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Historical carpentry corner log joints—Numerical analysis within stochastic framework

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ABSTRACT

The paper presents the results of numerical analysis performed on historical, traditional carpentry corner log joints of two basic topologies: the short-corner dovetail connection and the saddle notch connection. These types of carpentry joints are commonly used in currently preserved objects of wooden architecture. All connections have been modelled in pinewood, which has been defined in the Finite Element software MSC.Marc/Mentat as an orthotropic material. The numerical calculations have been carried out for two types of connections with two different boundary conditions and load types. The contact phenomenon between the individual elements of the connections has been taken into account. The main purpose of the research is to select the most damage-resistant type of connection and to determine the stress distributions on the contact surfaces, which demines the damage areas. However, a lot of uncertainties appear in the studied models, e.g. due to the natural variability of the material properties of wood and the uncertainty of friction coefficient. Therefore the uncertainty quantification and global sensitivity analysis has been performed in order to include these uncertainties and study their effect on variation of the mechanical response of the connections. A regression-based non-intrusive polynomial chaos expansion method has been employed to complete the task.

The state-of-the-art knowledge about the damage-prone zones in the considered connections is immensely important since many wooden buildings, mostly historical, require maintenance, renovation and the reinforcement of existing, especially historical elements. On the contrary, there are not many results of related research published yet.

1. Introduction

Formerly, wood was extensively used in the structural engineering due to good strength parameters and a wide accessibility of the material. In civil engineering, concrete and steel are still more widespread structural materials than wood, which is more complicated in analysis and design due to its heterogeneity and the lack of isotropy. Wood defects such as knots, slope of grain, shake decay, burls, defects caused by fungi, stains and rots, and defects due to insects are often additional reasons for this heterogeneity [1]. As a natural material, wood is highly sensitive to moisture and damage by biological agents [2,3], its limits in terms of strength and elasticity depend primarily on humidity, temperature, density and aging [4]. All these impacts result in high variability of material properties of wood. In recent years a general awareness has grown with regard to the necessity of rehabilitating historic buildings especially of a heritage value. Due to economic and cultural factors nowadays, more attention is focused on the rehabilitation and restoration of old structures and on decreasing the level of waste [5]. A reliable structural analysis leads to an efficient repair or supports solutions necessary to ensure the safety of the structure, thus it must be based on relevant modelling of the material, the joints and the entire structure.

Many types of carpentry joints can be distinguished with respect to their form and expected function [6]. A number of research works focusing on carpentry joints have been published recently, especially on joints in pieces at an angle, such as the birdsmouth joint in rafter to tie beam joints, the mortise and tenon joint, scarf joint, dovetail joint, as well as joints where the members are connected by their ends to achieve greater lengths (e.g., [7,8]). But the vast majority of research on carpentry connections concern analysis of typical joinery in the historic roof structures using monotonic tests [9], photo-elasticity tests and numerical analysis (see e.g., [10,11]). An approach taking into account the effect of temperature and humidity on the strength of wood is presented in [12–14]. Also a stress distributions and failure analysis of timber structures [15,16] as well as some experimental [17,18] and numerical [19–21] research are reported in the literature.

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The study is based on a probabilistic approach, which although having been used in the analysis of timber structures, is not yet used in simulations of corner log connection. One of the issues in numerical modelling of timber structures are uncertainties e.g. due to the natural variability of wood properties. The uncertainties of different sources can be included in models and design by means of random approach. It has been completed for design and robustness analysis of timber structures [22] and reliability analysis of old timber truss [23]. Non-intrusive probabilistic methods are based on a number of deterministic computations, to be employed in the “black-box” models created in commercial FE software. The Monte Carlo (MC) simulation method is a widely implemented non-intrusive method of uncertainty propagation in timber structures too [24]. Nevertheless, the method is computationally expensive since it requires a large number of simulations. In the case of complex FE models, triggering expenses to a single simulation the MC can be intractable. Some methods to reduce the computational cost of uncertainty propagation have been developed as presented in [25]. Kandler and Füssl [26] compared perturbation method and polynomial chaos expansion method with the MC and experimental results on the example of glue laminated timber. In order to investigate the effect of variation of each random variable on global uncertainty of the model response, sensitivity analysis methods can be employed. Sobol’ indices [27] are widely-used global sensitivity measures. They have been used to study the importance of micromechanical parameters of wood on its macroscopic properties [28].

However, while applied mostly during past centuries in historical buildings, one can hardly find studies on carpentry joints related to corner joints of the solid walls in log-system buildings, where the joists are laid horizontally (see e.g., [29] or the Authors preliminary work [30]). Few, but interesting studies refer to the walls behaviour under seismic load and to the material modelling and experimentation [31,32]. The knowledge of the corner carpentry connections is enormously useful due to the necessary maintenance, renovation and the reinforcement of existing elements in many historical timber structures [33].

The development of carpentry, dated to the period from the 13th to 17th century, contributed to significant improvements in craft and techniques for making joints that allowed the use of a number of newly invented types of carpentry joints, and which modified those already known [34]. The modifications of the connections mainly consist of geometry variation and the introduction of locks inside the joint. The log buildings had hardly been the work of professional carpenters; they were rather constructed by the owners’ families with the help of neighbours, there was an oral building tradition passing from one generation to another [29]. To this day, one wonders about the reason for constructing very complex connections, including hidden locks discovered during renovation and restoration [35].

The corner joints are essential parts of the structural system of the building, ensuring proper force transmission from external loads, as well as providing the spatial stiffness of the object. While conducting a 3D analysis of a corner joint, the distribution of internal forces is variable at the height of the wall, which is due to the dead load of the wall. In addition, the configuration of forces in the corner also depends on the architectural form of the building, including the roof systems, the thickness and slenderness of the walls and the technical state of the building.

The numerical modelling of the corner wall connection is a complex issue. The study presents models of historic carpentry corner log joints of two basic topologies (see e.g., [32]): the short-corner dovetail joint and the saddle notch joint, using different boundary conditions and different load systems to perform the finite element analysis. The main goal of the study is to find the stress distribution in the loaded wall with traditional corner carpentry joints constructed from logs in different ways, to learn about their static behaviour, and thus provide the basis for their reliable rehabilitation. Moreover, due to the modelling uncertainties, a probabilistic approach has been employed. The polynomial chaos expansion (PC) method in a non-intrusive regression variant [36] has been employed to propagate the uncertainties. The Sobol’ indices have been computed in order to study the influence of the input uncertainties on the variation of the response of the modelled joint. The sensitivity of mean and extreme values of principal stress has been studied in a chosen location in the corner carpentry joints on variations of the Young’s modulus of wood and of its friction coefficient.

2. Material and methods

2.1. Geometry of carpentry joints and material parameters

The entirety of surviving connections in the authentic historical buildings shows the cases of various geometries of a given connection. They are usually affected by location and time of a structure erection. In the study, the geometry of the connections described by [37] has been assumed with dimensions scaled into 1:2. The scale 1:2 has been selected due to preparation for laboratory tests. Each analysed carpentry joint taken for the analysis consists of five logs. The cross-sectional dimensions of a single log are 75×135 mm. The length of each wooden beam is 1000 mm for the short-corner dovetail connection and 1075 mm for the carpentry joint with protrusions, the saddle notch joint. The geometry of each carpentry joint scheme is presented in Fig. 1.

It is assumed that all carpentry joints are made of pinewood, because this is one of the most widely-used kinds of wood in traditional timber houses in southern Poland and western Ukraine. Their material properties vary with the direction of fibres thus they are considered orthotropic. The anatomical directions in the wood can be distinguished according to the following three directions: *R*—radial direction, *T*—tangential direction and *L*—longitudinal direction to the surface of each layer of the fibres [38,30]. The Young’s modulus along the fibres E_L has been determined on the basis of the 4-point bending tests. The scheme of the laboratory stand is presented in Fig. 2. Eight bending tests with the test velocity 0.05 mm/s has been performed. The values of the Young’s modulus E_L, obtained from the tests are presented in Table 1.

Other moduli E_T, E_R, G_{RT}, G_{TL}, G_{LR} are related to the Young’s modulus E_L (see Table 2). In turn the Poisson’s ratios ν_{RT}, ν_{TL}, ν_{LR} are taken from the literature [1].

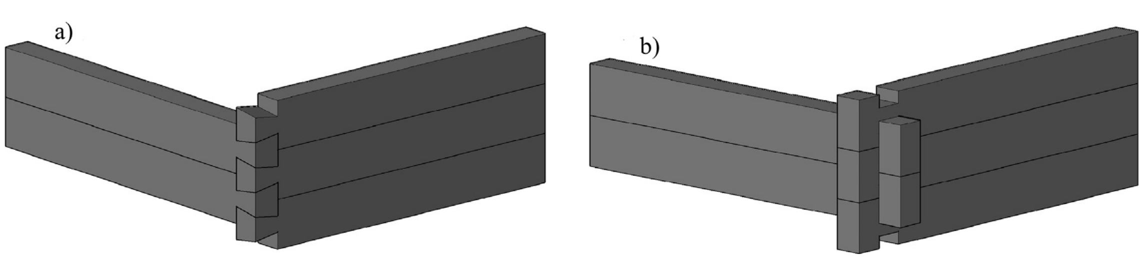

Fig. 1. Structure of corner log joints: (a) short-corner dovetail connection (Type 1), (b) saddle notch (Type 2).