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Lapped scarf joint with inclined faces and wooden dowels: Experimental and numerical analysis

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ABSTRACT

Experimental and numerical analysis were performed to investigate the mechanical behavior of a lapped scarf joint with inclined contact faces and wooden dowels which is a commonly used connection for repairing damaged beams in historical structures. This study aimed to define and suggest most effective parameters that influence this particular joint's performance. Experimental testing was done on the full scale specimens. Four- and two-dowel-joints with half-beam-width laps and with 3/8-beam-width laps were tested. Experimental data analysis concluded that the width of the lap element should be kept as half of the beam width, therefore this type of joint was further analyzed using numerical approach. Finite element models were constructed for joints with four, two, and three wooden dowels. These models and theoretical criterion according to EC5 were used to select a number of dowels used for connection, joint's length and location. It was concluded that a lapped scarf joint with 3 wooden dowels that is 1.38 m long and located at 1/5 L from support is the most efficient joint (in terms of strength, stiffness, and manufacturing) for the beam-end reparation; however, location of joint must consider both preservation of the most of the original material and the extent of damage. Numerical model can be used for designing joints with different parameters in beams with different dimensions. It was also calculated that a jointed beam provides between 65% and 75% of the original beams' strength while the linear stiffness is not influenced significantly.

1. Introduction

A lapped scarf joint discussed in this study is intended for beam-end reparation in historical timber beams. The joint is used to replace a damaged part of a beam while preserving the most of the original structural element. The damage occurs commonly at the ends of a beam due to contact with other materials such as masonry walls. In the bearing areas a beam would undergo moisture damage or would suffer from a fungi or insects attack. A lapped scarf joint, placed up to one third of the beam span from the support, would have to be able to carry both shear load and bending moment. As the oblique contact faces provide relatively large areas it is expected that a joint would not suffer from shear related failures at these contact faces. However, a flexural strength of the beam will depend on the number of wooden dowels and their location in the joint. Oftentimes this type of joint tends to be over designed as there are no design codes for such historical connections. Practitioners who base their design on experience very often use four to six dowels with relatively large diameters and sometimes additional wooden keys for this type of lapped scarf joint.

Timber joints in Europe are designed according to European standards such as Eurocode 5 (EC5, [1]) where principles for designing dowel connections are based on Johansen's yield theory [2]. However, the historical timber joints are commonly approached by experimental and FE research techniques.

Excellent pure experimental work on dowel-type connections was done by Dorn et al. [3] who found that his results agreed with the EC5 standards while the slight conservative nature of the code was underlined. Xu et al. [4] made experiments on dowel-type joints loaded in tension parallel-to-grain and expanded the study with a 3D FE model for which several failure criteria were applied. Feio et al. [5] and Koch et al. [6] investigated mechanical response of tenon-mortise joint using experimental and FE model stating that the numerical modeling is a suitable tool for assessment of timber joints performance. Caldeira et al. [7] performed experiments on steel dowels which connected a steel plate with a wood

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member. The latter numeric model was validated and the results showed agreement between the experiments and the model which was able to predict the failure modes. Another successful combination of experiments and numerical modeling of double-shear single dowel wood connection was made by Santos et al. [8]. Good prediction especially for joint stiffness was attained by Sangree and Schafer [9] who performed full-scale tests on traditional timber scarf joint with a key.

Next to investigating the joints performance also a research on load carrying capacity of pegs/dowels and the surrounding wood is being carried out. Loading wood in perpendicular direction to the grain was made by Schoenmakers and Jorissen [10] using both experiments and FE modeling. Patton-Mallory et al. [11] wrote a comprehensive review about the work on bolted connections done until 1997. Pull-out experiments ($n = 168$) made by Shanks et al. [12] helped to understand the edge/diameter distance of wooden pegs. Guan et al. [13] made an analysis of wood beam–column connection using both experimental and numerical methods arguing that wooden connectors could be even better than the steel ones. Daudeville et al. [14] showed an alternative approach while investigating the bolted joints from the point of linear fracture mechanics. Oudjene and Khelifa [15] introduced a new material model suitable for dowel modeling. Another fracture mode of dowel which is not present in the standard code was published by Miller et al. [16]. New optical techniques of investigating the timber response (e.g. DIC) were introduced by Stelmokas et al. [17].

The literature review shows ability of the modern numerical methods to model properly the complicated nature of organic materials with their non-linearity. The outcomes may demonstrate that stiffness of the models is usually comparable to the experiments while the assessment of the failure/fracture force is not so successful due to the usual scatter in the experimental data.

This research on behavior of a lapped scarf joint combines two approaches, experimental and numerical. Experimental testing is the most reliable but expensive method for investigating the structure's response while numerical analysis is a time- and cost-effective method that provides possibility to expand knowledge about behavior of structural connections under varied geometries and loading conditions. The main goal of this research is to analyze behavior and loads distributions in a lapped scarf joint with wooden dowels. Moreover, parameters that influence mechanical behavior of this type of joint such as number of dowels, joint's location along the beam span, and joint's length will be discussed. Finally, this study intends to optimize a lapped scarf joint's parameters that are most effective for the beam-end reparation.

2. Materials and methods

This research consisted of two main steps: (a) experimental testing in which the full-scale beams with lapped scarf joint with wooden dowels were tested, and (b) virtual testing of the joints using finite element analyses (FEA). Experimental data was collected for four-dowel-joints with half-beam-width laps and with 3/8-beam-width laps and for two-dowel-joints with half-beam-width laps and with 3/8-beam-width laps (Fig. 1). To provide reference data for specimens with joints three continuous beams without joints were also tested. Experimental tests were also used as a validation of the finite element models. Virtual testing using FEA expanded the study about behavior of lapped scarf joints with dowels and allowed performing optimization analyses focusing on influence of geometrical parameters on mechanical behavior of joints.

2.1. Experimental tests

The purpose of the experimental testing was to analyze yield load and stiffness of timber beams with lapped scarf joints connected by wooden dowels. It was also desired to compare these results with the outcomes from testing the reference beams without joints. Moreover, gathered experimental data was also used to compare behavior of the joints with different parameters such as number of dowels and lap element widths. Lastly, experimental data could be used for validation of numerical models.

All joints used for experimental testing were manufactured by a craftsman using hand tools only; the specimens used were made of Norway Spruce (*Picea Abies* L.). The dowels, 24 mm diameter each, were manufactured by hand with oak wood. All beams tested were 6 m long with cross section 0.2×0.24 m (Fig. 1). All beams were subjected to three-point bending test with load imposed at the mid span and simply supported at each end. During all tests the displacements at five different locations were measured using LVDTs: one near the first support, second at the beam mid-span, third at the joint's face toward the load application, fourth at the joint's center, and the last near the second support. The force applied to a beam was recorded from the pressure of the hydraulic inducers GTM series K (max. force 50 kN) that were used for loading the specimen. The loading rate was 30 mm/min. All tests were carried out until failure occurred; hence the ultimate strength was also obtained. Absolute moisture content was measured for each beam and the mean value was 19%.

Three reference specimens without significant natural defects (e.g. drying cracks, large knots, raisin pockets, fungi attack or wood grain misalignment) were tested. Results of these experiments

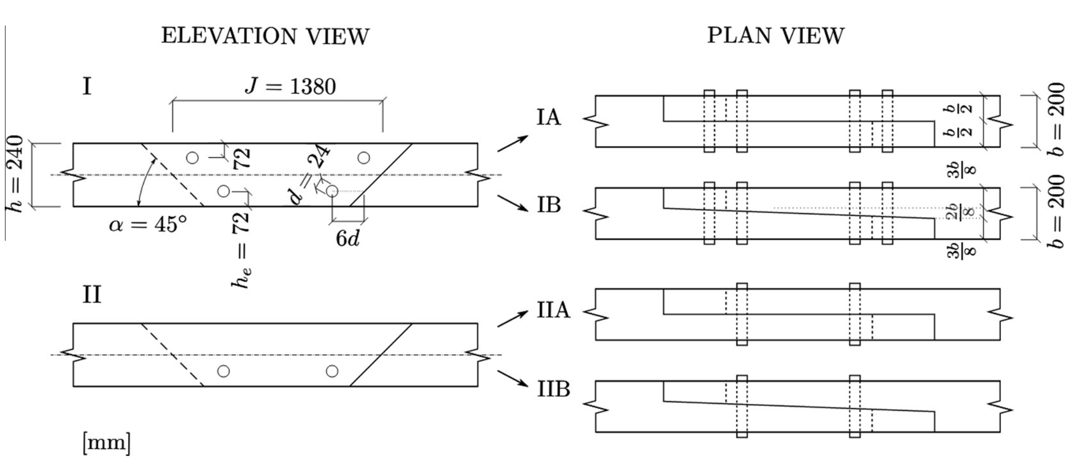

Fig. 1. Four-dowel-joint (I) and two-dowel-joint (II) with various geometries: 3/8 beam width lap (A), and 1/2 beam width lap (B).