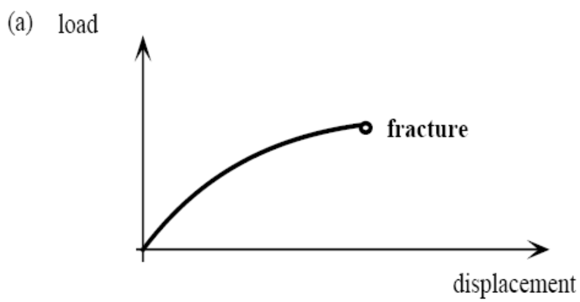


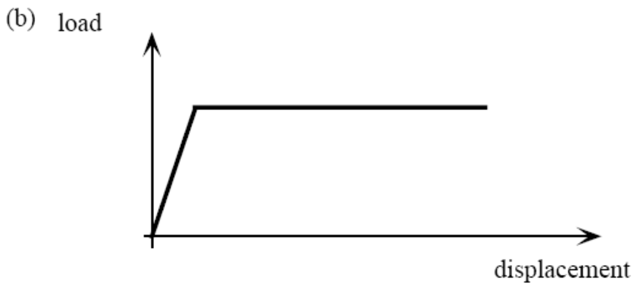




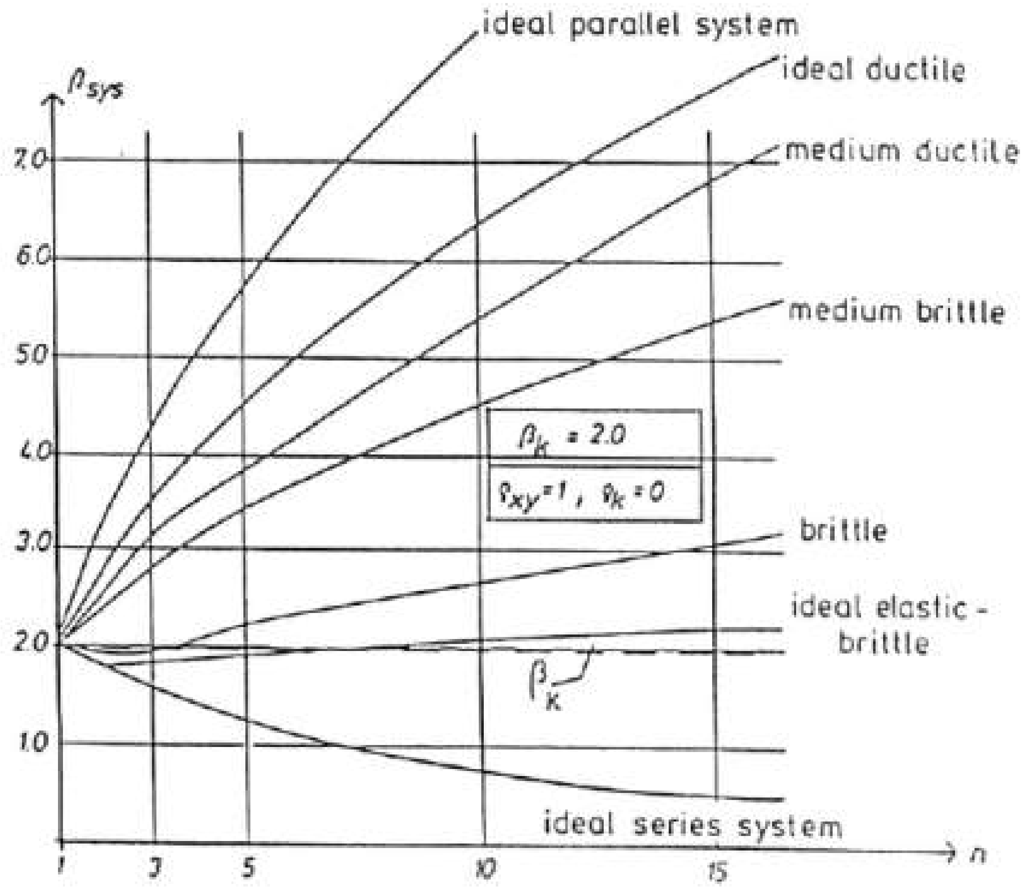
General systems





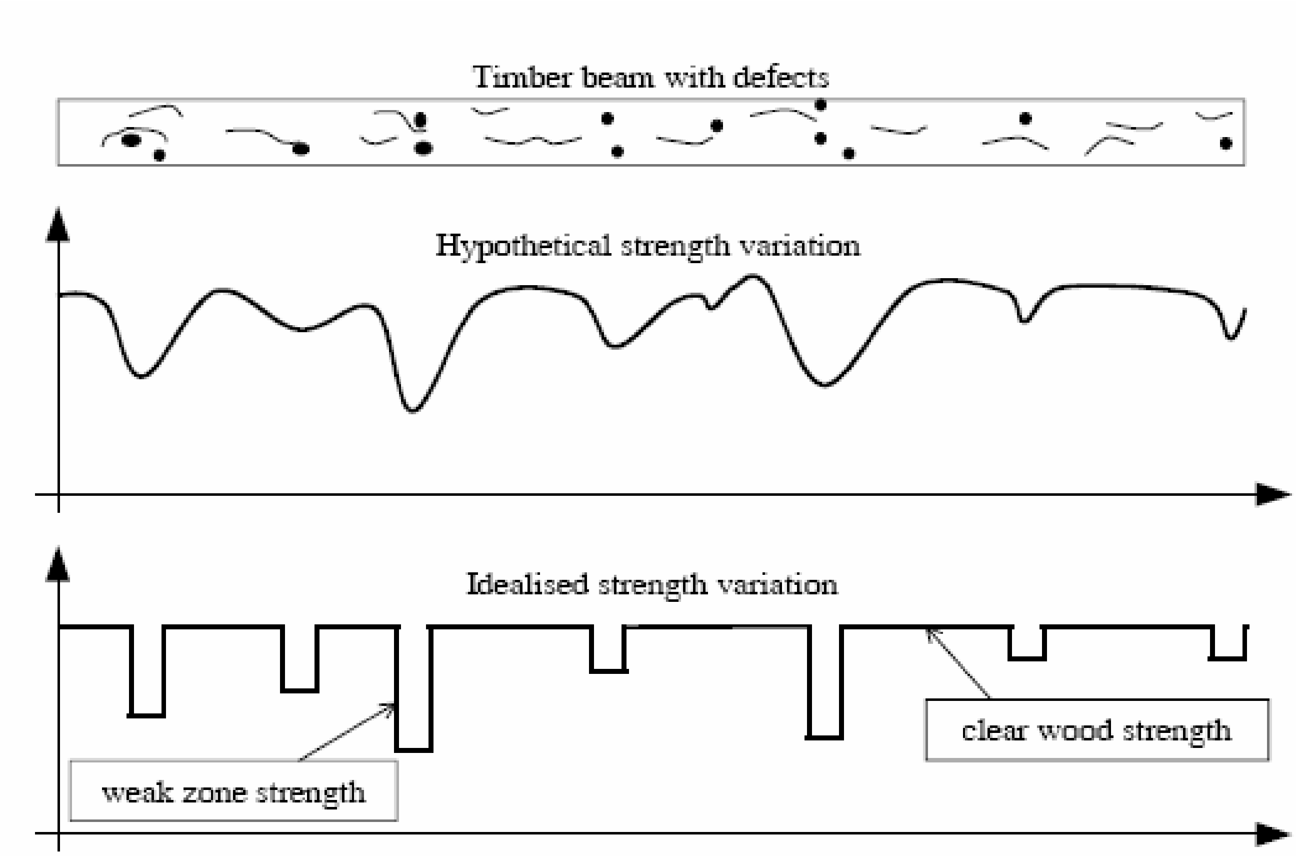


General systems



Gollwitzer & Rackwitz 1990

Systems – one beam



Systems – one beam

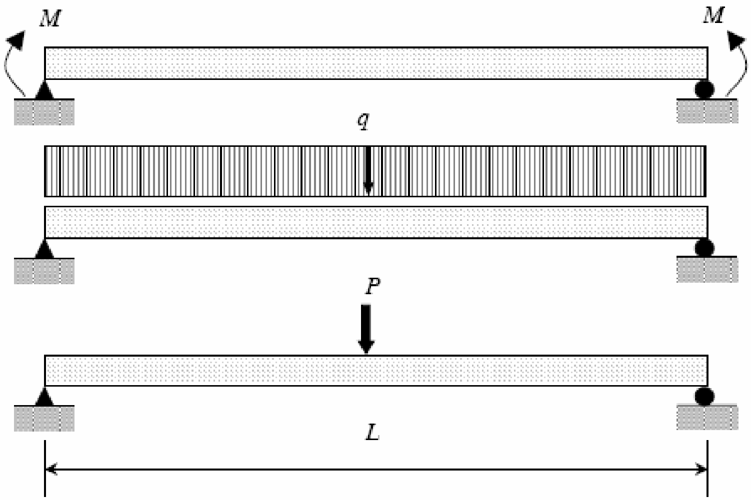
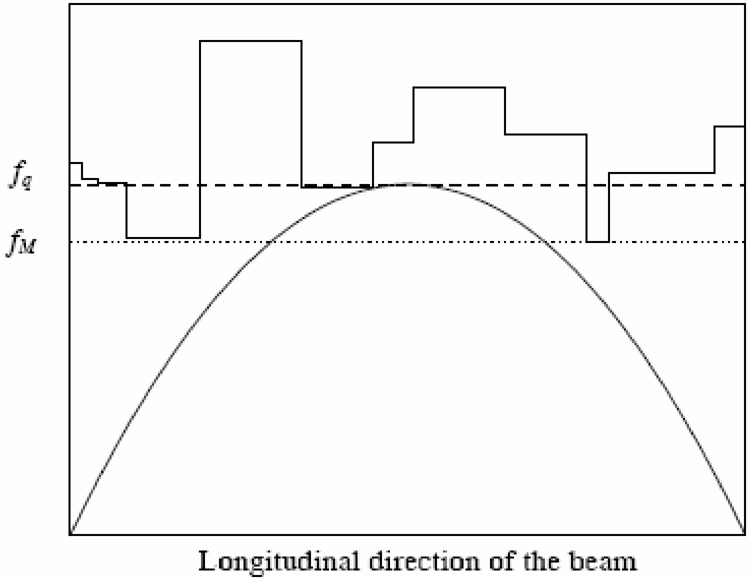
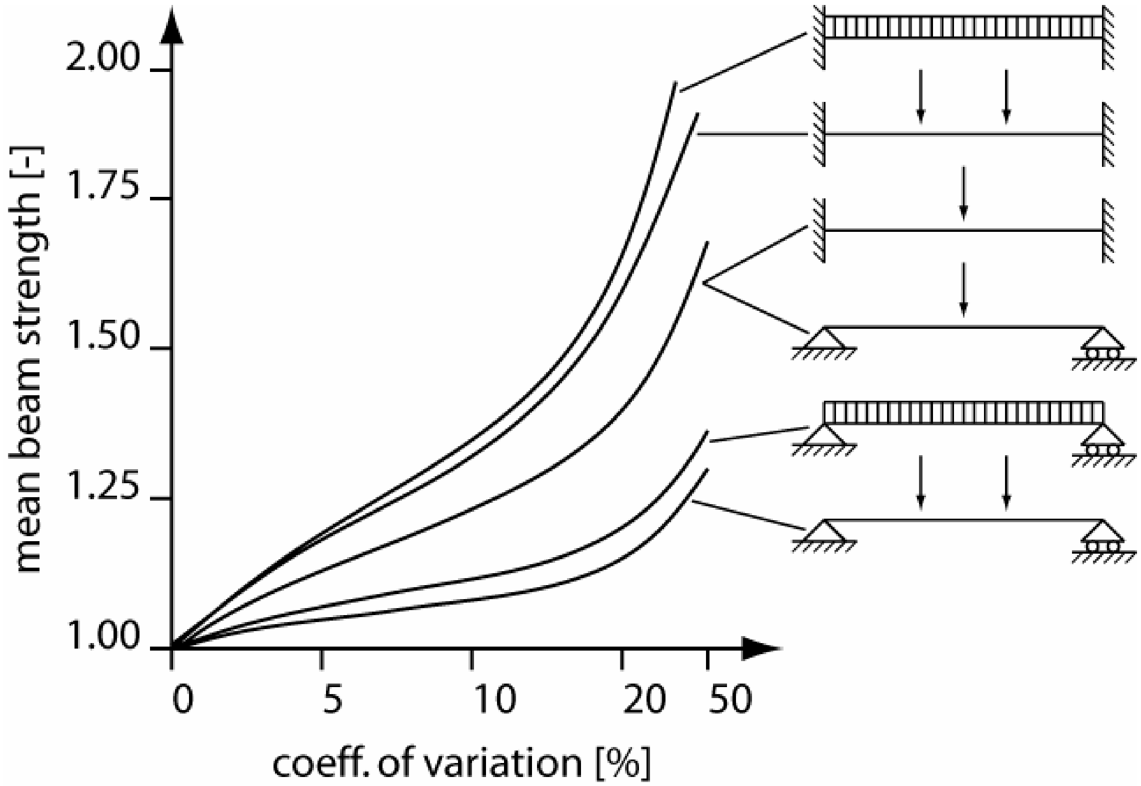


Figure 3: Load configurations. Isaksson (1999).

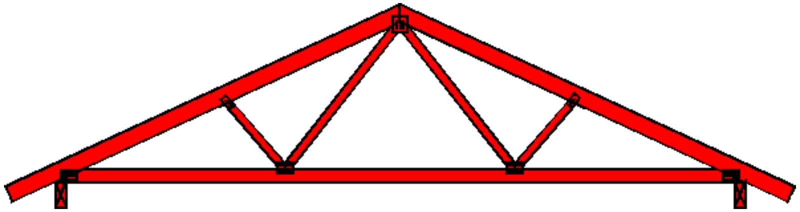


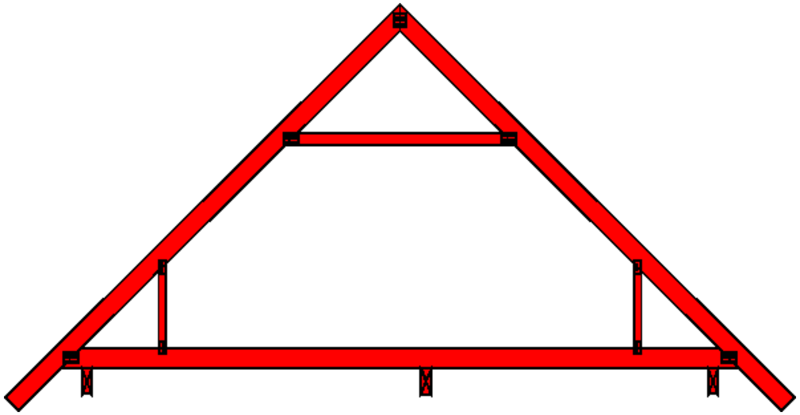
Systems – one beam



Load bearing capacity of roof trusses

- Stochastic model for strength of timber beam
- Load bearing capacity of roof truss
- Statistical characteristics
- Reliability aspects





Based on paper by Sørensen, Damkilde & Munch-Andersen, 2004

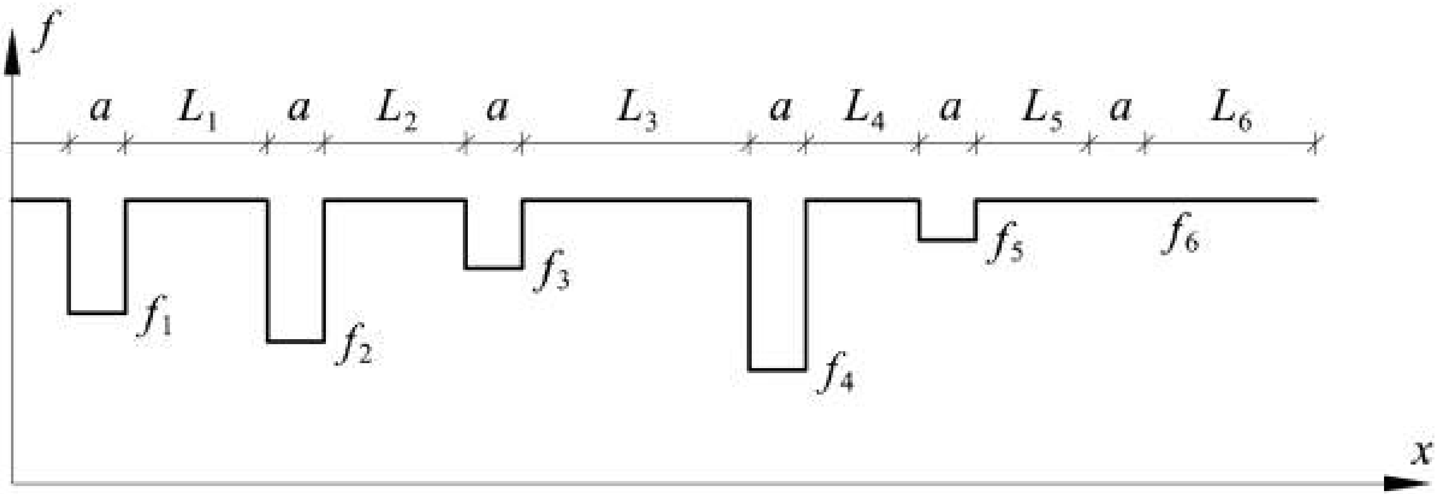
Load bearing capacity of roof trusses

- Structural timber elements: strength and stiffness vary randomly along elements due to natural variability
- Systems effect in timber systems due to
  - unlikely that maximum load effects occur at cross-sections with very low strength
  - redistribution of load effects such that cross-sections with low strength and stiffness will generally not have large load effects
  - non-linear material behaviour
- Stochastic model for
  - bending strength and stiffness of timber beams
  - typical timber structural systems such as roof trusses

- Statistical characteristics of load bearing capacity

Stochastic model

- Bending strength of timber beam



Stochastic model

Bending strength:

- Lognormal distributed: $f_{ij} = \tau_i \ \varepsilon_{ij}$ $COV = 0.25$

  τ_i = mean strength of beam no i: Lognormal

  ε_{ij} = difference between mean strength of beam i and strength in cross-section j: Lognormal
- 40% and 60% of the variance of f_{ij} are related to τ_i and ε_{ij}

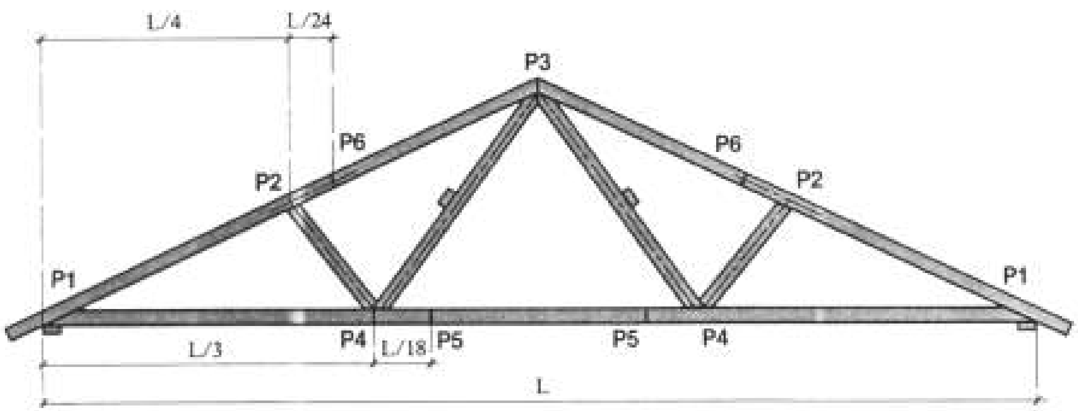
Compression strength:

- Lognormal distributed $COV = 0.15$

Tension strength:

- Lognormal distributed $COV = 0.30$

Example 1 – roof truss

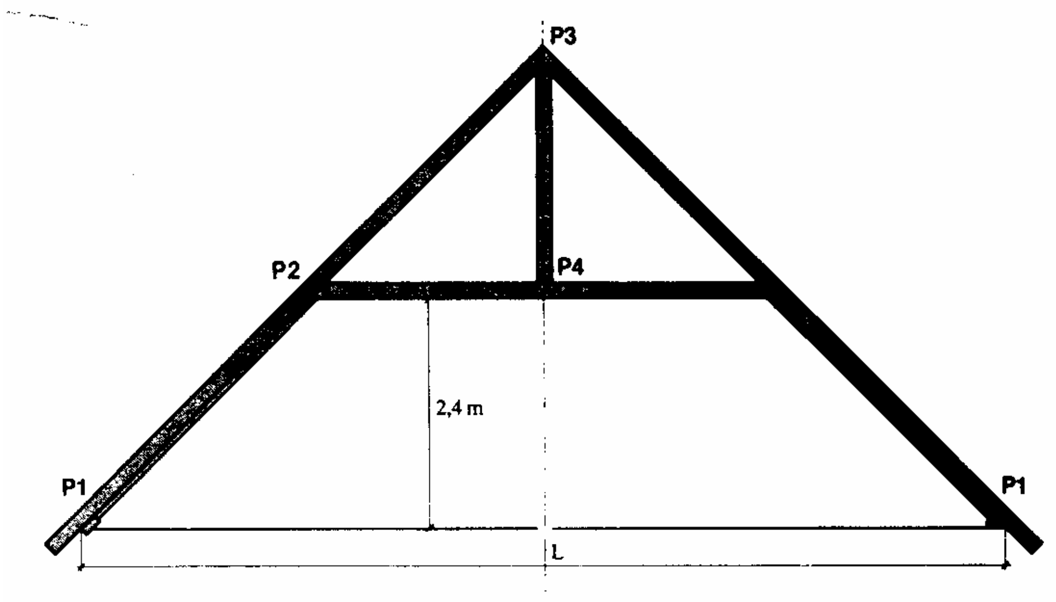


Load: permanent + snow

Example 1 – roof truss

Load:	permanent		snow		permanent + snow	
	COV	$P_{0.05}$	COV	$P_{0.05}$	COV	$P_{0.05}$
Non-parametric	0.13	2.51	0.12	2.80	0.13	2.33
LogNormal	0.17	2.51	0.14	2.79	0.17	2.32
Weibull-2p	0.10	2.53	0.09	2.81	0.11	2.33
$P_{0.05}$		2.47		2.88		2.08

Example 2 – collar tie roof truss



Load: permanent + snow + imposed

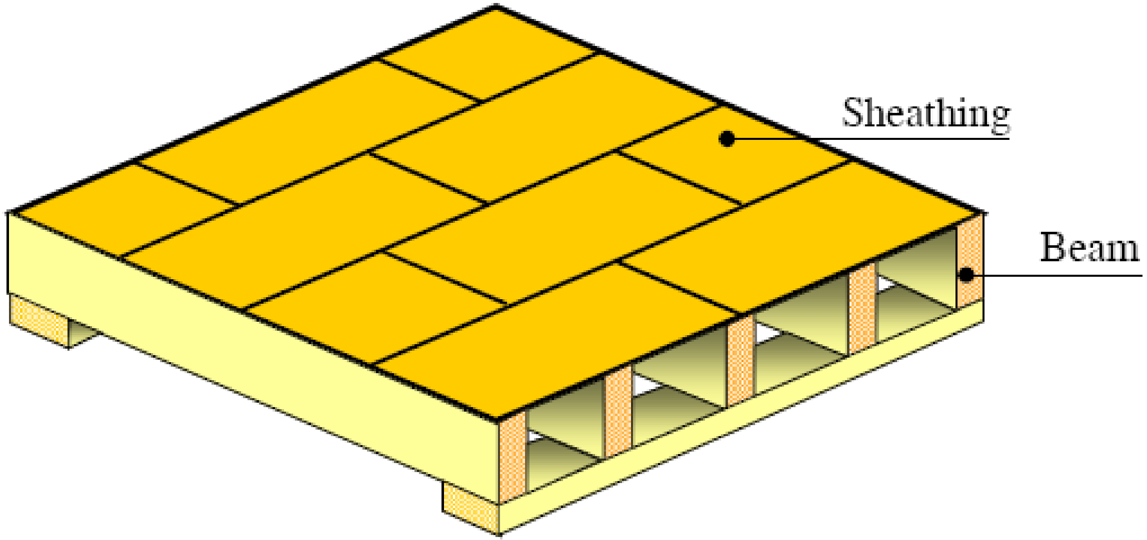
Example 2 – collar tie roof truss

Load:	Permanent load		Imposed load		Snow load		Imposed + permanent load		Snow + imposed + permanent load	
	COV	$P_{0.05}$	COV	$P_{0.05}$	COV	$P_{0.05}$	COV	$P_{0.05}$	COV	$P_{0.05}$
Non-par.	0.09	3.19	0.16	5.70	0.13	9.97	0.18	4.69	0.15	7.87
LogNormal	0.13	3.17	0.18	5.67	0.16	9.87	0.21	4.66	0.20	7.77
Weibull-2p	0.08	3.19	0.11	5.72	0.10	9.94	0.13	4.70	0.13	7.84
$P_{0.05}$		2.99		5.55		9.80		3.65		6.14

Summary for truss element examples

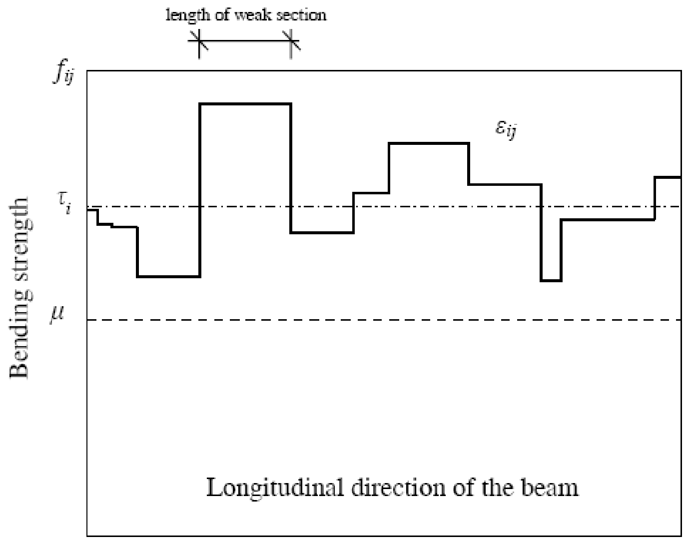
- Load-bearing capacity: COV is approximately 15% $\rightarrow$ system factor = 1.1
- Characteristic values are at least 10% higher $\rightarrow$ system factor = 1.1
- System factor = 1.2 for design load bearing capacity

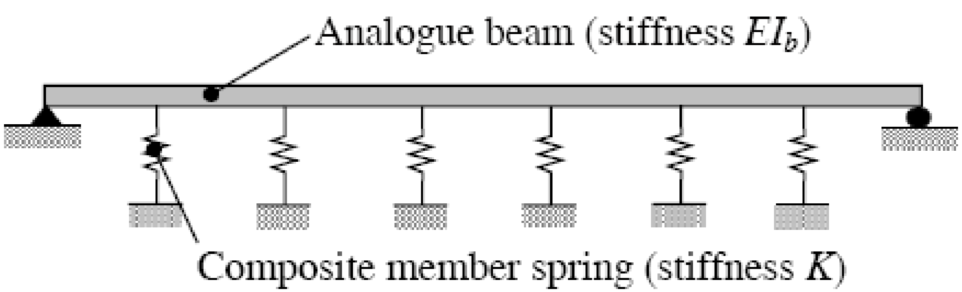
Roof elements

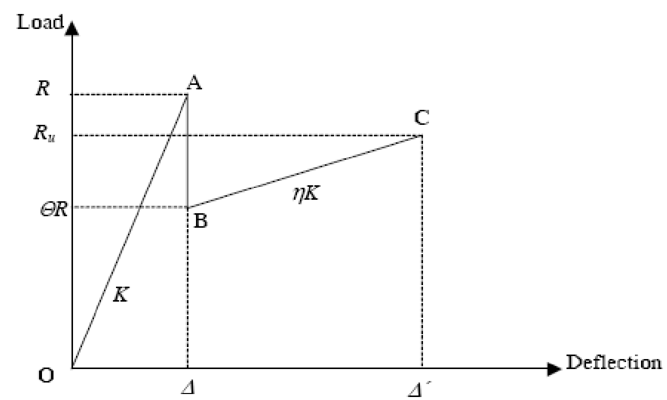


Hansson & Isaksson 2005

Roof elements - models







Roof elements

One beam:

5th percentile [MPa]	Mean value [MPa]	COV [%]
31.28	45.23	20.9

System:

Failure: - weakest section

- collapse of system (roof element)

Table 5: Simulation results for weakest T-section in the system and for the failure load of the system.

Parameter set	c [m]	n	Lj [m]	layer	k [N/m]	t : [m] n]	θ	η	Weakest T-section in system: 5th percentile [kN/m²]	mean [kN/m²]	COV [%]	Failure load: 5th percentile [kN/m²]	mean [kN/m²]	COV [%]
1	0.6	15	4.00	5	1	0.012	0.4	0.2	3.19	4.05	12.09	4.01	4.84	10.07
2	0.6	15	4.00	5	10^{75}	0.012	0.4	0.2	4.42	5.54	11.36	5.40	6.50	9.63
3	0.6	15	**5.00**	5	1	0.012	0.4	0.2	2.04	2.56	11.88	2.59	3.08	9.29
4	0.6	15	**5.00**	5	10^{75}	0.012	0.4	0.2	2.84	3.51	11.11	3.48	4.12	8.87
5	0.6	15	4.00	**7**	1	**0.018**	0.4	0.2	3.20	4.06	12.07	4.14	4.92	9.64
6	0.6	15	4.00	**7**	10^{75}	**0.018**	0.4	0.2	5.28	6.60	11.33	6.52	7.76	9.49
7	0.6	10	4.00	5	1	0.012	0.4	0.2	3.36	4.25	12.98	4.14	5.02	10.91
8	0.6	10	4.00	5	10^{75}	0.012	0.4	0.2	4.64	5.79	12.19	5.59	6.72	10.28
9	**0.4**	15	4.00	5	1	0.012	0.4	0.2	4.78	6.07	12.09	6.20	7.37	9.60
10	**0.4**	15	4.00	5	10^{75}	0.012	0.4	0.2	6.63	8.31	11.36	8.29	9.82	9.34
11	0.6	15	4.00	5	1	0.012	**0.2**	**0.1**	3.19	4.05	12.09	3.94	4.74	10.41
12	0.6	15	4.00	5	10^{75}	0.012	**0.2**	**0.1**	4.42	5.54	11.36	5.26	6.34	10.09

Roof elements

System:

Failure: - weakest section
- collapse of system (roof element)

Parameter set	Weakest T-section in system 5th percentile [kN/m²]	mean [kN/m²]	COV [%]	Failure load 5th percentile [kN/m²]	mean [kN/m²]	COV [%]
1	3.19	4.05	12.09	4.01	4.84	10.07
2	4.42	5.54	11.36	5.40	6.50	9.63
3	2.04	2.56	11.88	2.59	3.08	9.29
4	2.84	3.51	11.11	3.48	4.12	8.87
5	3.20	4.06	12.07	4.14	4.92	9.64
6	5.28	6.60	11.33	6.52	7.76	9.49
7	3.36	4.25	12.98	4.14	5.02	10.91
8	4.64	5.79	12.19	5.59	6.72	10.28
9	4.78	6.07	12.09	6.20	7.37	9.60
10	6.63	8.31	11.36	8.29	9.82	9.34
11	3.19	4.05	12.09	3.94	4.74	10.41
12	4.42	5.54	11.36	5.26	6.34	10.09

Summary

- Robustness
  - Key elements
  - Redundancy – local failure does not imply collapse
  - Ductility
  - 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

WG3 – focus points

Reliability of timber systems:

- Spatial dependence for material strength parameters / loads
- Reliability / risk assessment of
  - Roof trusses / Roof elements / Glued laminated beams / timber systems of solid timber / …

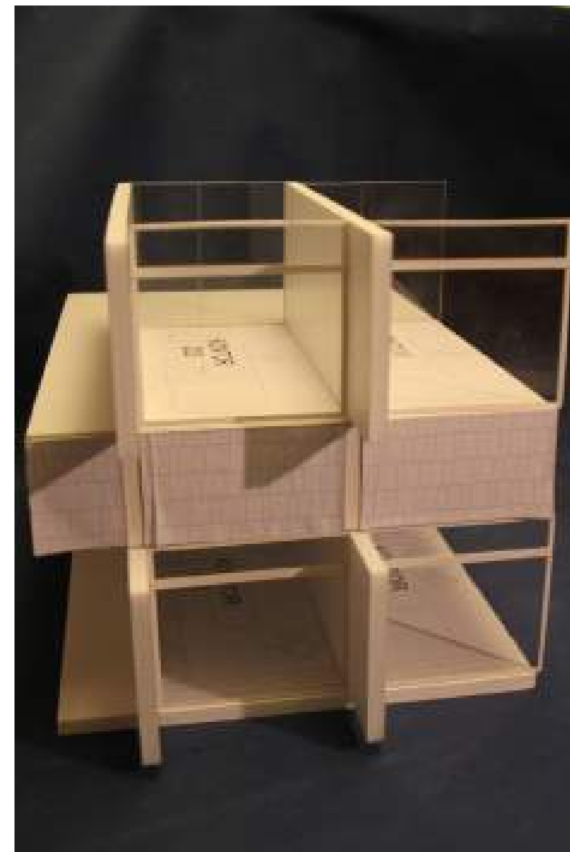
Robustness of timber structures:

- Reliability / risk based requirements related to consequences of direct failure and follow-up consequences
- Consensus on the characteristics of timber systems regarding redundancy and robustness
- Development of simplified approaches for assessment of robustness, suitable for day-to-day engineering purposes

Robustness of timber systems

Example:

Solid timber structures – robustness problems?



WG3

Link to:

- JCSS Task-Group on Robustness – report primo 2008
- COST TU601 – Robustness of Structures

- COST E55-WG3: Application on timber structures

WG3

Working questions:

- How to model and assess reliability of timber structures modelled as systems?
- Ductile / brittle failures?
- Key elements – how to design? To which reliability level?
- Robustness index for timber structures?
- How is robustness requirements in Eurocodes handled for timber structures? Information in National Annexes?