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Rotational mechanical behaviour of wood-wood connections with application to double-layered folded timber-plate structure

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HIGHLIGHTS

- The rotational behaviour of wood-wood connections is studied.
- Different engineered wood products are compared.
- Single and double-layered connections are tested for a real project.
- The first full-scale double-layered timber folded-plate structure is presented.

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ABSTRACT

This paper is focused on the structural design of an innovative wood-wood connection designed for a full-scale double-layered timber folded-plate structure: the new Vidy theatre pavilion (Lausanne, Switzerland). Investigations into the potential of these new connections have been ongoing since 2010 in the Laboratory for Timber Constructions (IBOIS) at Ecole Polytechnique Fédérale de Lausanne (EPFL). As a continuation of this research line, the mechanical characterization of the Vidy pavilion connections in rotation was performed using different engineered wood panels. This research was realized in order to help the *Bureau d'Etudes Weinand* to understand the rotational behaviour of such connections for the real project. This experimental work was conducted in two parts: one focused on single-layered joint and the other on double-layered one. The key findings of the paper show that Cross-Laminated Timber (CLT) panels have strong qualities for rotational applications and the double-layered connections have a high rotational resistance. Finally, the connection is able to resist the maximum moment of the project considering this type of engineered timber panels.

1. Introduction

The construction of the new Vidy theatre pavilion that was designed in the Laboratory for Timber Constructions (IBOIS) at Ecole Polytechnique Fédérale de Lausanne (EPFL) is the first application of a full-scale double-layered timber folded-plate structure (Fig. 1). The objective of such a project is to develop the knowledge gained from the laboratory research and implement it in real applications. The panels are joined at the edge using an innovative wood-wood connection that was inspired by traditional joinery and was studied by Robeller during his thesis [1]. Using this connection, a double-layered prototype based on the Miuri-Ori pattern was studied to explore the potential of the connections [2]. A unique property of wood-wood connectors is that they are an integral part of the panels. A construction using these connectors therefore requires a customized prefabrication: the connectors are required to be cut in the factory along with the panels in a single operation [3]. Once assembled, these wood panels alone ensure the building structure and minimize the use of metal connectors.

The mechanical behaviour and potential resistance of these connections have been investigated by Roche since 2013 [4]; in particular, the rotational stiffness was studied [5,6], which is an important parameter of a folded-plate structure [7,8]. The global mechanical behaviour of the connectors is complex, especially owing to the anisotropic characteristics of wood materials. In previous works, only Laminated Veneer Lumber (LVL) panels were studied because of their small thickness, homogeneity, and relatively good resistance. However, this project was required to be compliant with a sustainable development policy and the use of Swiss wood panels was essential. Furthermore, very few manufacturers produce LVL, and therefore, it was decided that Cross-

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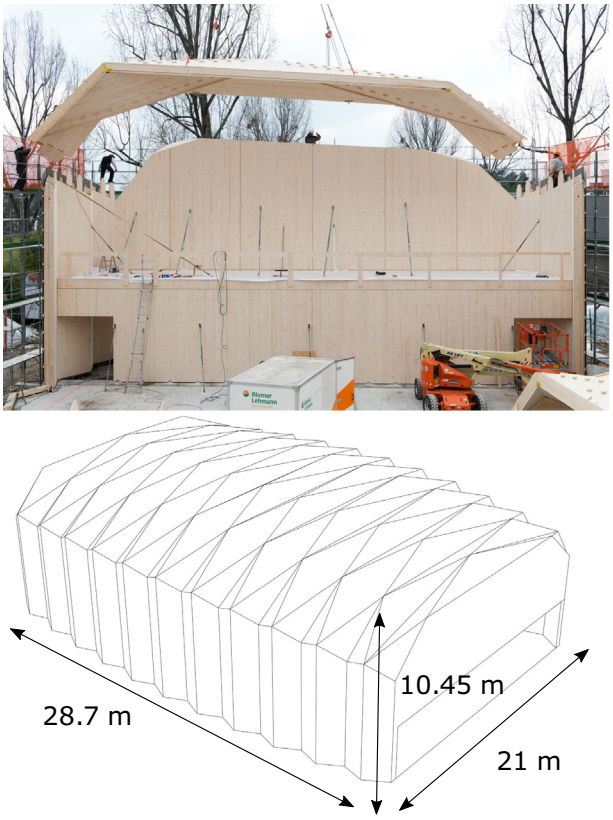

Fig. 1. Photo of ongoing Vidy theatre building site [Photo: Ilka Kramer Photography] and building size.

Laminated Timber (CLT) panels would be used in this study. Different wood-based panels were thus tested to choose the best option for the project in order to assist and collaborate with the *Bureau d'Etudes Weinand* in the rotational mechanical characterization of this innovative connection.

2. Parametric design and fabrication process

The construction of the Vidy theatre Pavilion has been made possible through the development and application of computational tools specific to this project. Two main programs have been developed using the RhinoCommon Software Development Kit using the programing language C#; this enabled the development of custom plugins for the 3D computer-aided design (CAD) software Rhinoceros 3D.

The construction system builds upon earlier versions of timber folded-plate structures. The first folded-surface structure was built by hiendl.schineis Architekten in 2001 for the Musikprobenhalle Thannhausen near Augsburg in Germany [9]. While this project was a frame-type structure with 3 segments along the direction of its span and 30 timber plates in total, a second prototype of a barrel vault structure made from timber plates was introduced by Hani Buri et al. in 2006 [8]. The design and fabrication of this Miura-Ori origami-inspired prototype with 144 plates was made possible through the repetitive use of identically shaped plates. These plates could be cut with a circular saw and assembled at the correct dihedral angles by using a small number of custom-made templates. In 2010, this design concept was applied to the Chapel of St Loup [10], where 39 differently shaped plates were CNC-cut with miter joints. Architecturally, this project demonstrated the novel possibilities of shaping spaces using the freedom of form that is achievable with 3D CAD software.

Owing to the subsequent increase in the number of individually shaped plates and the complexity of the structural shapes, a rapid yet precise and simple assembly of large numbers of individually shaped plates became increasingly important. The possibility of integrating joints into the shape of the parts, while taking advantage of both their connector and locator features, was demonstrated in a folded-plate prototype that was presented at the Advances in Architectural Geometry Conference in 2014 [11]. Using dovetail joints at all the plate edges, the shape of the plates in this prototype allowed to embed the assembly instructions into the form of the components.

The integration of these joints was facilitated through the use of a 3D CAD application programing interface (API) that allowed algorithms to be used for the generation of the plate geometry and computer numerical control (CNC) G-code (ISO6983/DIN6625). The development of a 5-axis CNC-code generator enabled the automatic generation of parametric, project-specific details like connections, which would not have been feasible to draw or program using manual shop floor programing. The same applies to the drawing of the joint and plate geometries using the CAD software. Hence, this project took advantage of the new possibilities with 5-axis-enabled CNC technology in the automatic fabrication of complex-shaped joints as well as automated geometry generation using a CAD API and automated machine code generation. Finally, the advantages of this automatic pipeline could be demonstrated using a folded-surface structure that was applied to a doubly curved target surface. The integral joints allowed for a rapid yet precise assembly of these 104 individually shaped plates, which were connected by integral joints only. A structural analysis showed that deformations under asymmetric loads could be reduced by up to 39% as compared to a geometrically simpler, singly curved variant of this prototype [11]. Therefore, algorithmic tools for the generation of integrally connected freeform timber-plate structures do not only provide new architectural possibilities, but also potential for structural optimization.

The Vidy theatre project implements a double-layered version of this prototype that takes particular advantage of the integral attachments ability to join very thin plates. Instead of one thick layer of wood, two separate layers have been used in the project, which also allows the integration of thermal insulation between the two layers (see Fig. 3). The fully integral assembly of such double-layered antiprismatic folds with single-degree-of-freedom joints was introduced as a four-step design process [1]. An algorithmic implementation of the technique using "double-through-tenon joints" was first introduced at the RobArch 2016 Conference in Sydney by Robeller and Weinand, and was the case study of a Miura-Ori type folded-surface structure [2]. In the Vidy theatre, the design process is first applied to a hybrid folded-plate structure, with prismatic folded wall segments that connect seamlessly to an antiprismatic folded-plate roof structure.

Fig. 1 shows the basic surface model of the design. The double-layered folded plate (DLFP) (see Fig. 2) design software plugin that was custom developed for the project allowed the automatic generation of the geometry of all the plates based on 1. this surface model, using the double-connected-edge-list polygon network format [12], 2. key parameters for the plate thickness t_plate and the distance between the two layers t_offset, and 3. an Excel spreadsheet that contained joint-specific information such as plate insertion directions and manual overrides for the automatically generated parameters.

3. Single-layered connection

As previously mentioned, the use of CLT panels has been investigated in this project but almost all IBOIS works were generally