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Reliability-based robustness analysis for a Croatian sports hall

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ABSTRACT

This paper presents a probabilistic approach for structural robustness assessment for a timber structure built a few years ago. The robustness analysis is based on a structural reliability based framework for robustness and a simplified mechanical system modelling of a timber truss system. A complex timber structure with a large number of failure modes is modelled with only a few dominant failure modes. First, a component based robustness analysis is performed based on the reliability indices of the remaining elements after the removal of selected critical elements. The robustness is expressed and evaluated by a robustness index. Next, the robustness is assessed using system reliability indices where the probabilistic failure model is modelled by a series system of parallel systems.

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1. Introduction

1.1. Robustness of structures in the codes

Robustness of structural systems has attracted renewed interest due to a much more frequent use of advanced types of structures with limited redundancy and serious consequences in case of failure. The interest has also been stimulated due to severe structural failures such as that at Ronan Point in 1968 [1] and at the World Trade Center towers in 2001. In order to minimise the risk of such disproportionate structural failures many modern building codes consider the need for robustness in structures and provide requirements, strategies and methods to obtain robustness, see e.g. [2,3]. The requirement for robustness is specified in most building codes in a way like the general requirements in the two Eurocodes, EN 1990 Eurocode 0: Basis of Structural Design [2] and EN 1991-1-7 Eurocode 1: Part 1–7 Accidental Actions [3]. The first provides the basic requirements, 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". The second provides strategies and methods to obtain robustness though actions, and design situations to consider.

1.1.1. Robustness measures

During the last few decades a variety of researchers have attempted to quantify aspects of robustness such as redundancy and to identify design principles that can improve robustness. All the proposed attempts for quantification of robustness can be divided into three main categories of measures: deterministic, probabilistic and risk based.

1.1.2. Deterministic robustness measures

A simple and 'easy-to-use' deterministic measure is given in [4]. In this robustness measure the ratio of the base shear capacity of the platform and the design load are compared. The base shear capacity is estimated using non-linear structural models with and without failed elements. In [5] a measure of robustness is proposed where the stiffness matrix of the intact structure and the stiffness matrix after removal of a structural element are compared and a robustness index is derived. The same authors also proposed energy and damage based definitions of robustness. Quite recently, a multi-level framework for the progressive collapse assessment of building structures subject to sudden column losses was presented by Izzuddin et al. [6]. The proposed assessment framework employs three stages: first determination of the nonlinear static response, then a simplified dynamic assessment and finally a ductility assessment. In [7] is presented an application of the proposed design-oriented method for progressive collapse assessment of multi-storey buildings.

1.1.3. Reliability-based robustness measures

In the late '80s [8] proposed reliability-based indices as measures of structural redundancy though the residual strength of a damaged system. The same authors also proposed a redundancy factor where the reliability indexes of the both intact and damaged systems are used to determine this factor. Lind [9] proposed a generic measure of system damage tolerance, where

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a vulnerability parameter is used as an indicator of the loss of system reliability due to damage. As progressive collapse is characterised by the disproportion between the magnitude of a triggering event and the resulting collapse of a large part or the entire structure [10] defined the probability of such collapse as a chain of partial probabilities: the probability of an abnormal event that threatens the structure (generally a hazard), the probability of local damage as a result of this event and the probability of failure of the structure as a result of the local damage. The term hazard refers to abnormal loads or load effects [11]. 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 design and construction (human errors). These loads usually act over a relatively short period of time in comparison with ordinary design loads. The loads generally are time-varying, but may be static or dynamic in their structural action [11].

Recently Starossek and Haberland [12] proposed a definition of both the progressive collapse and the robustness. Similar to the approach described above the probability of disproportionate collapse is calculated as a product of probabilities: the probability of an abnormal event that threatens the structure, the probability of initial damage as a result of the event and the conditional probability of a disproportionate spreading of structural failure due to the initial damage. Based on this, there are the three main strategies to limit the probability of a disproportional collapse, first is to prevent the occurrence of abnormal events, the second is to prevent the occurrence of an initial damage in consequence of the occurrence of abnormal events. A third strategy is to prevent disproportionate spreading of failure of the initial damage. This part relates to the internal properties of the structure though its robustness. As such the robustness is a property that depends on the structure itself and the amount of initial damage [12]. Vulnerability is defined as the susceptibility of a structure to suffer initial damage, when affected by abnormal events. Vulnerability is related to local conditions while robustness is related to global system behaviour [12].

An example of a robustness assessment is presented in [13] where the robustness analysis is based on the 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 [14]. The framework mentioned above considers the structural robustness at system-level and has the potential to take into account uncertainties inherent in the description of unintentional loads and defects, static layout and structural composition. Cizmar et al. [15] generalised this approach and used a robustness index defined as a ratio of the reliability indices of the damaged and intact structure with values between 0 (non robust structure) and 1 (ideally robust structure).

1.1.4. Risk based robustness measure

A few years ago, an index of robustness was proposed taking its basis in decision theory (a risk based definition) following [16] which states that a decision theory framework can be used to assess robustness in a general manner. The index of robustness is obtained by computing both the direct risks, which are associated with the direct consequences of potential damages to the system, and the indirect risks, which correspond to the increased risk of a damaged system. Indirect risks can be interpreted as risks from consequences disproportionate to the cause of the damage, and so the robustness of a system is indicated by the contribution of these indirect risks to total risk. This framework was then as an example applied to assess the robustness of an externally and internally post-tensioned highway bridge designed according to present best practice [17].

1.2. Robustness of timber structures

In the last few decades research in the assessment of reliability of timber structures has been quite intensive, but the robustness of timber structures has not been shown much attention. One of the reasons for the lacking interest about the robustness of timber structures is that a unified approach for the assessment of robustness in general has not been available. Since timber is a rather complex building material, the assessment of robustness of timber structures is difficult to conduct.

In the frame of the COST E55 Action [18] have made a deterministic robustness analysis of the collapses of both the Siemens Arena and the Bad Reichenhall Ice Arena. The Siemens Arena was built in 2001 as a large span timber truss system; two of the trusses collapsed without warning at a time with almost no wind and only a few millimetres of snow. The partial collapse happened just a few months after the inauguration of the arena. An investigation showed that the cause of the failure could be localised to one critical cross-section in the tension arch near the support, where the load-bearing capacity was found to be between 25% and 30% of the required capacity. It is noted that the collapse did not occur due to an unknown phenomenon. The design of the trusses was not checked by the engineer responsible for the entire structure due to unclear specification of the responsibility and duties of that engineer. The Bad Reichenhall Ice-Arena built in 1971/1972 is a large span roof structure supported by 2.87 m high main girders produced as timber box-girders. The box-girders featured upper and lower glued laminated timber members and lateral web boards. On January 2nd 2006, the entire roof collapsed without warning during a period of significant snowfall [19]. The review of the structural calculation revealed severe human errors in design and heavy misuse of building codes. These errors, humidity exposure and general lack of maintenance lead to the collapse of a structure.

Based on the robustness framework described above [13] presented a reliability-based robustness analysis of a glued laminated frame structure supporting the roof over the main court in a Norwegian sports centre. Progressive collapse analyses are carried out by removing potential critical elements, and then assessing the reliability of the remaining structural elements. The results show that the timber structure of the Norwegian sports centre can be characterised as robust with respect to the robustness framework used for the evaluation.

The robustness analysis in this paper is based on the general framework mentioned above [13] and a probabilistic modelling of the timber material proposed in the Probabilistic Model Code [14] of the Joint Committee on Structural Safety (JCSS). The main difference with respect to the work by Kirkegaard and Sorensen [13] is that in this paper the robustness of the structure is assessed at two different levels. First the robustness assessment is made on componential level where the reliabilities of the remaining components (after failure of one critical element) are compared with the reliabilities of the intact elements, and next on a system level, where a robustness index is formulated using system reliability measures.

2. Overview of a structure

Many recent structures in Croatia, especially sports halls, swimming pools, tourist objects, passages and pedestrian bridges were built using timber (mainly glued laminated timber). A sports centre in Samobor (small town near Zagreb, Croatia) is considered