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Original article

The numerical assessment of a full-scale historical truss structure reconstructed with use of traditional all-wooden joints

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ABSTRACT

This paper focuses on description of the mechanical behavior of the historical gothic truss of St. James's Church in Brno. The numerical approach using finite element analysis (FEA) provided virtual assessment of the truss with a prediction of its behavior after simulated restoration using joints at locations of possible failure. The historical truss was subsequently analyzed by both beam truss structure and detailed 3D solid lap scarf joint modeled by reduction technique using substructuring. Static analyses were carried out using the finite element method (FEM) in order to establish a reliable numerical model and assess the static risks. The finite element models in ANSYS software assume fully orthotropic material properties of wood (Norway spruce and European beech) with elastic behavior. Results portrayed very good design of the assessed truss in the global mechanical behavior despite the rigidity of joints varied in longitudinal and transverse directions of the frames. Changes in global truss behavior were observed, but the changes in objective vertical displacement were not high. The differences based on rigidity level were not more than 7% of maximum vertical displacement of beams. The minor differences were recognized in the global truss behavior owing to new positions of implemented joints in the truss. Analyses showed each member in the truss contributes to global truss rigidity and stability to different degree. Further, analyses showed areas in the truss where it was necessary to correct joints orientation.

1. Research aims

The assessment of mechanical behavior of historical timber structures such as churches, castle, etc. is currently under scrutiny in the Czech Republic, and across Europe. The present paper applies a novel methodology for virtual assessment of mechanical behavior of a historical truss; the gothic truss in St. James's Church in Brno, Czech Republic, a valuable site for preservation of original techniques and cultural value from structural and architectural perspectives. Some members of St. James's Church truss were damaged, therefore was decided about their reconstruction with using of all-wooden joints. The high historical value of the truss structure as well as complexity of structure repairs mechanics necessitated the modern assessment methods. The main objectives of this paper are:

- describe mechanical behavior of whole truss structure owing to different joints rigidity;
- describe the real loading of a joint corresponding to the primary function of the joint in the truss structure during loading owing to different positions implemented in the truss;
- use reduction technique of modeling combining beam structure with 3D detailed solid model.

Numerical approaches based on FEM were used for prediction of the global mechanical behavior of the truss and joints. The detailed finite element analyses (FEA) were performed in the full-scale of the truss including both without and with a detailed 3D solid lap scarf joint for which a substructuring method was used. The lap scarf joint is a traditional joint that is used for replacement of damaged parts in the restoration of valuable historical structures.

2. Introduction

In reconstructions of valuable timber structures, there are requirements for very sensitive approach that respects the cultural value, specific environment conditions and preservation of

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Fig. 1. St. James's Church in Brno, Czech Republic.

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original material. The way to fulfill these requirements is to replace damaged parts of beam members by an insertion of a new wooden element with the use of traditional all-wooden joints without use of modern iron fittings. The all-wooden joints are not used to such an extent because engineers are still missing relevant standards for design and making of wooden truss reconstructions. Development of standards requires complex mechanical analysis of several types of all-wooden joints. The mechanical analysis consists of detail decription of material behavior, description of interaction between parts of joints including dowel and the description of loading of joint.

In general, there is a need to evaluate the structural safety of valuable historical truss monuments, which attest heritage from the past [1]. The Czech Republic located in Central Europe is rich with historical timber structures that require renovation owing to biotic and abiotic degradation. The investigated truss structure presented in this paper belongs to one of the oldest churches with cathedral-like disposition in South Moravia region – St. James's church that is located in the center of Brno, Czech Republic (Figs. 1 and 2).

The truss structure has two types of frames with four height levels (Fig. 3). The connection between individual frames provides by longitudinal purlins and so-called St. Andrew's crosses (Figs. 2 and 6). St. Andrew's crosses are actually double crosses that are diagonally spanned between two full frames and under the truss rafters in the two common frames, which are providing longitudinal stiffening (Figs. 2 and 6). Most of the beam connections into structure are made only of wood including wooden dowels. The St. James's church was established in 1220 in the Romanesque style, but it was completely rebuilt into a much bigger church in the late Gothic style. Throughout the time the church gained a few Renaissance and Baroque elements, but its Gothic character stayed mostly preserved and even emphasized in late 18th century after it was neogothicized. The truss structure is neogothic and is dated into 1724 when it was finished by carpentry master Anton Ebenberger [2].

In general, the renovation of such structures should be supplemented by a structural assessment based on surveys according to e.g. [3]. For the analysis of complicated structures such as baroque or Gothic truss structures, it is advantageous to use a numerical approach, in particular FEA, instead of analytical calculations. The advantages of using FEA for such tasks are emphasized even more when connections in a truss must be included in the analysis. The reason is that FEA enables modeling a global beam structure (truss) and 3D solid body (joint) including the contact among connection parts at the same time. Such a task is often accomplished through reduction techniques, one of those is commonly known as substructuring [4]. Reduction techniques are often used when reduction of computation time and detailed stress-state is needed at the same time and can be applied on any material and construction [5–8].

The dowel-like connections in the truss structure of the St. James's church are usually simple dowels made of predried oak wood (±4% moisture content). Afterwards, the equilibrium moisture content of dowels is reached depending on surrounding conditions. As a result the rigid connection of joined parts is reached during its service. For their basic analysis with known boundary conditions, the Johansen theory for single-shear joint can be used, as implemented in Eurocode 5 [9,10]. For more complicated boundary conditions, numerical modeling must be employed. Review of numerical analyses of such wooden connections covering period from 1950s up to late 1990s can be found in [11] and thus will be omitted here. More recently, an experimental analysis of wooden composite beams connected by dowels welded into the beam layers by rotation welding was performed [12]. It was shown that a higher number of dowels affected the beam stiffness more than the ultimate load. FEM and the boundary element method (BEM) are the most popular numerical methods in the research of wooden joints, they are illustrated in reviews of numerical models of joints ranging between the years 1990 to 2015 [13–15]. In terms of dowel joints, there are many FE techniques implemented in software that an analyst can currently use, within which there are four basic model categories – solid bolt, coupled bolt, spider bolt and no-bolt [16–18]. Despite the preferences for 3D solid dowels, successful use of beams simulating nail connection was presented in recent study too [19].

3. Materials and methodology

3.1. Preliminary visual and measured truss surveys

Visual survey of the truss structure of St. James's church showed large defects including decayed members due to the long-term leaking of water into structure and, therefore, renovation is needed. The survey also provided information about the positions of potential replacements using joints that were considered in FE models. The truss members are damaged by decaying fungi and insectwhich

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