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ROBUSTNESS ANALYSIS OF TIMBER TRUSS STRUCTURE

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ABSTRACT. The present paper discusses robustness of structures in general and the robustness requirements given in the codes. Robustness of timber structures is also an issues as this is closely related to Working group 3 (Robustness of systems) of the COST E55 project. Finally, an example of a robustness evaluation of a widespan timber truss structure is presented. This structure was built few years ago near Zagreb and has a span of 45m. Reliability analysis of the main members and the system is conducted and based on this a robustness analysis is preformed.

KEYWORDS: robustness, reliability, probabilistic, timber truss structure

1 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 [6]. Structural design usually provides a certain amount of additional strength and ductility that is available to withstand abnormal loads and progressive collapse. But, due to "structural revolution" (use of computers, high performance materials and modern building systems) much of the inherent strength has been taken out [6]. Progressive collapse is characterized by disproportion between the magnitude of a triggering event and resulting in collapse of large part or the entire structure. Robustness of structures has been recognized as a desirable property because of a several large structural system failures, such as the Ronan Point Apartment Building in 1968, where the consequences were deemed unacceptable relative to the initiating damage. After the collapse of the World Trade Center, robustness has obtained a renewed interest, primarily because of the serious consequences related to failure of advanced types of structures. In order to minimize the likelihood of such disproportional structural failures many modern building codes require robustness of the structures and provide strategies and methods to obtain robustness.

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2 ROBUSTNESS REQUIREMENTS IN CODES

Robustness requirements are provided in two European documents: Eurocode EN 1990: Basis of Structural Design [2] and EN 1991-1-7 Eurocode 1: Part 1-7 Accidental Actions [4]. The first document provides the basic principles, e.g. it is stated that a structure shall be "designed in such a way that it will not be damaged by events like fire, explosions, impact or consequences of human errors, to an extent disproportionate to the original cause". It also states that potential damage shall be avoided 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 localized damage; avoiding as far as possible structural systems that can collapse without warning; tying the structural members together". The EN 1991-1-7 document provides strategies and methods to obtain robustness, actions that should be considered and different design situations: 1) designing against identified accidental actions, and 2) designing unidentified actions (where designing against disproportionate collapse, or for robustness, is important). The methods used to design for robustness of a structure are divided into several levels based on the potential consequences of structural failure (Consequence Class). CC1 represents low consequence class with no special requirements, CC2 are structures with medium consequences that can be handled using a simplified analysis, while CC3 stands for high consequence class where a reliability or risk analysis is recommended [1]. However, there are no specific criteria which could be used to quantify the level of robustness of a structure.

In the JCSS Probabilistic Model Code [7] a robustness requirement is formulated as: "A structure shall not be damaged by events like fire, explosions or consequences of human errors, deterioration effects, etc. to an extend disproportionate to the severeness of the triggering event". In order to attain adequate safety in relation with accidental loads, two basic strategies are proposed: non-structural measures (prevention, protection and mitigation) and structural measures (making the structure strong enough to withstand the loads limiting the amount of structural damage or limiting the amount of structural damage).

According to Danish design rules robustness shall be documented for all structures where consequences of failure are serious. A structure is defined as robust when those parts of the structure essential for the safety only have little sensitivity with respect to unintentional loads and defects, or that an extensive failure of the structure will not occur if a limited part of the structure fails. The requirements regarding structural robustness are related to those unintentional loads and defects that are not included in the codes and design requirements. Such a robustness analysis framework is introduced in the Danish Code of Practice for the Safety of Structures [13].

3 ROBUSTNESS OF STRUCTURES

3.1 INTRODUCTION

In the last few decades many definitions of robustness have benne proposed. In this paper only a brief description of probabilistic measures relevant for robustness assessment is given.

Frangopol and Curley [16] proposed a probabilistic structural redundancy index (RI):

$$RI = \frac{P_{f(dmg)} - P_{f(sys)}}{P_{f(sys)}} \tag{1}$$

where $P_{f(dmg)}$ is the probability of failure of a damaged system and $P_{f(sys)}$ is the system failure probability (no damage). The redundancy index as defined above provides a measure of the residual strength of a damaged system. They also considered the following redundancy factor:

$$\beta_R = \frac{\beta_{int\,act}}{\beta_{int\,act} - \beta_{damaged}} \tag{2}$$

where β_{intact} is the reliability index of the intact system and $\beta_{damaged}$ is the reliability index of the damaged system.

Lind [17] proposed a generic measure of system damage tolerance, based on the increase in failure probability resulting from the occurrence of damage. The vulnerability (V) of a system is defined as:

$$V = \frac{P(r_d, S)}{P(r_0, S)} \tag{3}$$

where r_d is the resistance of the damaged system, r_0 is the resistance of the undamaged system, and S is the prospective loading on the system $P(\cdot)$ is the probability of failure of the system, as a function of the load and resistance of the system. The vulnerability parameter indicates the loss of system reliability due to damage. As progressive collapse is characterised by disproportion between the magnitude of a triggering event and resulting in collapse of large part or the entire structure [20], Ellingwood and Leyendecker [19] defined the probability of such collapse as a chain of conditional probabilities:

$$P(F) = P(F|DH) \cdot P(D|H) \cdot P(H) \tag{4}$$

where $P(H)$ denotes the probability of an abnormal event that threatens the structure (generally the hazard H), $P(F|DH)$ is the probability of local damage D as a result of event H and $P(D|H)$ is the probability of failure F of the structure as a result of local damage D or H.

$$P(F) = \overbrace{\underbrace{\overbrace{P(F|D\cap H)}^{\text{robustness}} \cdot \overbrace{P(D|H)}^{\text{element behaviour}}}_{\text{vulnerability}} \cdot \underbrace{\overbrace{P(H)}^{\text{event control}}}_{\text{hazard}}}^{\text{collapse resistance}}$$

Figure 1: *Progressive collapse*

The term hazard refers to abnormal loads or load effects. Abnormal loads can be grouped as pressure loads (e.g., explosions, detonations, tornado wind pressures), impact (e.g., vehicular collision, aircraft or missile impact, debris, swinging objects during construction or demolition), deformation-related (softening of steel in fire, foundation subsidence), or as faulty practice (e.g. human errors in design, execution or operation). The loads generally are time-varying, but may be static or dynamic in their structural action [20].

In this paper an index of robustness is defined as a ratio between the reliability index of a damaged structure (β_{dmg}) and the reliability of the intact structure (β_{int}):

$$I_{rob} = \frac{\beta_{dmg}}{\beta_{\text{int}}} \tag{5}$$

Generally, for this robustness index, system reliability indices are used, but in section 6.2 indices based only on components are calculated. Values of this index can vary between the 0 (no robustness) and 1 (ideally robust).

3.2 ROBUSTNES OF TIMBER STRUCTURES

In the last few decades there has been intensely research concerning reliability of timber structures but robustness of timber structures has not been shown much attention. One of the reasons for lacking interest / information about robustness of timber structures is that a unified approach for assessing robustness of any material is not available yet. Since timber is a complex building material, assessment of robustness is difficult to conduct. As there is obvious correlation between redundancy and robustness, redundant structures will, in principle, be a more robust than statically determinate. However, in respect to timber structures, there are not many highly redundant systems, and the obvious way to asses a robustness of such structures is to demonstrate that the part(s) of the structure essential for the reliability have little sensitivity with respect to unintentional loads and defects. In this article is presented a robustness investigation based on a probabilistic approach, of a timber truss structure built in Croatia a few years ago.

4 SPORT CENTER IN SAMOBOR

Many recent structures in Croatia, especially sports halls, swimming pools, tourist objects, passages and pedestrian bridges were built using wood (mainly glulam timber). The total area of the considered sport centre is 5910 m^2. 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). This paper will focus on the main hall. The main hall of this sport center was erected in 2005 and it is a plane frame truss spaced equally at 5 meters. 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. Figure 2 shows the built structure while figure 3 shows the static system. 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.

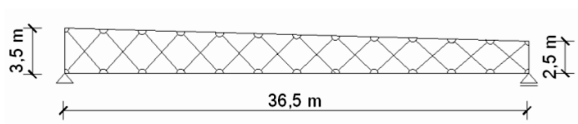


Figure 2: *Main hall of the sport centre in Samobor*

Figure 3: *Details of tensile and compressive elements*

Figure 4: *Timber truss structure of the sport hall in Samobor*

5 PROBABILISTIC MODEL OF A STRUCTURE

5.1 INTRODUCTION

In this paper probabilistic calculations were done by First-Order Reliability Methods (FORM) where a reliability index is estimated based on limit state functions for each of the considered failure modes. The probabilistic analysis is performed with a stochastic model for the strength parameters for whole structural elements, and not to the strength for the single laminates and the glue. Second order effects are neglected for beams subjected to compression and combined compression and bending, respectively. Buckling problems and lateral buckling is taken into account as in Eurocode 5 with deterministic coefficients. For the structural analysis a linear Finite Element analysis has been performed where the glulam truss has been modelled by beam and truss elements. Furthermore, only permanent and snow loads are considered in probabilistic analysis.

5.2 FAILURE MODES

Identification of the significant failure modes of this structure is difficult to perform since there are many possible failure elements. Based on the deterministic structural analysis four different failure modes are considered: 1) combination of bending and compression (M+N) in the upper chord, 2) combination of bending and tension (M+N) in the lower chord, 3) compression (N) and 4) tension in diagonal elements (N). The ultimate limit state failures are assumed to be brittle (i.e. when an element fails there is no bearing capacity left). The following failure elements are considered for these failure modes:

1. Failure in lower cord (N+M)
2. Failure due to tension in diagonal element (N)
3. Failure due to compression in diagonal element (N)
4. Failure in upper chord (N+M)

5.3 PROBABILISTIC MODEL

5.4 Probabilistic model

The stochastic model is shown in table 1 and is mainly based on information in [10]. For the calculations permanent load *G* due to self weight and a variable snow load are taken into account. The permanent load of the roof structure, is assumed Normal distributed with an expected value μ_G = 6.8 kN/m[1] and a coefficient of variation COV = 0.1.

For the region in Croatia where the structure is located the annual maximum snow load at the ground is Gumbel distributed with a characteristic value S_{gk}= 1.5 kN/m^2 (7.5 kN/m as the distance between the trusses is 5 meters) corresponding to a 98% quantile in the annual maximum distribution function. Based on this, snow load Q_{gk} on roof can be modelled by:

$$Q_{gk} = S_g \cdot C \tag{6}$$

where S_g refers to snow on ground and *C* (modelled as deterministic variable according to EC1) is the roof snow load shape factor. It is assumed that the coefficient of variation for the region near Zagreb is COV = 0.58. The following equations show how to calculate the mean value. If COV for ground snow load is assumed to be V_{Qg}, then the expected value μ_{Qs} can be determined from the Gumbel cumulative distribution function $F_{Qg}(\cdot)$ as:

$$F_{Qg}(Q_{gk}) = \exp(-\exp(-\alpha(Q_{gk} - \beta))) \tag{7}$$

$$\mu_{Qg} \approx \beta + \frac{0.577216}{\alpha}, \quad \sigma_{Qg} = \frac{\pi}{\alpha \cdot \sqrt{6}}, \qquad V_{Qg} = \frac{\sigma_{Qg}}{\mu_{Qg}} \tag{8}$$

The strength variables f_c, f_m and f_t (compression strength parallel to grain, bending strength and tensile strength, respectively) are calculated based on the reference properties given in table 1 [7]. Table 2 shows all probabilistic variables taken into account (designation, distribution, mean value and coefficient of variation). Correlations between the stochastic variables are taken as in [7] and [9].

Table 1: *Reference properties and respective distributions*

Variable	Distribution
Bending strength	LN
Bending MEO	LN
Density	N

Table 2: *Reference properties and coefficients of variation*

Variable	COV
Bending strength	0.15
Bending MOE	0.13
Density	0.10

Table 3: *Stochastic variables and respective distributions*

Variable	Distribution
MOE	LN
Model uncertain.	LN
Joint distance	N
Width of diagonals	N
Height of diagonals	N
Width of lower chord	N
Height of lower chord	N
Width of upper chord	N
Height of upper chord	N
Compression strength	LN
Bending strength	LN
Tensile strength	LN
Permanent load	N
Snow load	G

Table 4: *Stochastic variables and coefficients of variation*

Variable	COV
MOE	0.13
Model uncertain.	0.10
Joint distance	0.01
Width of diagonals	0.04
Height of diagonals	0.04
Width of lower chord	0.04
Height of lower chord	0.04
Width of upper chord	0.04
Height of upper chord	0.04
Compression strength	0.12
Bending strength	0.15
Tensile strength	0.18
Permanent load	0.10
Snow load	0.58

5.5 FORM ANALYSIS OF COMPONENTS

For each of the failure elements, the element reliability index β_i is estimated using the first-order reliability method (FORM). The element reliability indices shown in Table 3 indicate that the significant failure modes are 1 and 4. The relative ratio between the different reliability indices corresponds very well to the results from a deterministic analysis.

Table 3: *Beta indices for corresponding failure elements (reference period: one year)*

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

The requirements to the safety of the structure can be expressed in terms of an accepted minimum reliability index, i.e. a target reliability index. The Joint Committee on Structural Safety (JCSS) has proposed target reliability values for ultimate limit states (JCSS 2001). For the normal design situations the reliability index β_i (with a reference period equal to one year) should be larger or equal to 4.2. For the considered failure elements the reliabilities of the components are slightly larger (the lowest beta index is approximately 6% higher than target value given by JCSS).

5.6 SYSTEM RELIABILITY

5.6.1 Introduction

Any mechanical system may be assigned to one of the following three categories: series systems, parallel systems or combination of series and parallel system (also referred to as a hybrid system). In series systems failure of any element leads to failure of the system. Parallel systems are those systems in which the combined failure of each and every element of the system results in failure of the system. If a system does not satisfy these strict definitions of ‘‘series’’ or ‘‘parallel’’ systems, the system is classified as a hybrid system [5].

Calculation of the reliability of the hybrid structures is not an easy task to perform. It is assumed in this paper (based on the structural analysis) that failure elements 1 and 4 are connected in parallel meaning that only failure of both elements will lead into failure of the structure. The same assumption is made for failure elements 2 and 3, effectively meaning that a simplified system is a union of a two parallel systems as given in figure 4.

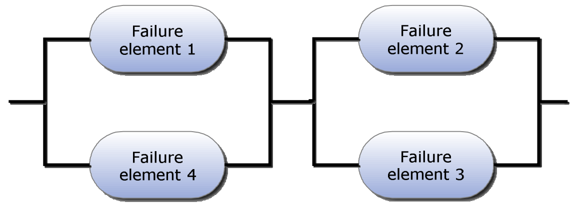


Figure 4: *System model of the structure*

5.6.2 Parallel system

If we consider a parallel system of n failure elements, than the probability of failure of the parallel system is defined as the intersection of the individual failure events:

$$p_f = P\left(\bigcap_{i=1}^{n}\{M_i \le 0\}\right) = P\left(\bigcap_{i=1}^{n}\{g_i(X) \le 0\}\right) \quad (9)$$

The FORM approximation of a parallel system can be written:

$$p_f \approx P\left(\bigcap_{i=1}^{n}\left\{\beta_i^J - \alpha_i^T \cdot U \le 0\right\}\right) = \Phi_{n,A}(-\beta^j, \rho) \quad (10)$$

where $\Phi_{n,A}$ is the multivariate n-dimensional normal distribution function and ρ is the correlation coefficient matrix where the correlation coefficients are obtained from the alpha vectors α_i and α_j:

$$\rho_{ij} = \alpha_i^T \cdot \alpha_j \quad (11)$$

Equations for the parallel system reliabilities are solved numerically in Mathematica [15].

5.6.3 Evaluation of the system reliability

The probability of failure of the series system is assessed using upper and lower bounds:

$$P_f \ge \max\left[P(F_i)\right]_{i=1}^{n} \quad (12)$$

$$P_f \le 1 - \prod_{i=1}^{n}(1 - P(F_i)) \quad (13)$$

where a lower and upper bounds correspond respectively to fully correlated and un-correlated safety margins. An estimate of the failure probability is obtained as the arithmetic mean of the upper and lower probability bounds.

The system reliability index of the intact structure becomes 5.33, see figure 5.

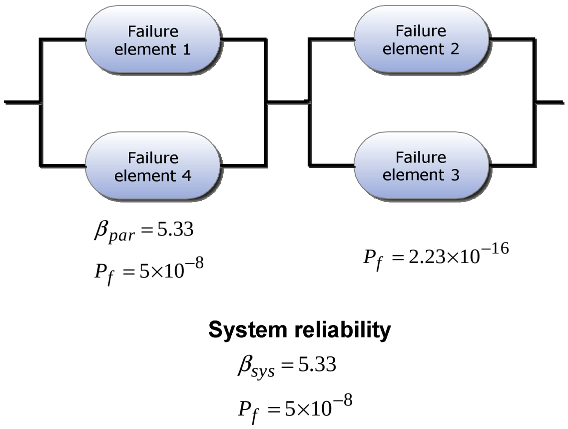


Figure 5: *System reliability of the intact structure*

6 ROBUSTNES ANALYSIS OF THE TIMBER TRUSS SYSTEM

6.1 COMPONENTAL ANALYSIS

The structure is statically indeterminate, meaning that a loss of one (or more) structural element(s) won't result in collapse of a whole structure i.e. if any of the inner (truss) elements fail, force redistribution will occur and the whole system will not necessarily collapse. For illustration the simplified approach explained in detail in [8] is used. For each of the failure elements defined previously failure is assumed (a failed element is assumed to fail in a brittle manner) and the reliability of the remaining failure elements is calculated. It is noted that only one failure element is assumed to fail at a time. In figure 6 robustness indices are shown for the remaining components after each assumed failure. Note that term failure element in figure 6 refers to failure mode defined in 5.2

Generally, after failure of one component, reliability of the other components is decreased (as the redistribution of the forces implies that the other elements have a higher utilization ratio). However, for an assumed failure of element 4 (e.g. failure in the middle of upper chord) the reliability indices for the tensile and compressive truss elements are slightly increased. In this case, redistribution slightly decreased the load effect for elements 2 and 3, but load effect for element 1 is highly increased and it can be concluded that the reliability is, for this scenario, insufficient. It is seen that with removal of the four different elements one by one, only for one failure scenario (e.g. failure in the middle of lower chord), a significant extensive failure of the entire structure or significant parts of it can be expected. This can be seen in the figure 6 where the lowest robustness index is 0.3 in case of the assumed failure of element 4. For the remaining assumed failures no significant extensive progressive failures can be expected (robustness indices are very high).

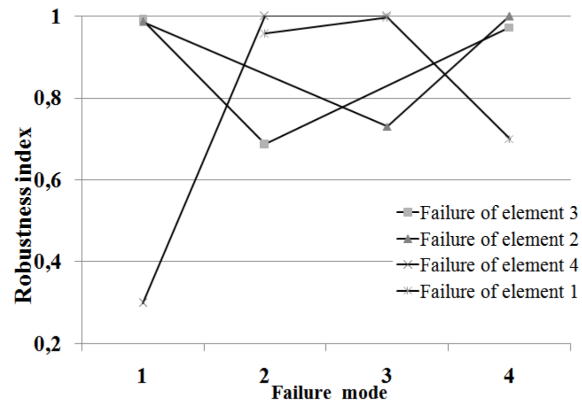


Figure 6: *Robustness indices (components)*

6.2 ROBUSTNESS ANALYSIS AT A SYSTEM LEVEL

As given in equation 5 index of robustness is based on the reliability of the system. It is assumed model as given in figure 5. System reliabilities for the damaged state are calculated according to the equations 9-13.

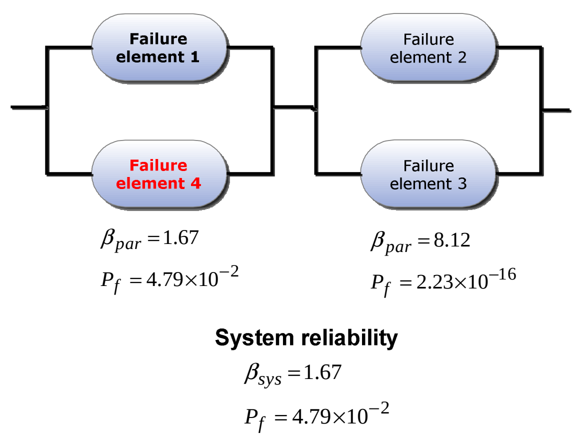


Figure 7: *System reliability with damaged element 4*

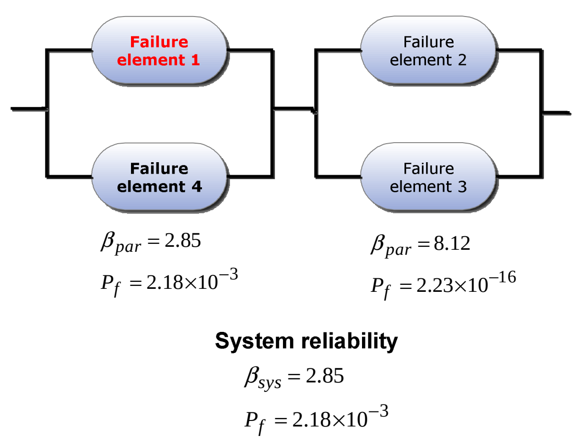
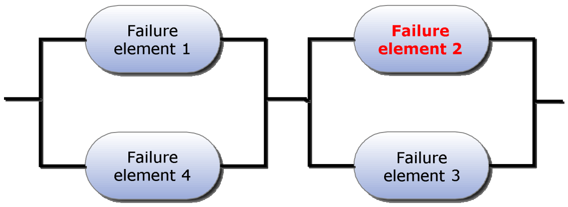


Figure 8: *System reliability with damaged element 1*



$\beta_{par} = 5.36$ $\quad$ $\beta_{par} = 5.09$

$P_f = 3.98\times10^{-8}$ $\quad$ $P_f = 1.79\times10^{-7}$

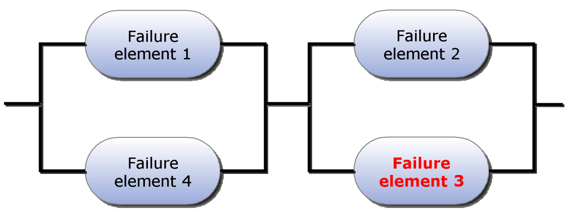
System reliability

$$2.18\times10^{-7} \geq P_f \geq 1.79\times10^{-7}$$

$$P_f \approx 1.99\times10^{-7}$$

$$\beta_{sys} \approx 5.07$$

Figure 9: *System reliability with damaged element 2*



$\beta_{par} = 5.5$ $\quad$ $\beta_{par} = 5.28$

$P_f = 1.88\times10^{-8}$ $\quad$ $P_f = 6.46\times10^{-8}$

System reliability

$$8.33\times10^{-8} \geq P_f \geq 6.46\times10^{-8}$$

$$P_f \approx 7.38\times10^{-7}$$

$$\beta_{sys} \approx 5.25$$

Figure 10: *System reliability with damaged element 3*

Table 4: *System beta indices*

System	Beta index
Intact	5.33
Failure of element 1	1.67
Failure of element 2	5.07
Failure of element 3	5.25
Failure of element 4	2.85

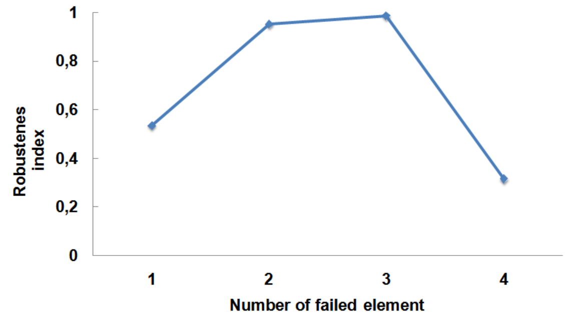


Figure 11: *Robustness index*

In figures 7 to 10 the reliability indices of the system are shown. Failed elements are denoted in red. Results are summarized in table 4. It is seen that the lowest system reliability occurs when element 4 is in failure. Due to force redistribution, the upper chord is heavily loaded implying that the system reliability is relatively low. The same conclusion can be drawn for assumed failure of element 1 - but in this case, the robustness index is much higher. 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. Figure 11 summarizes robustness indices for assumed failures of elements.

7 CONCLUSIONS

The paper considers robustness of structures in general and probabilistic approaches for robustness quantification. Special attention is made with respect to timber structures. The robustness analysis in the paper is based on the general framework for robustness analysis introduced in the Danish Code of Practice for the Safety of Structures and a probabilistic modelling of the timber material proposed in the Probabilistic Model Code (PMC) of the Joint Committee on Structural Safety (JCSS). Two different approaches were considered: first, where reliabilities of the remaining components are compared with the reliability indices of the intact structure, and second, where a robustness index is formulated at system level. Compared with a recommend target value, the reliability analysis of the structure shows low probabilities of failure for each of the considered failure modes. Progressive collapse analyses are carried out by removing four elements one by one. The results that the timber structure for three of the failure scenarios can be characterized as robust with respect to the robustness framework used for the evaluation. However, for one of the failure scenarios the robustness can be considered as relatively low.

Robustness analysis made on system level also shows similar results. For assumed damage in two of the truss elements the structure can be considered robust. Failures of the lower and upper chord of the structure result in a lower robustness index (minimal index is calculated for assumed failure of the lower chord). It is noted that the results obtained here are based on a simplified modelling of the timber structure which does not consider a non-linear behaviour of the joints or non linear behaviour of timber. Future investigations should also consider system effects and a modelling of possible gross errors, i.e. unintentional loads and defects.

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