Thin-Walled Structures 122 (2018) 314–328

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Experimental investigation of the influence of integral mechanical attachments on structural behaviour of timber folded surface structures

Andrea Stitic*, Christopher Robeller, Yves Weinand

Laboratory for Timber Constructions, Ecole Polytechnique Federale de Lausanne, CH-1015 Lausanne, Switzerland

ARTICLE INFO

Keywords:
Folded plate
Timber panels
Multiple tab and slot joint

ABSTRACT

Structural behaviour of timber folded surface systems greatly depends on the connections ability to transfer the occurring forces between the adjacent elements and finally to the supports. This paper focuses on multiple tab-and-slot joints (MTSJ), where digital prefabrication is used to integrate connectors through plate geometry. Multiple plates assembled within a large scale folded surface structure were tested to examine the influence of connection detail type on its global structural behaviour. For this purpose an innovative test setup was devised that approximates uniformly distributed surface load. The connection details used were chosen with respect to preliminary small scale bending tests. Three groups of distinct large scale structures were tested: (1) structures with miter joint detail and adhesive applied along the edges; (2) structures with open slot MTSJ; and (3) structures with closed slot MTSJ. Extensive investigation into the load bearing behaviour and failure propagation for each of the three different types of structures has been conducted. For analysing their feasibility, the tested structures were also reviewed in terms of fabrication time, assembly and on-site construction. The obtained results show that even though adhesively joined structures provide highest structural stiffness, they exhibit multiple disadvantages when considering building scale applications. Open slot MTSJ structures results indicate that these joints cannot provide sufficiently reliable structural behaviour. Structures with MTSJ closed slots show that their joint geometry greatly improves both the ultimate load-bearing capacity as well as stiffness. Furthermore, by transferring the edge occurring forces mainly in compression, they provide additional ductility to the global system. Within the scope of this paper, closed slot MTSJ proved to be a very efficient connection type which can constitute a robust folded structural system made as a multiple assembly of thin timber plates.

1. Introduction

In structural engineering folded surface structures present one of the concepts for construction of self supporting, column free systems. They utilize structural benefits of folding with regard to material saving and structural efficiency [1]. Additionally, high load-bearing potential and strength to weight ratio of timber panels, all lead to the realization of very efficient lightweight structural systems. As timber folded surface structures consist of a large number of discrete, thin plane elements, proper edgewise connection details are essential for ensuring an efficient load bearing system. For structures made from thin wood panels (thickness/average side ratio: $t/L \leq 0.05$ [2]), such connections present a great challenge. Recently, *integral mechanical attachments* were proposed by [3–6] as a new technical solution inspired by traditional woodworking joints. Rather than using additional connectors, this technique utilizes digital prefabrication to integrate connectors through the plate geometry. This paper focuses on a particular integral mechanical attachment technique, the so called one-degree-of-freedom multiple tab-and-slot joints (MTSJ). MTSJ geometry can be described with a set of three angles which define the inclination of their locking faces. These angles determine the unique assembly sequence when using such joints in a multiple plate structure. As a result, a geometrical solution for simultaneous joining of adjacent plates with multiple non-parallel edges was presented in [6]. Experimental testing of MTSJ mechanical behaviour suggested that they provide a suitable degree of bending as well as shear stiffness [7,8]. In these studies the MTSJ semi-rigid behaviour was found to be competitive to that of screwed connections, confirming that they can provide a highly feasible alternative to standard joining techniques. In addition to their good load bearing function, these joints also provide a locator feature for fast and precise positioning of thin elements. The latter being extremely important when multiple, non-parallel plate edges need to be assembled simultaneously. The tests performed by [7,8] concentrated on individual loading cases, i.e. bending and shear, imposed locally on the MTSJ connection detail. However in the global structure context, where the edge connections are subjected to combined influence of bending,

* Corresponding author.
E-mail address: andrea.stitic@epfl.ch (A. Stitic).

http://dx.doi.org/10.1016/j.tws.2017.10.001
Received 26 June 2017; Received in revised form 5 September 2017; Accepted 2 October 2017
Available online 13 November 2017

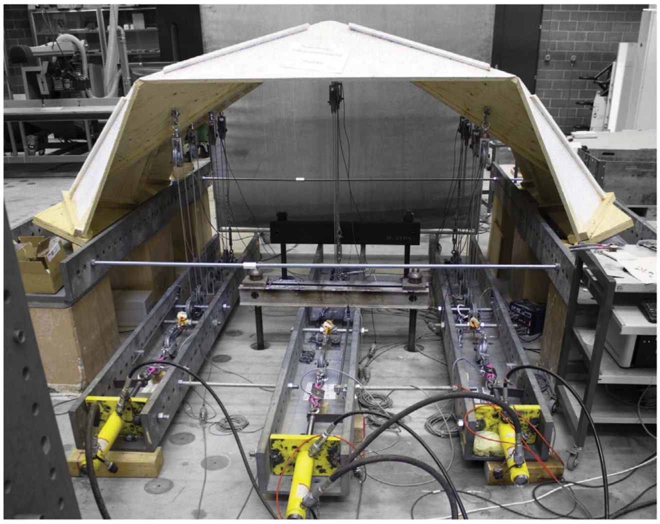

Fig. 1. Test setup devised for approximating uniformly distributed surface load.

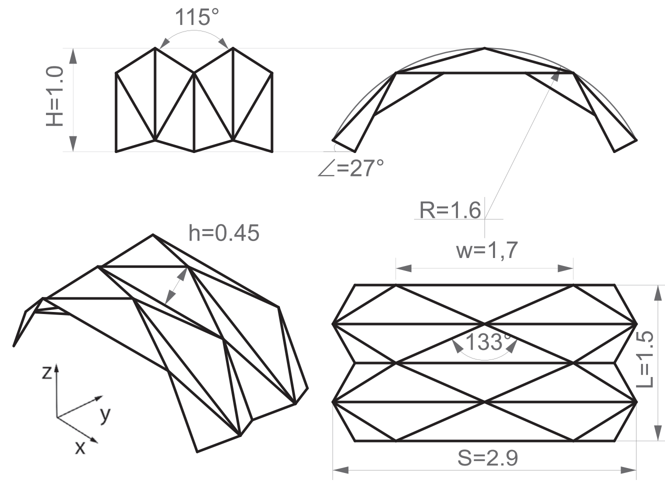

Fig. 2. Large scale structure geometry parameters.

shear, tension and compression, the potential feasibility of such semi-rigid connections has not been studied. It has been demonstrated, regardless of the material, that the connection behaviour has a very large influence on the structural performance of civil engineering structures [9,10]. Therefore, the characterisation of the MTSJ semi-rigidity within a global system is considered to be of crucial importance for establishing timber folded surface structures on a building scale.

This paper examines the influence of the type of connection detail on the global behaviour of folded surface system by performing experimental tests using an innovative test setup (Fig. 1). It is structured as follows. Section 2 presents the structure design including material, global geometry, connection details and the fabrication process. Section 3 includes preliminary experimental tests on connection details, together with the obtained results and final choice of their parameters, for use in large scale structures. Section 4 presents the test setup and three types of tested large scale structures. Sections 5 and 6 lay out the results and discussions on the large scale tests. Section 7 summarizes the main conclusions. Additionally, Appendix A and B are included for a more detailed description on the digital fabrication, along with the used test setup and instrumentation.

2. Structure design

Detailed geometry of the test structures was defined considering a series of constraints regarding material, fabrication, connection details and element assembly.

2.1. Material

Panel material was chosen as 21 mm thick Kerto-Q structural grade Laminated Veneer Lumber (LVL). It consists of seven 3 mm thick spruce peeled-veneer laminates from which one fifth is glued crosswise in a lay-up $| - ||| - |$. This kind of composition improves the lateral bending strength and stiffness of the panel. Also, in this way very homogenous and mechanically strong panels are obtained, which can be assumed as having orthotropic material properties [11].

2.2. Global geometry

It has been established that material, fabrication, connection details as well as element assembly constraints, dictate the range of feasible folding angles between adjacent plates, φ, as well as individual plate geometry [12,7]. Respectively, the final design of the folded surface was chosen as a regular "Yoshimura" pattern with maximum fold angles equal to 115° and a transversal cross section following a constant curvature, $R = 1,6\ m$. It consists of twenty discrete elements with maximal plate size of $1,7\ m \times 0,45\ m$, which form a structure with 3 m span in the transversal direction ($-x$ axis, see Fig. 2) and $1,5\ m$ length in longitudinal direction ($-y$ axis, see Fig. 2). The height of the structure in its midpoint is equal to 1 m.

2.3. Connection details

In the experimental tests presented in this paper, three different types of structural plate connection details were considered: MTSJ with open slots, MTSJ with closed slots and adhesively bonded connections (see Fig. 3). The use of metal fasteners was not considered relevant, since their application either highly restricts the requirements for minimal plate thickness, or a large amount of fasteners is necessary for achieving a sufficient connection stiffness [13]. Therefore, in the presented case of edgewise connections between 21 mm thin plates, such detailing was not feasible.

MTSJ with open slots. These prismatic connections consist of interlocked tabs and slots assembled along a specified vector of insertion. Their geometry can be described by using a set of three Bryant angles, θ_1, θ_2 and θ_3. They further define the contact locking faces of adjacent edges, as well as the three-dimensional subset of feasible insertion vectors [7]. Their load bearing capacity, i.e. stiffness, greatly depends on the mentioned set of geometrical parameters. Bending and shear load tests, performed on two plate assemblies with various geometries, showed that the highest stiffness of such joints can be expected for the following set of angles: $\theta_1 = 0°$, $10° \leq \theta_2 \leq 30°$, $15° \leq \theta_3 \leq 30°$ [7,8]. These values are further constrained by the requirement for simultaneous assembly of two plate edges where the individual edge insertion vectors have to be parallel [6]. Finally, for such edges, i.e. skewed edges of the triangular plates, angle values were chosen so that they result in insertion vectors parallel to the structure's $-y$ axis; $\theta_1 = 0°$, $\theta_2 = 27°$, $\theta_3 = 20°$. Concerning the remaining straight edges, i.e. those parallel to the structure's $-x$ axis, there existed two possibilities for governing the values of their Bryant angles: (1) either the insertion vector of the straight edges is chosen equal to those of the skewed edges, resulting in different values for the straight edges Bryant angles set, $\theta_1 = 0°$, $\theta_2 = 0°$, $\theta_3 = 20°$; or (2) Bryant angles set values are kept equal to those of skewed edges, resulting in different insertion vector directions for the straight edges. The latter option was chosen in order to maintain equal joint geometry within the entire structure (Fig. 4).

MTSJ with closed slots. In literature, these kind of joints are also referred to as *through type joints*. Their geometry can be defined in a similar way as for the open slot ones [14], main difference being that their insertion vector is constrained to a two-dimensional subset. This is