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# THE ROBUSTNESS EVALUATION OF A WOODEN BUILDING

BY

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**Abstract.** The concept of robustness is relatively new and has emerged as a result of reaching the collapse of some buildings in accidental or exceptional circumstances, collapse incompatible with the initial degradation that represented "ground zero" of the axis of collapse production. Eurocode 1 defines robustness as "the ability of a structure (or portion of the structure) to withstand extreme events (such as fire, explosion, impact or consequences of errors due to human nature) without suffering degradation disproportionate the original cause".

Robust design of a structure should not be seen as an oversizing of all elements, but as an additional sizing of elements to make a structure to have a satisfactory reaction to the emergence of exceptional actions.

This paper presents methods and models to assess the robustness of a wooden building, analysing risk of accidental actions and measures that can ensure structural robustness.

**Key words:** wooden building; robustness; probability; reliability.

## 1. Introduction

The collapse of several structures, due to causes that should not have to affect their integrity, has captured the attention of structural engineers all across

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the globe. The design and execution of buildings that offer a high level of safety to exceptional loads is one of the new challenges of structural engineers.

Because the design and execution of 100% safe structures is impossible at the time, the literature recommends the design of robust structures that can offer a high level of safety for the given loads and for the hazard. A robust structure is one that exhibits the ability to redistribute load and remain stable after localized the severe damage to key elements.

Quantification of the “robustness” term is still a highly studied problem all over the world. Robustness has been the subject of numerous studies worldwide over the past few years. Robustness is defined according to EN 1991-1-7 as the ability to resist disproportionate (progressive) collapse. Robustness is an attribute given to complex structures and especially to multi-storey buildings. In economics, the robustness model is regarded as the property of a model to keep the result even if there are changes in some assumptions underlying the model. Methodological robustness analysis is a natural strategy to find erroneous assumptions underlying the model (Woodward, 2006).

With the manifestation of hazard, the risk of life loss and property damage is minimized if, besides the normal load, the designers has a duty to provide and what other charges arising from the operation of construction or development environment as exceptional actions: a potential risk of explosion for a building that is heated with natural gas or one near an explosives warehouse, a failure for a dam or a river, fire for a building located near a forest or a store with combustible. The probability of recurrence should not be taken into account because, once manifesting exceptional action, the entire structure has expert’s report and is redesigned to meet the new requirements set out in legislation.

In contrast, the probability of exceptional action appearances must be the starting point in calculating new robust construction.

Mathematical models underlying the design and implementation of a structure are "credible models", but cannot fully express the real behavior of the structure during operation. Therefore, these variables can be modeled as probabilistic. The robustness is classified into four categories (Woodward, 2006) namely

a) deductive robustness (result depends on different modeling assumptions auxiliary);

b) derivational robustness (result depends on different assumptions in modeling);

c) measuring robustness (triangulation of quantities or values by different means of measurement);

d) causal robustness (the result refers to the causal dependencies of the environment).

In light of the four categories above mentioned, the building robustness should be evaluated. Analysing the environmental factors and the mode of operation of the building, key factors that can produce the degradations or collapse on a given structure can be identified.

According to Pareto's Principia (known as: the 80-20 rule, the law of the few and the vital or the principle of spreading factor), to design a robust structure, it is necessary to identify and eliminate those 20% causes which produce 80% of the effects.

The paper covers the basic principles of timber structures robustness. The robustness shall be documented for all structures where consequences of failure are serious. A timber building is a complex building due to the material mechanical behaviour and the behaviour of this type of structures at fire. Identification of the significant failure modes of this structure is difficult to perform since there are many possible failure elements.

## 2. Methods for Evaluating the Robustness

In addition to building robust design methods, in the literature can also be found robustness assessment methods for an existing building or for a project phase. The methods usually involve removing a vertical strength element (which can fail when an accidental or exceptional action occurs) and the check of the new structure (Izzuddin *et al*., 2008).

The principal methods to assess the robustness of structures are:

a) Robustness Index Method (RIM);

b) Monte Carlo Method (MCM).

### 2.1. Robustness Index Method (RIM)

The method proposed by Baker *et al*. (2008) involves determining a direct ratio between the direct risk and total risk that a building confronts. The robustness index is defined as

$$\mathrm{RI} = \frac{R_{\mathrm{Dir}}}{R_{\mathrm{Total}}} = \frac{R_{\mathrm{Dir}}}{R_{\mathrm{Dir}} + R_{\mathrm{Indir}}}, \tag{1}$$

where: RI is the robustness index; $R_{\mathrm{Dir}}$ – the risk due to direct consequences; $R_{\mathrm{indir}}$ – the risk due to indirect consequences; $R_{\mathrm{Total}}$ – the total risk.

To determine the risk, Sørensen, (2011), rewrote the equations established by Baker *et al*., (2008), under the folowing form:

$$R_{\mathrm{Dir}} = \sum_i \sum_j C_{\mathrm{Dir},ij} P(D_j \,|\, \mathrm{EX}_i) P(\mathrm{EX}_i), \tag{2}$$

$$R_{\mathrm{Dir}} = \sum_i \sum_j \sum_k \; C_{\mathrm{Indir},ijk} P(S_k \,|\, D_j \cap \mathrm{EX}_i) P(D_j \,|\, \mathrm{EX}_i) P(\mathrm{EX}_i), \tag{3}$$

where: $C_{\mathrm{Dir},ij}$ is the consequence (cost) of damage (local failure), $D_j$ , due to exposure $\mathrm{EX}_i$; $C_{\mathrm{Indir},ijk}$ – the consequence (cost) of comprehensive damages (folow-up/indirect), $S_k$ , given the local damage (local failure), $D_j$ , due to exposure $\mathrm{EX}_i$; $P(\mathrm{EX}_i)$ – the probability of exposure $\mathrm{EX}_i$; $P(D_j|\mathrm{EX}_i)$ – is the probability of damage, $D_j$ , given the exposure $\mathrm{EX}_i$; $P(S_k\ |D_j\cap\mathrm{EX}_i)$ – the probability of comprehensive damages, $S_k$ , given local damage, $D_j$ , due to exposure $\mathrm{EX}_i$.

### 2.2. Monte Carlo Method (MCM)

Monte Carlo methods vary, but tend to follow a particular pattern: to define a domain of possible inputs, to generate inputs randomly from a probability distribution over the domain, to perform a deterministic computation on the inputs and to aggregate the results. In reliability engineering, the use of Monte Carlo simulation should generate the mean time between failures and mean time to repair for components.

To determine the probability of failure for a building (Guedri *et al.*, 2012), it is proposed the equation (4):

$$P_f \approx \frac{N_f}{N}, \tag{4}$$

with

$$\mathrm{COV}\left(P_f\right) = \sqrt{\frac{1-P_f}{NP_f}}, \tag{5}$$

where: $N$ is the total number of simulated cases; $N_f$ – the number of failure cases; COV – the coefficient of variation.

This estimate of $P_f$ is unbiased and its accuracy does not depend on the geometry of the failure domain. Instead, the $P_f$ only depends on the number of simulated cases $N$ used in the robustness assessment. It is recommended to measure the statistical accuracy of the estimated probability of failure by computing its coefficient of variation (COV). The COV of $P_f$ is given by equation (5). The smaller the coefficient of variation (COV) the better the accuracy of the estimated probability of failure is attained. For a small probability of failure and a small number of simulated cases, the variance of $P_f$ can be quite large. Consequently, it may take a large number of simulated cases to achieve a specific accuracy.

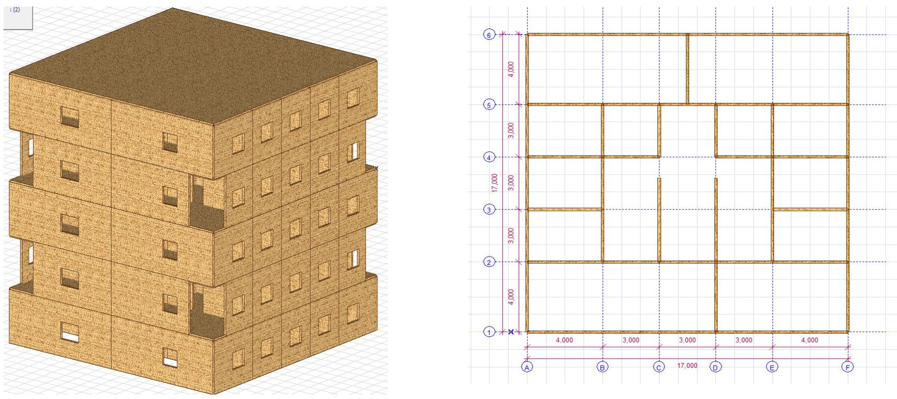
The failure indicator function that takes values of 0 for failure or 1 for survival is then expressed as

$$I_f = \frac{P_f N}{\sum_{i=1}^{N} \frac{f_x\left(x_{1i},\ldots x_{ni}\right)}{h_x\left(x_{1i},\ldots x_{ni}\right)}}, \tag{6}$$

where: $N$ is the number of simulations; $f_X(x_{1i},\ldots,x_{ni})$ – the original joint density function; $h_X(x_{1i},\ldots,x_{ni})$ – the importance density function; $I_f$ – the failure indicator function.

### 3. The Assessment of Timber Structures Robustness

Robust assessment of timber structures can vary for each type of structure in part. The goal of this study is to investigate the behavior of a cross laminated timber (CLT) building (Fig. 1), according to three different structural configurations. The CLT system (Fig. 2), offers high protection from fire, high mechanical strength and rigidity. Layers composing the wall panel are made of planks of wood that changes fiber direction 90º in each layer.



*a* *b*

Fig. 1 – CLT building: *a* – building structure; *b* – ground floor – the first (initial) configuration.

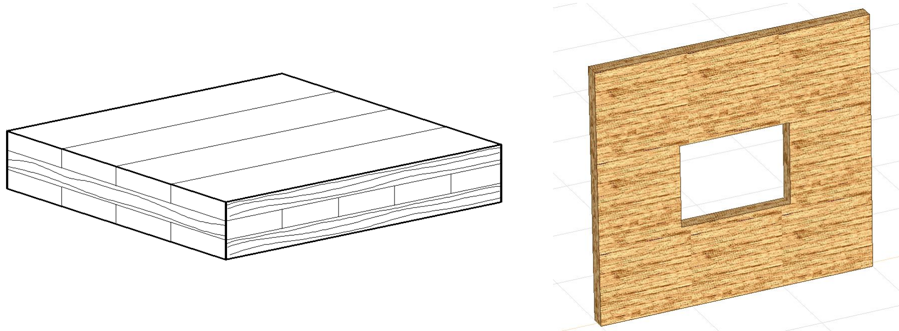


Fig. 2 – CLT wall panel.

**3.1. Cross Laminated Timber (CLT) Structures. Study Case**

Three building configurations with different ground floor partitions were analysed, the initial configuration and other two considering an explosion on the ground floor and part of the walls were destroyed (Figs. 3 and 4).

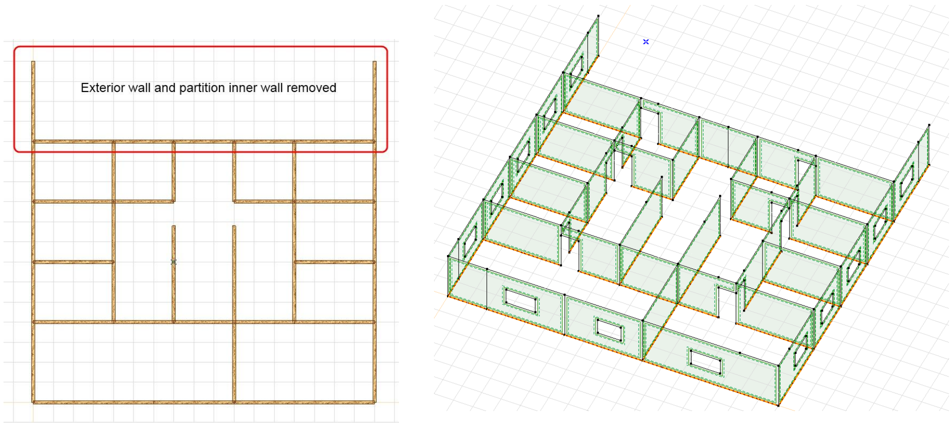



Fig. 3 – Damaged ground floor – the second configuration.

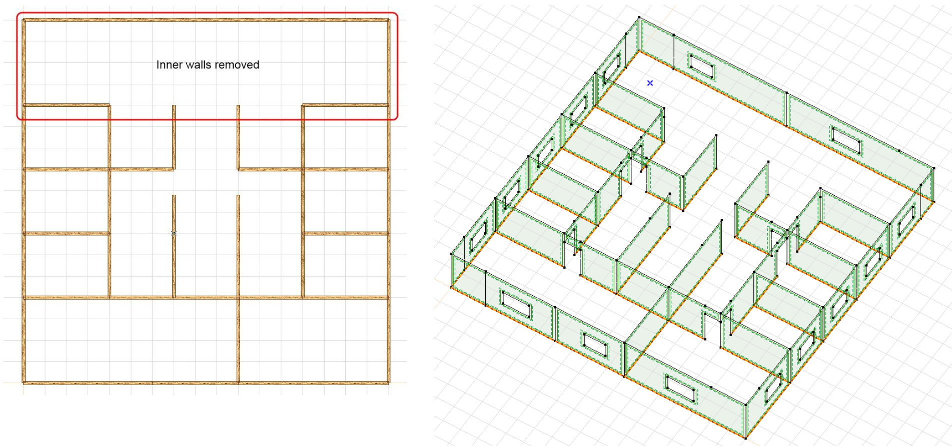



Fig. 4 – Damaged ground floor – the third configuration.

The finite element models (FEM) of the different configurations highlight the aspects of the stress and displacement analyses. The input data for FEM analyses are sustained by experimental results of testing timber elements and by the stipulated formula in technical codes.

The structure has 5 floors supported by CLT 150 mm walls. The timber used was from C18 class.

The load assumptions are the usual load for a building located in an area defined by $a_g$ = 0.2 g, the control (corner) period, $T_c$ = 0.7 s and the dynamic amplification factor, $\beta_0$ = 2.75. The building is considered of importance class II (construction of particular importance where necessary to limit the damage taking into account their consequences), the ductility class *3* and the coefficient of importance of the construction is $\gamma_i$ = 1.0.

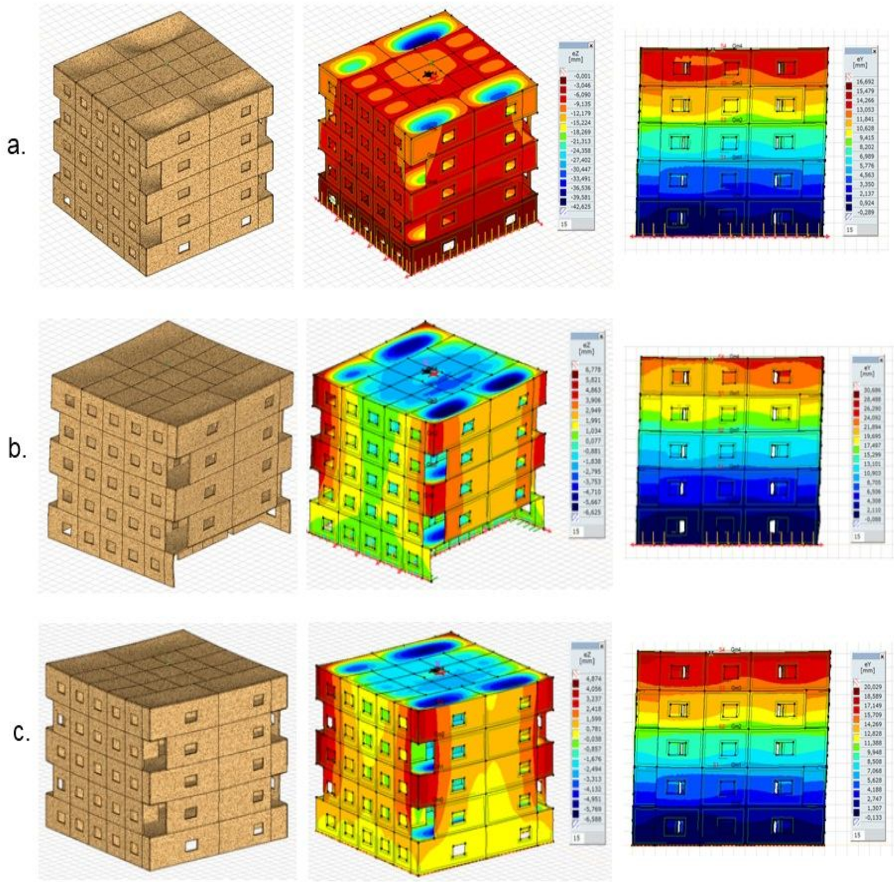



Fig. 5 – The deformed shape of CLT building: *a* – building in the first (initial) configuration; *b* – building in the second configuration; *c* – building in the third configuration.

The deformed shapes of the building with different configurations are presented in Fig. 5, and the maximum values of the top building displacements are presented in Table 1.

**Table 1**
*Maximum Displacements for Building Configurations*

| No. | Building type | Maximum displacement on the top of the building | | |
|---|---|---|---|---|
| | | *OX* mm | *OY* mm | *OZ* mm |
| 1 | Building in the first (initial) configuration | 16.692 | 17.767 | 42.625 |
| 2 | Building in the second configuration | 17.203 | 30.686 | 38.512 |
| 3 | Building in the third configuration | 14.115 | 20.029 | 42.450 |

### 3.2. Monte Carlo Method Evaluation on CLT Structure

In the present study, a risk assessment of the three systems is performed epressed by the evaluation of probability of failure, $P_f$, and the coefficient of variation, COV. The authors have considered that the failure occurs in the last two scenarios. The probability of failure, $P_f$, and the coefficient of variation, COV, are evaluated by following relations:

$$P_f \approx \frac{N_f}{N} = \frac{2}{3} = 0.6667, \tag{7}$$

$$\mathrm{COV}\left(P_f\right) = \sqrt{\frac{1-P_f}{NP_f}} = \sqrt{\frac{1-0.6667}{3\times 0.6667}} = 0.4082. \tag{8}$$

An analytical evolution of the probability *vs*. failure factor, $P_f$, and the coefficient of variation, COV, is presented in Fig. 6. Their evolution is related to the number of failure cases, $N_f$.

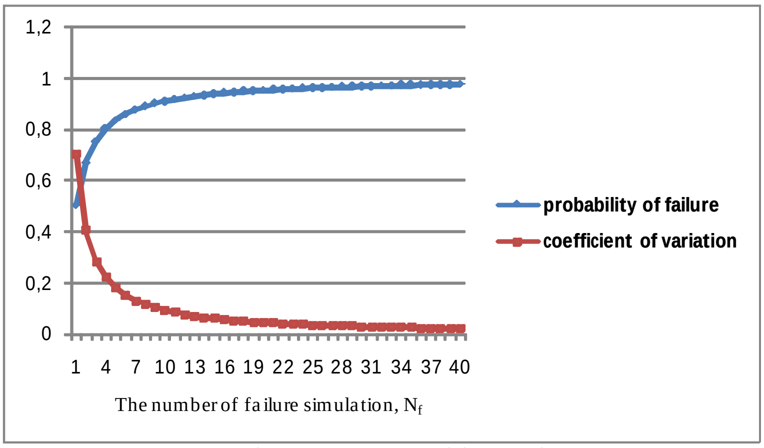



Fig. 6 – Evolution of the probability of failure factor, $P_f$, and the coefficient of variation, COV.

## 4. Conclusions

As a result of the first order linear analysis, the stresses developed in the structure were at very low levels (1/10 of the strength capacity). The good strength/density ratio and the good behaviour at tension as well as compression proves that the wood is an ideal material to build with and this CLT building system keeps the stresses at low levels. Future research should be pointed towards the buckling of the wall (see Fig. 5 *b*). It should be noted that the joints between panels and between panels and floor boards were considered rigid connections starting from the consideration that the type of joints are tongue and groove. The authors have not done extensive evaluations and appropriate to reality because the aim of the paper is to make an assessment of the robustness exercise, applying principles of the presented Monte Carlo method, considered to be appropriate in cases of risk assessment for a timber building failure.

Analysis results of the maximum displacements in Table 1 leads to the conclusion that the system is rigid and existing perimeter enclosures and the rigid connections between CLT elements provides enough structural stability to the horizontal actions, even in case of removal of interior partitions. Lack wall, which would have to provide closure on the ground floor, is the cause that produces approximately 100% increase in displacement in the direction perpendicular to the mentioned wall. This result highlights the increased risk of failure of the building in the second configuration.

Even though the values of the stresses were far from the values that make C18 timber to break, the authors assumed that the last two models collapsed. The COV value is far from zero, and this means that the probability of failure isn’t accurate enough. More collapse scenarios should be used for a better accuracy and according to the graphs presented in Fig. 6, it seems to be required at least ten probable failure scenarios in structural design process, so that to be considered a satisfactory design in terms of the building ability to resist disproportionate (progressive) collapse.

The $P_f$ and COV factors, specified by Monte Carlo method, are control indicators for the building designer and show the performance levels achieved in identifying all action scenarios for the designed building. Identification of possible collapse scenarios is appropriate when the probability of failure, $P_f$ , is close to one, and the coefficient of variation, COV, is close to zero.

In light of the presented analysis the authors believe that the Monte Carlo method is an appropriate method to determine the probability of failure for a timber building.

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## EVALUAREA ROBUSTEȚEI UNEI CLĂDIRI DIN LEMN

(Rezumat)

Conceptul de robustețe este relativ nou şi a apărut ca o consecință a prăbușirii unor clădiri în situații accidentale sau excepționale, colaps incompatibil cu degradarea inițială (datorită uzurii fizice intervenite în perioada de utilizare a clădirii) care reprezintă momentul "zero" pe axa de producere a evinementelor de colaps. Eurocod 1 defineşte robustețea ca fiind "capacitatea unei structuri (sau o parte a structurii), pentru a rezista la evenimentele extreme (cum ar fi incendiu, explozie, impactul sau consecințele erorilor cauzate de natura umană), fără să sufere o degradare disproporționată în raport cu cauza inițială".

Proiectarea prin prisma principiilor care definesc robustețea unei structuri nu ar trebui să fie văzută ca o supra-dimensionare a tuturor elementelor, ci ca o dimensionare suplimentară de elemente pentru a face ca structura să poată avea o reacție satisfăcătoare la apariția unei acțiuni excepționale.

Se prezintă metode şi modele pentru evaluarea robusteții unei clădiri din lemn, analiza riscului la acțiuni accidentale şi măsuri care pot asigura robustețea structurală.