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Reliability assessment and updating of notched timber components subjected to environmental and mechanical loading

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ABSTRACT

Cracking initiation and propagation are frequently recognized as main causes leading to failure of timber structures. Since the kinematics of both processes is largely influenced by environmental conditions, a comprehensive reliability assessment of notched structures should take into account such environmental factors. The main purpose of this paper is to propose a methodology for reliability assessment and updating of notched timber components based on mechanical (A-integral formulation) and reliability (simulation and Bayesian networks) methods, and experimental data. The A-integral formulation is used to estimate energy release rates in modes I and II by taking into account thermal effects; but its numerical implementation is time-consuming for uncertainty propagation. In order to deal with this problem, Bayesian networks were used for reliability assessment and updating. The experimental data used for updating purposes were obtained from measurements of deflection, temperature and relative humidity on a notched beam (Douglas Fir specie) exposed to outdoor environment and constant loading. The whole proposed methodology was illustrated with the reliability assessment and updating of the studied notched beam. The results indicated that the proposed approach is able to integrate measurements of temperature and deflection for reliability updating.

1. Introduction

Timber is a traditional material that has been widely used for various types of structures. For example, there are about 27,000 timber bridges over a total of 40,000 bridges in Australia [1]. By observing historical buildings around the world, it can be seen that timber structures guarantee a long-term service life with a high durability level. However, in timber structures, cracking initiation and propagation are frequently recognized as main causes leading to structural failure [2,3]. Hansson [4] provided a comprehensive survey and analysis of failures in 127 timber structures in Sweden. This author found that crack initiation and propagation play an important role in timber structural failure. Mechanical behavior of notched timber structures is affected by environmental conditions (moisture, temperature, etc.) [5,6] that could produce a higher risk of crack growth in timber structures [7,8]; as a consequence, the lifetime assessment of notched timber structures should take into account the influence of these environmental conditions.

Rational reliability and lifetime assessments require a realistic modeling of the mechanical behavior. Concerning crack growth initiation, many numerical methods have been developed to characterize mechanical fields at the crack tip vicinity [9,10]. Among them, the most popular energy methods enable an evaluation of fracture parameters such as energy release rate and stress intensity (J-integral [11] and Noether's Theorem [12]). These methods however are inefficient when solving mixed-mode crack growth problems that require separating the displacement fields into symmetric and asymmetric parts. To deal with this problem, the M-integral [13] separates fracture modes based on a bilinear form of the strain energy density by introducing real and virtual mechanical fields according to Sih's singular forms. Unfortunately, these tools remain mathematically limited to simple loadings and simple boundary conditions. This work, considers an extension of the T-integral formulation called A-integral to take into account the effect of thermal loading and therefore improve the estimation of the fracture parameters, such as stress intensity factors and energy release rates (see [2,14,15] for more information on the definitions and formulations of T

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and A-integrals).

Several authors [16–23] used reliability theory and methods to evaluate the structural safety of new or existing timber structures. Brites et al. [16] used reliability analysis based on Monte Carlo simulations to evaluate the safety of the timber truss system subjected to decay. Köhler et al. [19] focused on the development of comprehensive probabilistic models of timber material properties including spatial variability. More recently, Köhler and Svensson [20] worked on a probabilistic representation of the duration of load effects. Sørensen [21] provided a theoretical framework for robustness assessment of timber structures on the basis of structural system reliability and risk analysis. Kirkegaard et al. [22] studied system reliability of timber structures considering its ductile behavior. The results of such a study showed that considering the ductile behavior of timber materials could increase the reliability of a structural timber system. Other authors [1,18,24] assessed the structural safety of existing timber structures by using reliability analysis and measured data (from inspection results and non-destructive tests) for updating purposes. However, these studies did not account for some aspects that might lead to inaccurate assessments such as the presence of notches and the interaction between environmental conditions and mechanical behavior.

A Bayesian based approach is a suitable tool that could incorporate all these issues for reliability assessment. In the form of multi-events, it turns in the form of Bayesian network (BN) for describing the relationship between random variables. This approach has been used for reliability updating in some previous studies related to chloride-ingress into concrete [25–28]. Within this context, the objective of this study is to propose a methodology for reliability assessment and updating of cracked timber structures from experimental data by coupling mechanical (A-integral formulation) and probabilistic (simulation and BN) methods. The proposed framework is modeled by a BN that represents the structural performance, provides an estimation of the failure probability and could be updated by introducing experimental information. With respect to previously mentioned works on reliability assessment [1,16–24], Analytical formulations, numerical tools and experimental data presented in this paper were developed within the framework of the JCJC2013 CLIMBOIS (effects of climatic and mechanical variations on the durability of timber structures) research project (funded by the French National Research Agency).

The paper starts describing the experimental setup and the inspection data that will be used for reliability updating (Section 2). Section 3 summarizes the A-integral formulation as well as the considerations for its numerical implementation in the finite element software Cast3M. Section 4 introduces the methods for reliability propagation, assessment and updating. Finally, the proposed methodology is applied to the notched beam and the results are presented and discussed in Section 5.

2. Experimental setup

2.1. General description

This section summarizes the experimental setup considered in this study. The tests were carried out on notched beams of Douglas fir (*Pseudotsuga menziesii*) specie, dimensioned as presented in Fig. 1 according to the Eurocode 5 [29]. Three beams (D3, D6 and D9) have been loaded during this period but only the beam D9 has been studied in this paper. The beams D3 and D6 were broken 2 and 4 h respectively after the beginning of the experiment. Since this work focuses on environmental effects of climate and loading conditions on the time response of cracked timber beams and the data for beams D3 and D6 is scarce, we will only focus on the results for the beam D9. The initial crack size, a_{ini}, had a length of 25 mm. The beams were subjected to two constant loads, P, induced by concrete blocks applied in two points. Before the experiment, the beams were conserved under controlled room environmental conditions (relative humidity $RH = 40\%$, and temperature $T = 22$ °C). Some defects were observed on the beams: knots and annual rings not oriented in the direction of the grain. They were placed at the Clermont Auvergne University (Clermont-Ferrand, France) and subjected to outdoor climatic conditions (Fig. 1).

Before applying the load, comparators and a linear graduated line were placed on the two faces of each notched beam to follow the crack opening and propagation during the test campaign (Fig. 1). In addition, an LVDT sensor placed on the middle of the beam followed the evolution of the deflection at this point during the test. In parallel, a neighboring weather station provided information about the climatic conditions during the experiment. Indeed, the evolutions of Relative Humidity (RH) and Temperature (T) are continually and automatically recorded (all the 5 min) and provided by the Laboratory of physical meteorology of Clermont University, which is at 100 m from the experimental device, during the experimental phase. In summary, this experimental setup allows us to obtain a regular follow-up of the evolution of the following parameters: opening of crack, length of the crack, deflection and environmental conditions. Among the available data, only deflection and climate measurements will be used in this study for updating the probability of failure of the beam.

2.2. Experimental results

The results presented in this section concern one beam of Douglas fir that was tested until breaking from June to July 2016. The results of this beam will be used in this paper to illustrate the proposed methodology for reliability assessment and updating. Evolution of measurements (deflection (w) and climate parameters (T and RH)) is shown in Fig. 2. According to this figure, it is observed that in the long term the absolute value of the defection increases until the end of the experiment by a coupled interaction between creep and crack propagation processes. For short time periods, it is also noted that there are direct relationships between the cycles of T and RH and the deflection during the test. For example, in the period from 300 to 400 h, the absolute value of deflection increases during drying and heating phases (Fig. 2).

The experimental observations presented in this section highlighted the larger influence of climate conditions on deflection. Consequently, it is paramount to include these environmental effects combined with experimental measurements for improving reliability assessment. Since tests presented in this section are time-consuming, a comprehensive numerical model is also required for the efficient understanding of fracture phenomena subjected to mechanical and environmental loading. Such a model is able to consider only temperature effects and is summarized in Section 3. The experimental data (geometry, loading, material properties, temperature and deflection) will be used afterwards for reliability assessment purposes by considering the Bayesian framework proposed in section 4. Particularly, temperature variations and deflection measurements will be used to update the instantaneous probability of failure (Section 5).

3. Mixed-mode fracture formulation and numerical implementation

This section first summarizes the mathematical formulation of the A-integral [14]; afterwards, it describes the considerations for its numerical implementation in a Finite Element Analysis (FEA) software that will be used to propagate uncertainties.

3.1. A-integral formulation

In order to implement the A-integral in a FEA software, it is easier to take into account a surface domain integral. Within this context, the curvilinear path is transformed into surface domain by introducing a vector field $\vec{\theta}$ as shown in Fig. 3. This mapping function is continuously differentiable and takes these values: $\vec{\theta} = (1,0)$ inside the ring **S**, and: $\vec{\theta} = (0,0)$ outside it, Fig. 3. Hence, the use of the Gauss-Ostrogradsky