Robustness analysis of a timber structure with ductile behaviour in compression

UNIVERSITY OF ZAGREB
FACULTY OF CIVIL ENGINEERING
STRUCTURES DEPARTMENT
10000 Zagreb, Kačićeva 26
tel. 385 1 4639 390, fax: 385 1 4828 052

AALBORG UNIVERSITY
Department of Civil Engineering

Dean Čizmar
John Dalsgaard Sørensen
Poul Henning Kirkegaard,
Vlatka Rajčić

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Introduction

- *A progressive collapse of a building is defined as a catastrophic partial or total failure that starts from local damage, caused by a certain event, that can't be absorbed by the structural system itself (Ellingwood).*

World Trade Center, 2001.

Alfred P. Murrah

Introduction

- *Progressive collapse is characterized by disproportion between the magnitude of a triggering event and resulting in collapse of large part or the entire structure*

Ronan Point, 1968.

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Introduction

Robustness of large-span timber roof structures — Two examples (Jorgen Munch-Andersen, Philipp Dietsch,2011)

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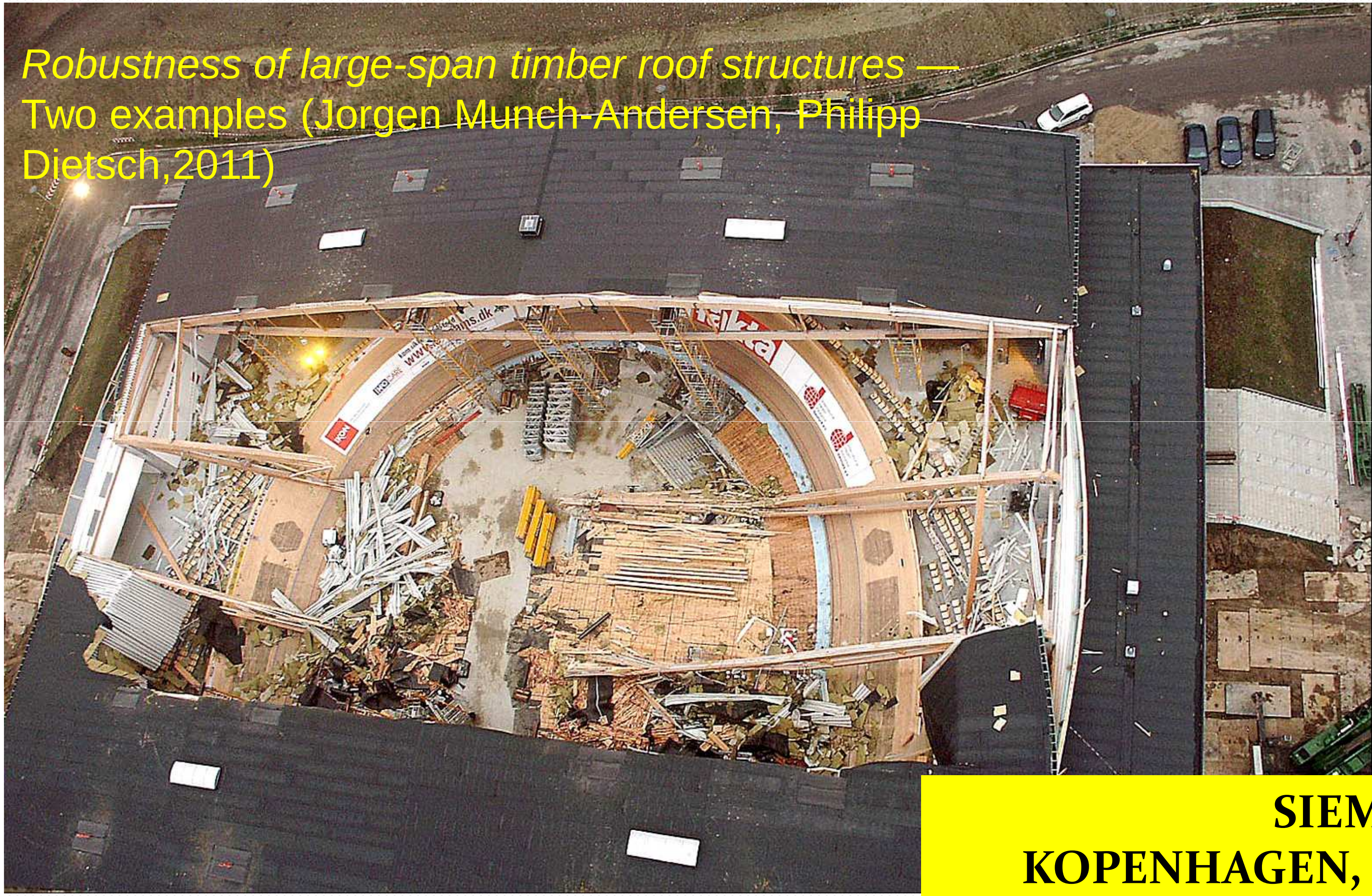
Bad Richenhall (1970), 2006.

Introduction

Robustness of large-span timber roof structures — Two examples (Jorgen Munch-Andersen, Philipp Dietsch,2011)



SIEMENS ARENA, KOPENHAGEN, 2001.

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Introduction

Different definitions of robustness

Introduction

PROBABILISTIC (RELIABILITY BASED) DEFINITIONS

Frangopol and Curley - probabilistic structural redundancy index (RI):

$$RI = \frac{P_{f(dmg)} - P_{f(sys)}}{P_{f(sys)}}$$

high robustness : $RI \to 0$

low robustness : $RI \to \infty$

redundancy factor

$$\beta_R = \frac{\beta_{\text{int}\,act}}{\beta_{\text{int}\,act} - \beta_{damaged}}$$

high robustness : $\beta_R \to \infty$

low robustness : $\beta_R \to 0$

The vulnerability (V) of a system (Lind):

$$V = \frac{P(r_d, S)}{P(r_0, S)}$$

Very hard to classify structures according to these robusteness indices – range $[0, \infty >$

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Introduction

A new robustness index is proposed (system level):

$$I_{rob,l} = \min\left\{\frac{\beta_{sys,dmg,l}}{\beta_{sys,\text{int}}};1\right\} \quad \forall\beta_{sys,dmg,l} \geq 0, \forall\beta_{sys,\text{int}} > 0 \qquad I_{rob} \in [0,1]$$

Ideal robust structure $I_{rob} = 1$

Non robust structure $I_{rob} = 0$

Introduction

- Robustness index can be simplified and extended to componential level:

$$I_{rob,k,l} = \min\left\{\frac{\beta_{dmg,k,l}}{\beta_{\text{int},k}};1\right\} \quad \forall\beta_{dmg,k} \geq 0, \forall\beta_{\text{int},k} > 0$$

$I_{rob,k,l}$ Robustnes index of component *k* when component *l* is damaged (failed)

2. Sport centre in Samobor

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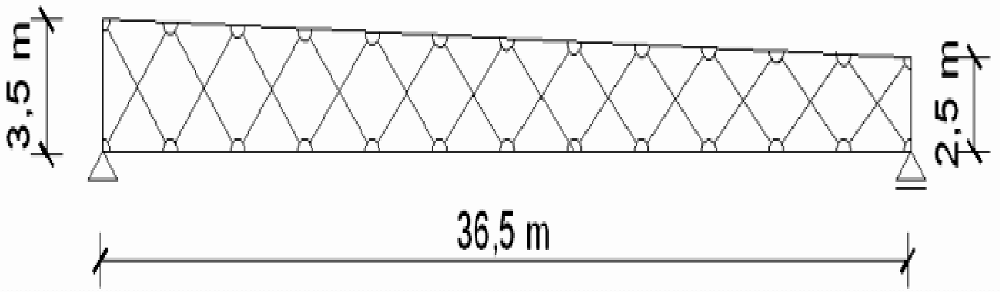
2. Sport centre in Samobor



The total area of the considered sport centre is 5910 m². It consists of three main parts: 1) main hall with dimensions 36,5x45 m, 9 (m) height for 600 visitors, 2) swimming pool with dimensions 12, 5x25, 10 (m) and depth from 1, 8 to 2, 4 (m) and 3) two smaller halls with dimensions 20x15 (m).
The structure was calculated according to Eurocode 5. The design was performed by Chair for the timber structures at the Faculty of Civil Engineering (prof. Rajcic), University of Zagreb

2. Sport centre in Samobor

For design characteristic values of permanent load (g= 6.38 kN/m), snow load (s=7.5 kN/m) and wind load (w=0.9 kN/m) are used. The material is timber GL32k. Based on the design the following cross section dimensions were chosen: **upper chord 20/52 cm, lower chord 20/69 cm and diagonal elements 20/24 cm.**

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3. Probabilistic model

Reliability index is estimated by means of FORM

Second order effects are neglected for beams subjected to compression and combined compression and bending

Buckling problems and lateral buckling is taken into account as in Eurocode 5 with deterministic coefficients.

3. Probabilistic model

Identification of the significant failure modes of this structure is difficult to perform since there are many possible failure elements.

Assumed failure modes:

Failure in lower cord (N+M)

Failure due to tension in diagonal element (N)

Failure due to compression in diagonal element (N)

Failure in upper chord (N+M)

3. Probabilistic model

Limit state equations (for given failure elements)

$$g_1 = X - \frac{N_E}{0.8 \cdot ft \cdot b\_dp \cdot h\_dp \cdot k_{mod}} - 6 \cdot \frac{M_E}{0.8 \cdot fm \cdot b\_dp \cdot (h\_dp)^2 \cdot k_{mod}}$$

$$g_2 = X - \frac{N_E}{0.8 \cdot ft \cdot b\_d \cdot h\_d \cdot k_{mod}}$$

$$g_3 = X - \frac{N_E}{fc \cdot b\_d \cdot h\_d \cdot k_c \cdot k_{mod}}$$

$$g_4 = X - \frac{N_E}{k_c \cdot ft \cdot b\_dp \cdot h\_dp \cdot k_{mod}} - 6 \cdot \frac{M_E}{k_{crit} \cdot fm \cdot b\_gp \cdot (h\_gp)^2 \cdot k_{mod}}$$

3. Probabilistic model

Probabilistic variables

Label	Designation	Distribution	Mean value	COV
Es	MOE	LN	1170	0.13
X	Model uncertain.	LN	1	0.10
a	Joint distance	N	304.08	0.01
b_d	Width of diagonals	N	20	0.04
h_d	Height of diagonals	N	24	0.04
b_dp	Width - lower chord	N	20	0.04
h_dp	Height - lower chord	N	69	0.04
b_gp	Width - upper chord	N	20	0.04
h_gp	Height - upper chord	N	52	0.04
fc	Compression str.	L	2.66	0.12
fm	Bending str.	L	4.14	0.15
ft	Tension str.	L	2.48	0.18
g	Permanent load	N	0.068	0.10
s	Snow load	G	0.030	0.58

*Mean values of strengths are in kN/cm^2, dimensions in cm, actions in kN/cm^1.

4. Results

The element reliability indices

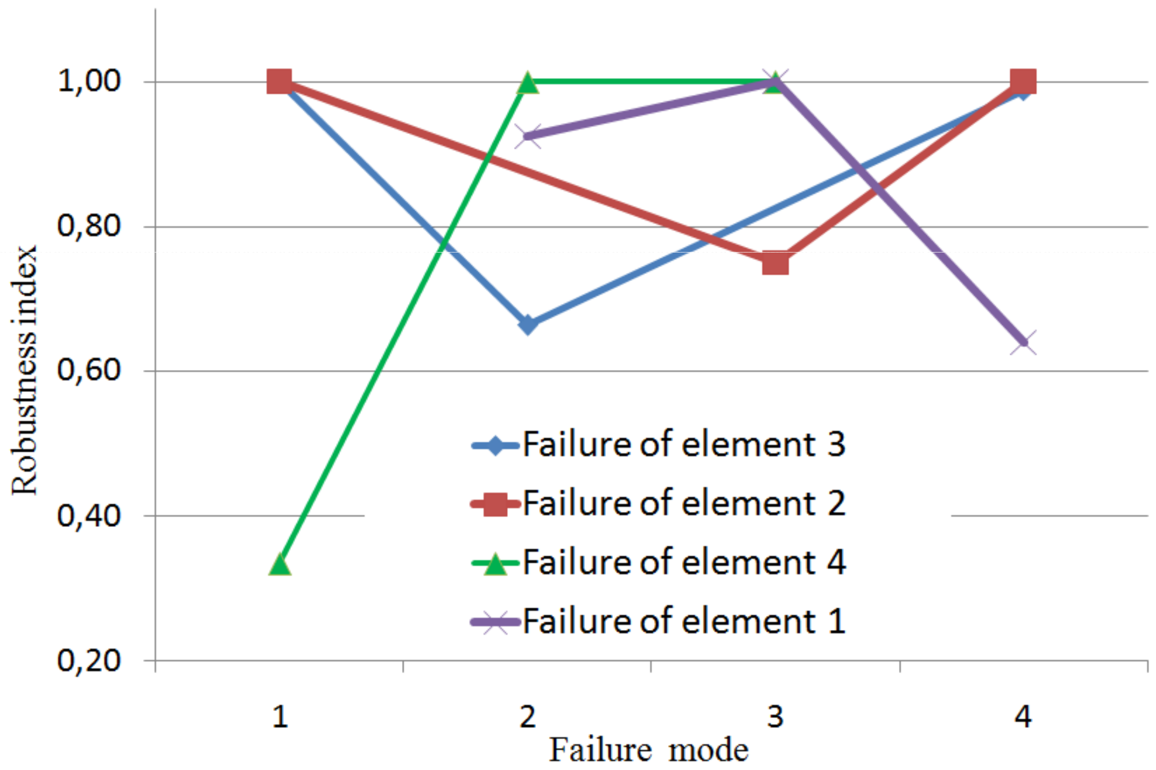
Element number	Beta index
1	4.99
2	7.76
3	7.04
4	4.46

Relative cost of safety measure	Minor consequences of failure	Moderate consequences of failure	Large consequences failure
Large (A)	$\beta = 3.1\ (P_f \approx 10^{-3})$	$\beta = 3.3\ (P_f \approx 5 \cdot 10^{-4})$	$\beta = 3.7\ (P_f \approx 10^{-4})$
Normal (B)	$\beta = 3.7\ (P_f \approx 10^{-4})$	$\beta = 4.2\ (P_f \approx 10^{-5})$	$\beta = 4.4\ (P_f \approx 5 \cdot 10^{-6})$
Small (C)	$\beta = 4.2\ (P_f \approx 10^{-5})$	$\beta = 4.4\ (P_f \approx 5 \cdot 10^{-6})$	$\beta = 4.7\ (P_f \approx 10^{-6})$

Target reliability values for ultimate limit states (JCSS 2001)

4. Results

ANALYSIS BASED ON COMPONENTS

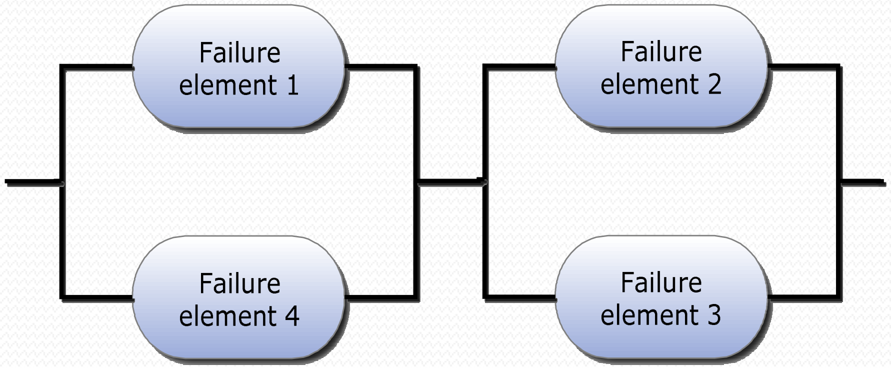


For an assumed failure of element 4 (e.g. failure in the middle of upper chord) the reliability index for element 1 is decreased to approx. 30% of intact structure

No extensive failure of the structure when elements 1,2, 3 fail

4. Results

ROBUSTNESS ON SYSTEM LEVEL



System model of the structure

The FORM approximation of a parallel system:

$$p_f = P\left(\bigcap_{i=1}^{n}\{M_i \le 0\}\right) = P\left(\bigcap_{i=1}^{n}\{g_i(X) \le 0\}\right)$$

$$p_f \approx P\left(\bigcap_{i=1}^{n}\{\beta_i^J - \alpha_i^T \cdot U \le 0\}\right)$$
$$= \Phi_{n,A}(-\beta^j, \rho)$$

$\Phi_{n,A}$: multivariate *n*-dimensional Normal distribution function

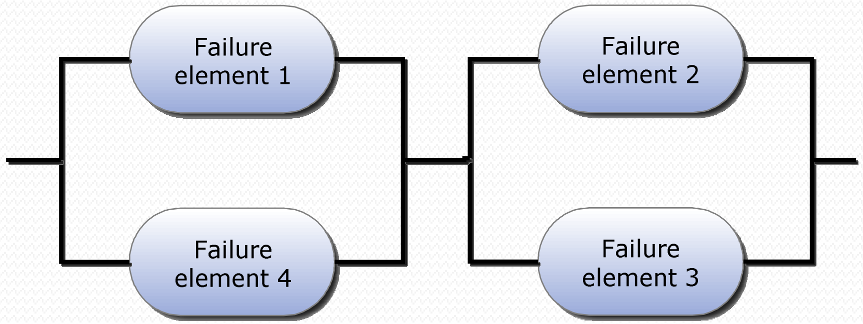
ρ: correlation matrix

4. Results

EVALUATION OF THE SYSTEM RELIABILITY

An estimate of the failure probability is: obtained as the arithmetic mean of the upper and lower probability bounds:

$$P_f^S \approx \frac{\max\left[p_{f,i}^P\right]_{i=1}^{j} + 1 - \prod_{i=1}^{j}(1 - p_{f,i}^P)}{2}$$



$\beta_{par} = 5.33$

$P_f = 5\times10^{-8}$

$P_f = 2.23\times10^{-16}$

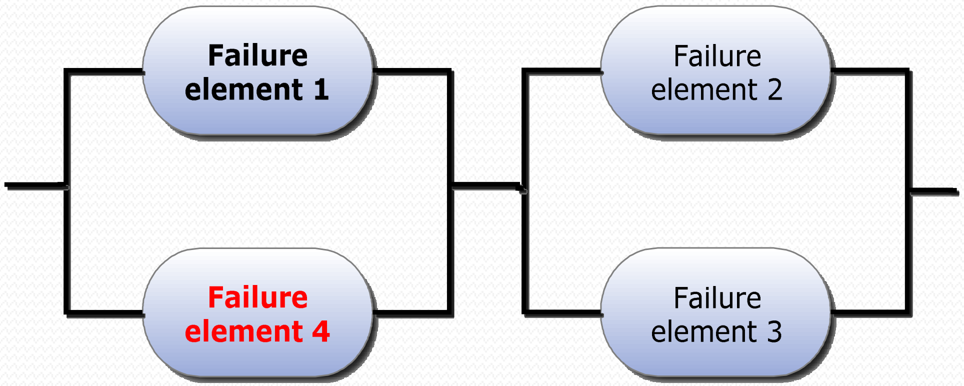
System reliability

$\beta_{sys} = 5.33$

$P_f = 5\times10^{-8}$

4. Results

For every component a failure is assumed and a system reliability is calculated :



$\beta_{par} = 1.67$

$P_f = 4.79 \times 10^{-2}$

$\beta_{par} = 8.12$

$P_f = 2.23 \times 10^{-16}$

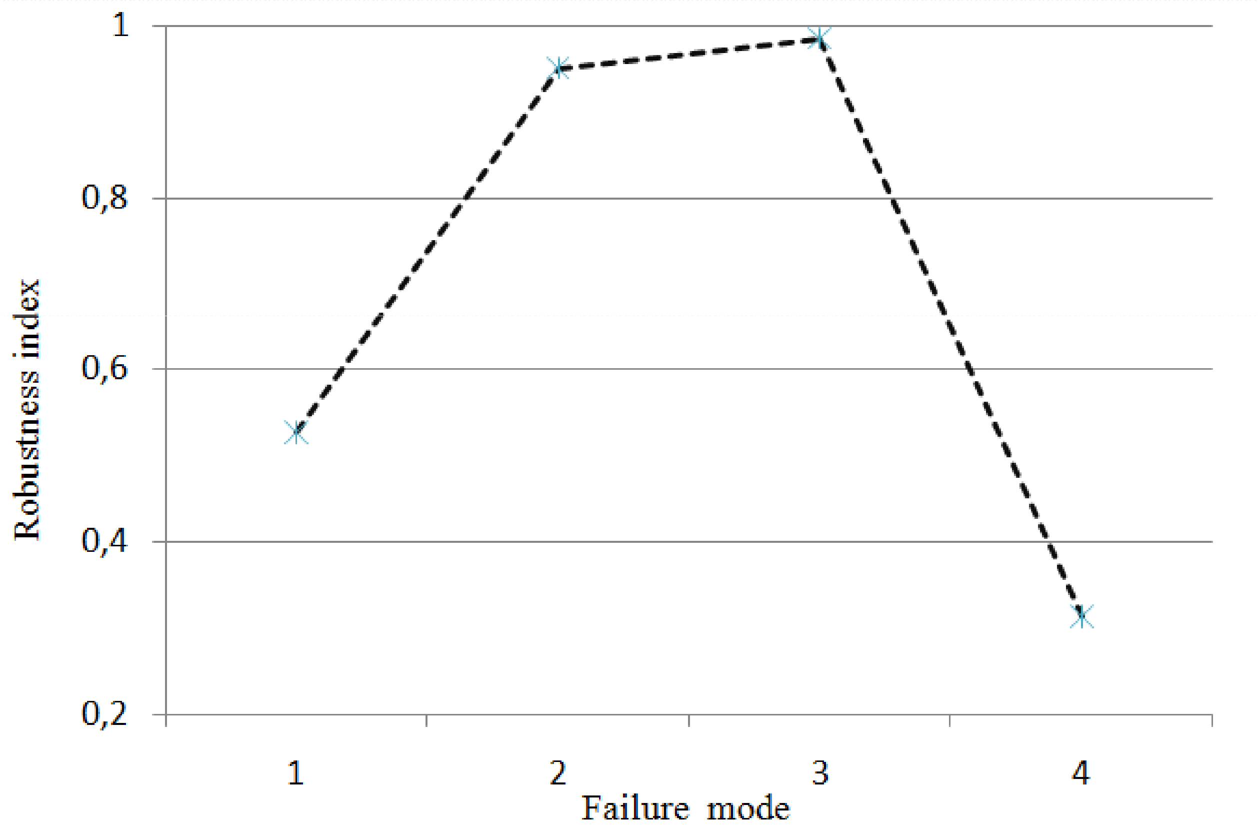
System reliability

$\beta_{sys} = 1.67$

$P_f = 4.79 \times 10^{-2}$

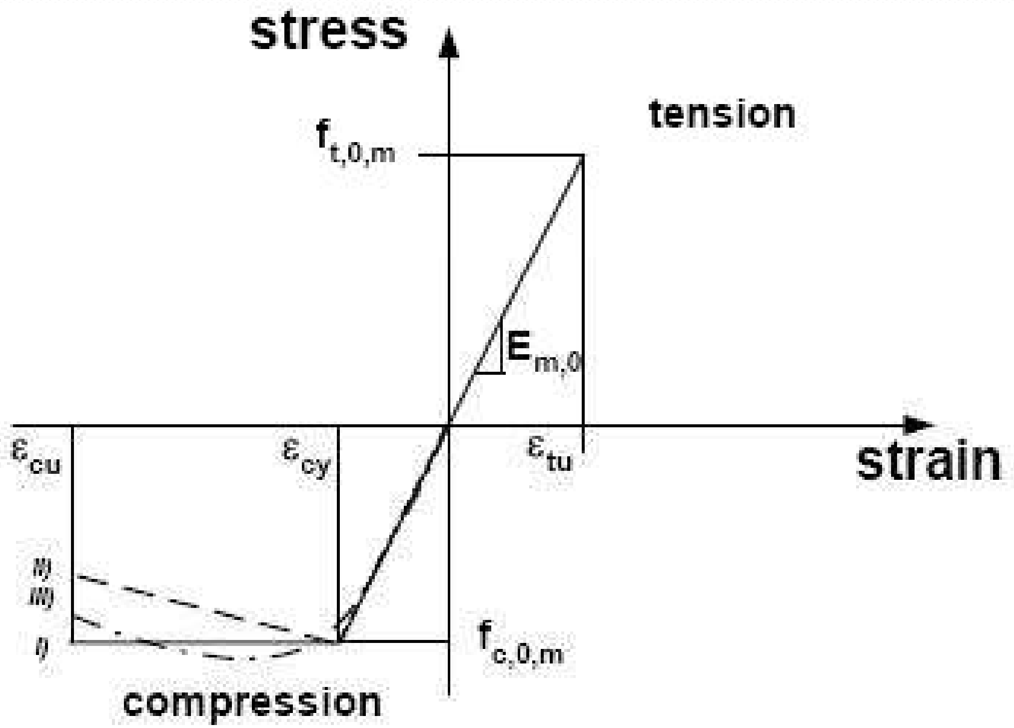
Example of failure of element 4

4. Results



- It can seen that the lowest system reliability occurs when element 4 is in failure.
- For the assumed damages in the elements 2 and 3 (e.g. tensile and compressive elements) no significant effect on the system reliability is observed, so the robustness index is high

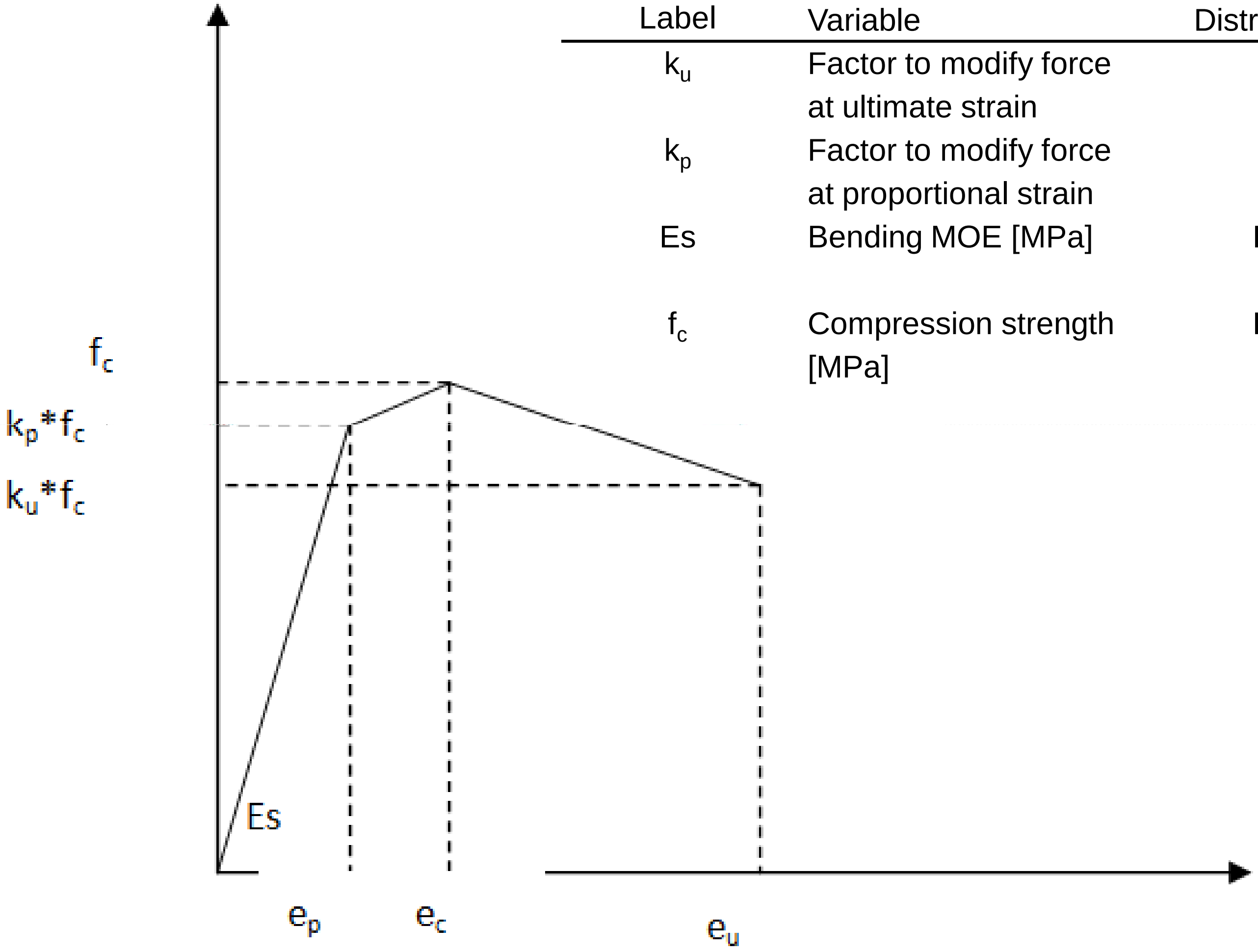
4. Results



Stress-strain diagram

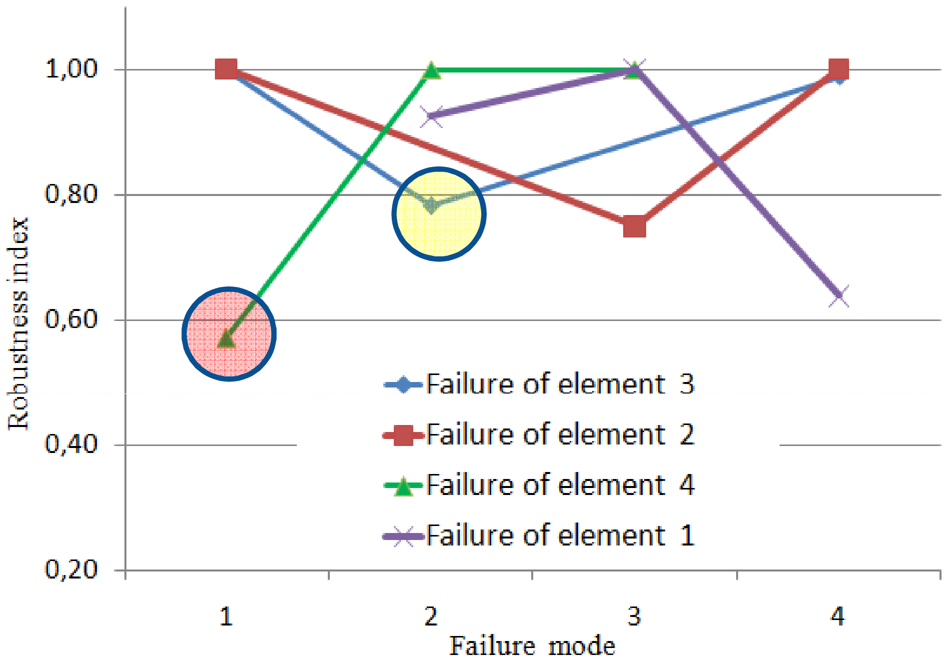
4. Results

Label	Variable	Distribution	Mean value	COV
k_u	Factor to modify force at ultimate strain	N	0.70	30%
k_p	Factor to modify force at proportional strain	N	0.80	5%
Es	Bending MOE [MPa]	LN	11700	11%
f_c	Compression strength [MPa]	LN	26.6	8.5%

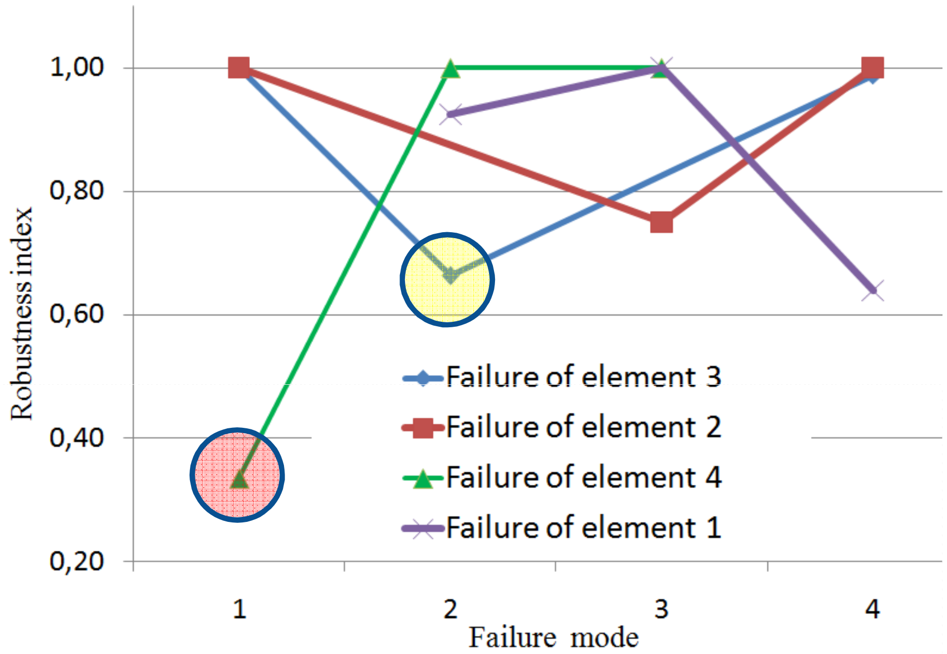


Probabilistic model

4. Results (ductility included)



Ductile behaviour



Brittle behaviour

5. CONCLUSION

- Two different probabilistic models were made (linear elastic models and ductile behaviour of timber in compression). Progressive collapse analyses are carried out by removing four structural elements one by one.
- The results based on brittle models show that the timber structure for three of the failure scenarios can be characterized as very robust with respect to the robustness framework used for the evaluation
- The results based on models with ductile behaviour of timber show that robustness indices are higher for asssumed failures of these ductile elements. Based on this model it can be concluded that for all of the failure scenarious the structure can be considered as robust.

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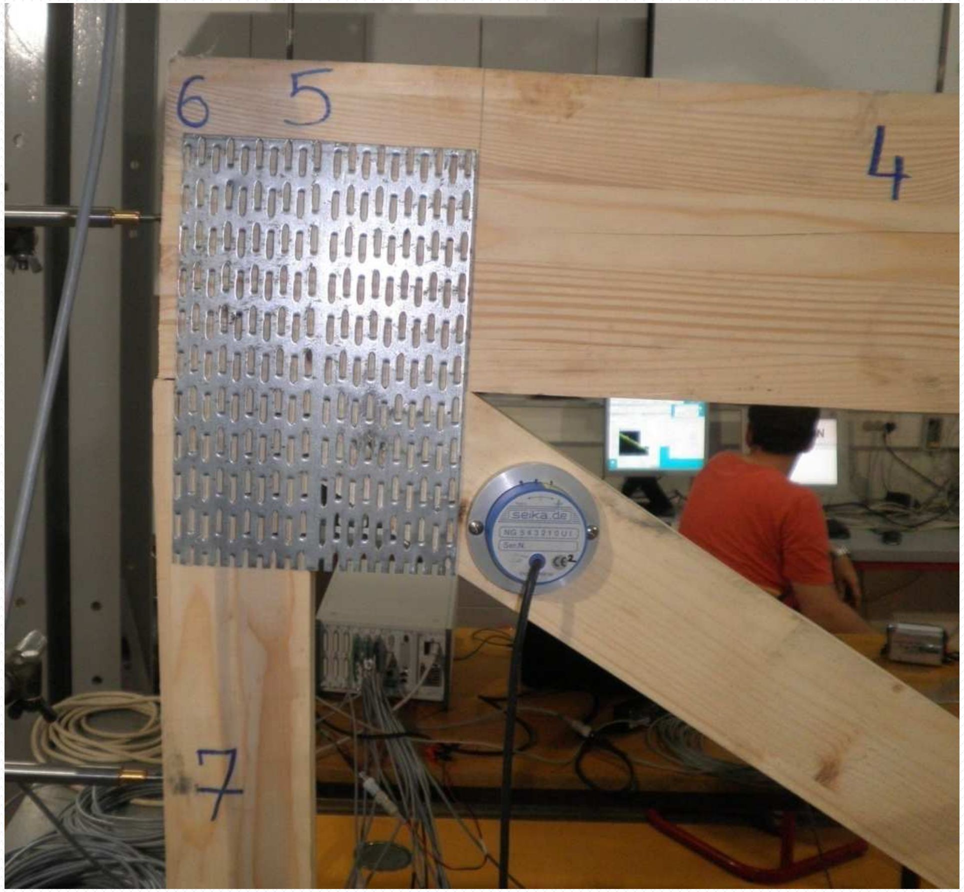
FURTHER RESEARCH

Brittle models → Material ductility → Fasterner ductility



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D1 Dean; 29.5.2011.

THANKS FOR ATTENTION

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