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MAKERJOINT, A NEW CONCEPT FOR JOINING MEMBERS IN TIMBER ENGINEERING – STRENGTH TEST AND FAILURE ANALYSES

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Abstract

The wood construction industries are becoming more focused on climate change and resource depletion, and individual and industrial consumption must reflect a greater degree of concern for the climate and environmental wellbeing. This paper presents a new concept for timber engineering, the purpose being to acquire information about the failure modes and the tensile and compressive strengths of two types of joint, the Simple Gooseneck and Thick Gooseneck, that can be used in a new concept for joining members in timber structures. This Makerjoint concept uses laminated veneer lumber (LVL) as nodes in regions with a pronounced non-uniform stress distribution and sawn timber in regions with a more uniform stress distribution. No metal fasteners or adhesives are used in the joint between timber and LVL. The concept is intended for joints using 3-axis CNC machinery and to be a system for on-site- and pre-fabrication of e.g. small houses, emergency shelters and exhibition stands. The joints have a higher compressive than tensile strength. The joints exhibited brittle failure in tension (beam and/or node failure) and buckling occurred in compression around the thinnest cross section of the beams. Suggestions are made for how the mechanical properties of the joints can be improved.

Key words: *prefabrication; digital fabrication; robotic; wood joints.*

INTRODUCTION

This paper describes a new concept for joining timber in construction. The concept is named Makerjoint, referring to the *maker movement* (Hatch 2014) and wood joints for timber structures. The Makerjoint concept consists of beams of sawn timber or glulam, and nodes of engineered wood products (EWP) where the beams are connected to each other. The beams are used in places with a uniform stress distribution (e.g. as beams, posts or bracing) and the nodes in places with a non-uniform stress distribution. This means that beams are under bending, tensile or compressive forces, and that they are connected to nodes to form a light-weight, load-bearing construction as exemplified in Fig. 1.

The inspiration for the Makerjoint concept came from observations in nature and the work of Mattheck (1998) regarding biological self-optimisation in trees, i.e. the structure is reinforced according to the load level to fulfil a structural function with a high degree of utilisation of the structure. It was also inspired by the makers of *wikihouse*, an open-source online collaboration between engineers and enthusiast to build houses of plywood using CNC machinery (Parvin 2013).

Other important initial sources of inspiration for the Makerjoint concept were the need for reutilization and recyclability of the materials and products used. The use of renewable materials for the concept is therefore central, e.g. using non-toxic bio-adhesives like lignin-tannin-adhesives (Mansouri et al. 2011) or at least lignin-based adhesives (Mansouri & Salvadó 2006; Müller et al. 2007; Zhang et al. 2013) for EWP such as plywood, CLT (cross laminated timber) and LVL (laminated veneer lumber). This makes the components of the structure easily reuseable for other purposes in the wood product chain, and it also simplifies recycling through the absence of toxic components, making the whole construction a part of nature's nutrient cycle (McDonough & Braungart 2003), like the "Holz 100" log-buildings of Thoma (2003). A general idea of the Makerjoint concept is to promote low energy consumption per unit of the final product. Energy-intensive materials (compared to sawn timber) such as EWP should therefore be used only where uniform material properties are necessary, such as areas with a pronounced non-uniform stress distribution in the nodes.

In the Makerjoint concept, the beam and node are pressed into each other and with neither metal fasteners nor other metal connectors. The Makerjoint concept as a construction system is similar to the timber-frame system (Kolb 2008) with its braces and studs, but the central nodes are not subjected to an eccentric load. By adding surface layers, insulation etc. to the frame structure, the degree of prefabrication can be considerably increased. A similar concept was described by Gehri (2001) to connect plywood and glulam, but using finger joints and adhesives. From a functional viewpoint, the Makerjoint concept is also similar to punched metal-plate fasteners at the nodes (Blass et al. 1995). Punched metal plate fasteners are used to join beams in trusses, combining nails and metal plates in a single fastener. Another connection with a similar appearance is the multiple-shear dowel connection with slotted-in steel plates, where a slot is cut in the beam and a steel plate is slid in and jointed with self-drilling dowels (Mischler 2001). The possibility of designing expandable structures by adding new nodes makes the structure universal and makes it possible to adapt it to the user's needs e.g. as part of an open-source urbanism as proposed by Fuller & Haque (2008).

Traditional joinery techniques have a very long tradition. A comprehensive overview of traditional Japanese, Chinese and European joinery techniques for timber construction has been given by Zwerger (2012), and for constructions and joint techniques from logs by Phleps (1982). A more detailed introduction on working with wood in Japanese joinery and construction solutions has been presented by Sato (1995) and Nakahara (1995). From a European perspective, Gerner (1992) and Graubner (1992) have developed taxonomy and documented common dimensions for wood joints in the German-speaking area of middle Europe The purpose of the present study was to acquire information about the failure modes and the tensile and compressive strengths of the Simple Gooseneck and Thick Gooseneck joints for the Makerjoint concept.

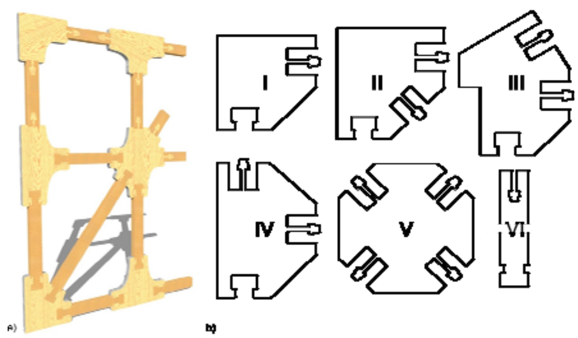

Fig. 1.
The Makerjoint concept. a) Sketch of a plane wall assembly, and b) examples of nodes: I+II - corner nodes, III - roof node, IV - multiple floor node, V - bracing node, VI - Makerjoint beam

MATERIALS AND METHODS

Two types of joints between the beams and the nodes have been tested in tension and compression, the Thick Gooseneck joint and the Simple Gooseneck joint, Fig. 2. To evaluate the node design of the Makerjoint concept, a number of different wood joints were designed and tested. The Simple Gooseneck and Thick Gooseneck joints were designed by revising traditional joinery techniques for use with modern production and design tools e.g. CNC machines. The Simple Gooseneck joint is derived from the simple Japanese gooseneck joint (Kamatsugi) cf. Graubner (1992). The Thick Gooseneck joint was also inspired by the Simple Gooseneck and dovetail joints.

Wood joint design and specimens preparation

The Simple and Thick Gooseneck joints used in the nodes are dimensioned in accordance with the material properties and the dimensions of the tools normally used for wood CNC machining.The design and dimensions for testing the joints are shown in Fig. 2.

The node for the Simple Gooseneck joint was made of LVL due to the greater shear strength of the material, which is important in the "head" area of the joint in order to resist tension-introduced shear forces (Fig. 2). The dimensions of the Simple Gooseneck joint were determined by linear-elastic theory and the characteristic strength values of the LVL and timber (CEN 2009; CEN 2004; DIBt

2011). The maximum tensile strength in the shear plane of the node head and protruding area of the beam for a length of 60mm was calculated.

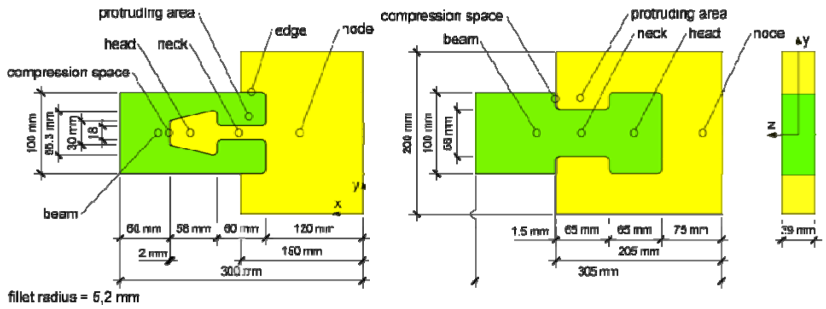

Fig. 2.
The Simple Gooseneck joint (left) and Thick Gooseneck joint (right). The beams are of timber and the nodes are of LVL (laminated veneer lumber)

The length was chosen based on carpenter´s experience (Nakahara & Sat 1995). The minimum width of the neck and the contact area between the timber beam and the LVL node for maximum tensile strength were calculated. The tensile strength of the joint is most critical since the wood has a lower shear strength than LVL. A moment introduced in the beam by a tensile force without the edges would tend to open the joint, and the edges of the node therefore enclose the beam on the sides. The dimensions of the Thick Gooseneck joint were determined in the same manner as for the Simple Gooseneck joint.

The joints were digitally handled as 3D parametric models, within the CAD software *SolidWorks 2013*. Based on the 3D model, 2D CAD-drawings were made to generate the machine code in *Alphacam 2013 r1* to operate the CNC for manufacturing. The CNC used for manufacturing was a *Morbidelli Author 600K* and finishing cutter (4-flute, diameter 10mm), i.e. a 3-axis CNC router. During the manufacturing process, care was taken to ensure that, as required for compression testing, the end-grain surfaces were plane and parallel to each another.

Material

Metsä Kerto Q LVL from Lohja Kerto Mill was used for the nodes. The LVL was conditioned at 40°C and 70% RH to an equilibrium moisture content (EMC) of about 12%. For the beams, strength-graded C24 Scots pine (*Pinus sylvestris* L.) with dimensions of 39x100 mm was used. The timber was conditioned at 20°C and 65% RH to about 12% EMC before manufacturing and testing the joint section. In the joint region, only timber without cracks or knots was used. The average oven-dried density of the LVL was 461 kg/m³ and of the timber specimens 437 kg/m³ determined via CT scans

Compression test

Five specimens of each type of joint were tested under compression in a press with an attached plane load cell as shown in Fig. 3, Table 1. The measurement accuracy of the load cell was ± 0.25%. The load was applied at a manually controlled constant load rate of approximately 0.5 mm/min parallel to the grain, based on EN 408 (CEN 2012) until the resistance of the joint decreased in an unrecoverable manner.

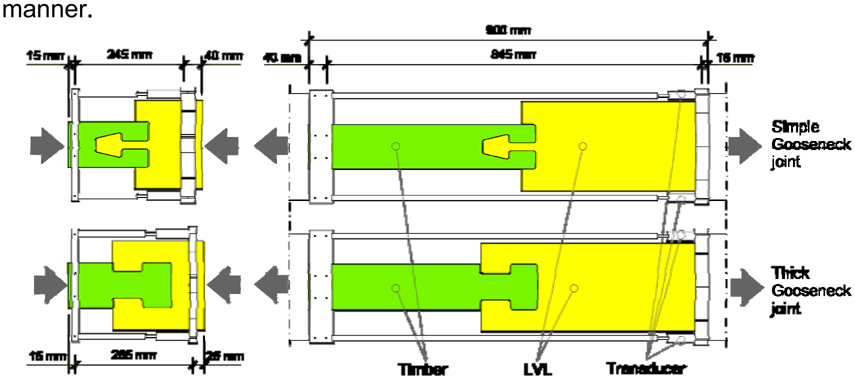

Fig. 3.
Makerjoint test setup for compressive (left) and tensile testing (right)

The displacement was measured with two linear displacement transducers at the side of the joints, separated by a distance of 245mm for the Simple Gooseneck and 265 mm for the Thick Gooseneck joint. The applied load for a displacement of 1.5mm and the ultimate load were determined (Heimeshoff & Köhler 1989). The slip modulus K is given by:

$$K = \frac{F_{0.4} - F_{0.1}}{\delta_{0.4} - \delta_{0.1}} \left[\frac{kN}{mm}\right] \tag{1}$$

where:
$F_{0.1}$ and $F_{0.4}$ are the applied load at 10% and 40% of the ultimate load, and
$\delta_{0.1}$ and $\delta_{0.4}$ are the corresponding displacements

Tension test

In tension, five specimens per joint were tested, Table 1. The tensile specimens were reinforced in the clamping regions, fixed at one side and pinned to the load cell. To eliminate any bending moment introduced by the single fixed side, the test rig was levelled manually. The load was applied at a manually applied constant load rate of approximately 0.25 mm/min parallel to the grain, based on EN 408.

The distance between the two linear displacement transducers attached at the side was 845mm. The applied load for a displacement of 0.5mm and the ultimate load were determined. The slip modulus was calculated according to Equation 1.

CT scanning

X-ray computed tomography (CT scanning) is a method developed by Hounsfield (1973), which makes it possible to determine the density of the wood specimen by reconstruction of the CT images e.g. with *ImageJ* (Abràmoff et al. 2004). Lindgren et al. (1992) have shown that CT scanning is a method of determining the wood density with an accuracy of 2.6 kg/m³. CT scanning was used to determine the density of the specimens and to examine the failure of the wood joints and areas of densification of the material.

RESULTS AND DISCUSSION

Table 1

Compressive and tensile data for Simple Gooseneck (SGJ) and Thick Gooseneck (TGJ) joints. n - number of replicates, $F_{c,1.5}$ and $F_{t,0.5}$ - the applied load at 0.5 mm and 1.5 mm displacement, $\sigma_{c/t,ult}$ - ultimate compressive (c) or tensile (t) stress based on a cross-section area of 100x39 mm^2, $CV_{c/t,ult}$ - coefficient of variation, $F_{c/t,k}$ characteristic values based on EN 14358 **(CEN 2006),** ***$\delta_{c/t,ult}$*** **displacement at ultimate load, K** ***slip modulus***

Compression	n	$F_{c,1.5}$	$F_{c,ult}$	$\sigma_{c,ult}$	$CV_{c,ult}$	$F_{c,k}$	$\delta_{c,ult}$	K_c
		[kN]	[kN]	[N/mm^2]		[kN]	[mm]	[kN/mm]
SGJ	5	72.2	100.6	25.8	0.04	90.7	2.68	91.6
TGJ	5	93.1	131.4	33.7	0.07	110.0	2.66	87.9
Tension	**n**	$F_{t,0.5}$	$F_{t,ult}$	$\sigma_{t,ult}$	$CV_{t,ult}$	$F_{t,k}$	$\delta_{t,ult}$	K_t
		[kN]	[kN]	[N/mm^2]		[kN]	[mm]	[kN/mm]
SGJ	5	9.4	21.1	5.4	0.09	16.7	1.34	18.4
TGJ	5	8.3	12.1	3.1	0.12	8.8	0.76	16.2

Compressive test

In the compressive test, both types of joints showed a strength higher than the characteristic strength of C24 timber or Kerto Q LVL. At the ultimate load ($F_{c,ult}$), all specimens buckled around the weak axis of the smallest cross section of the beam, the Simple Gooseneck joint around the z-axis and Thick Gooseneck joint around the y-axis (Fig. 4). In the CT-scans in Fig. 4, it is also possible to detect highly densified regions in the solid timber (beams).

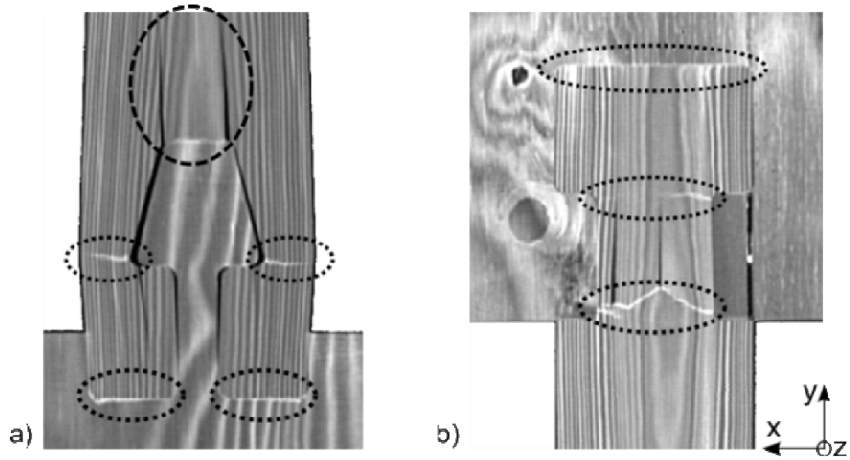

Fig. 4.
CT reconstruction of a a) Simple Gooseneck joint, and b) a Thick Gooseneck joint after compressive testing. Highly densified areas can be seen in the dotted areas as light lines. Splitting is also visible as dark low density areas (see e.g. the dashed area)

The observed buckling behaviour indicates that the stability of the joint can be improved, i.e. a higher strength can be achieved by increasing the thickness of the Thick Gooseneck and the width of the Simple Gooseneck beam (Fig. 2). Critical for the Simple Gooseneck joint is the splitting parallel to the grain from the node head into the beam (Fig. 4a). In two out of five replicates, splitting occurred before buckling. The observed splitting of the beam may also lead to abrupt failure if there is a fibre deviation in the wood material in the joint region of the beam. Splitting was not observed under the relative high applied load at 1.5mm displacement ($F_{1.5}$) compared to the ultimate load ($F_{c,ult}$). That the wood did not split may indicate that the beam will not split under service conditions, but the tension perpendicular to the grain introduced by the wedged-shaped node head is critical (see Fig. 2, left). To investigate the splitting in greater detail for the Simple Gooseneck joint, a specimen with a longer beam part should be tested.

In Fig. 5, the strength ot the Makerjoints is compared with the strength of a conventional steel-to-timber joint (CEN 2004) in tension and compression. It is clear that in compression, the Makerjoint is stronger than the steel-to-timber joint. The coefficient of variation (CV) for $F_{c/t,ult}$ is between 4 and 12% and is within the natural variance for timber according to Dinwoodie (2000), which mentions 10-30% as typical values for structural timber.

Fig. 6 shows the load-displacement plots in compression for the Simple Gooseneck joint, and the Thick Gooseneck joint. The values are calculated in accordance with Eurocode 5 (CEN 2004) for the dowels and EN 14358 (CEN 2006) for the Makerjoints for a beam cross-section of 39x100mm^2. In compression, the joints shows a favourable (Madsen 2000) ductile behaviour. Fig. 6 also shows a kink in two of the curves for the Thick Gooseneck joint in compression, which are related to a brief loss of pressure in the actuator. Apart from high compressive strength and ductility, the nodes have a compressive slip modulus of approximately 90 kN/mm (Table 1), which indicates possible applications for stiffer timber structures than e.g. those made with bolt connections.

The compressive strength of the Simple and Thick Gooseneck joints was two to three times higher, showing the potential for applications with predominantly compressive forces (Fig. 5).

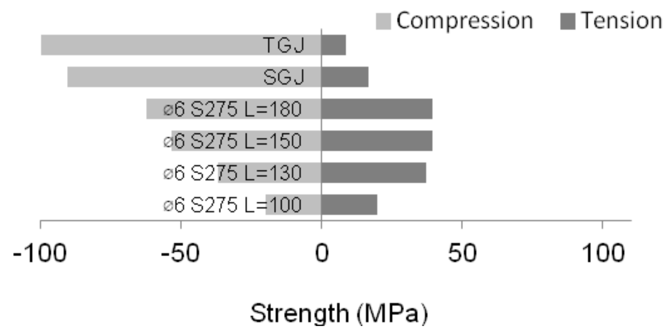

Fig. 5.
Comparison of characteristic tensile and compressive strength of Simple Gooseneck (SGJ), Thick Gooseneck (TGJ) joints and steel-to-timber dowel (ϕ6S275) connections (double shear with external thick steel plate)

Tension Test

The investigation revealed that the joints exhibit brittle failure behaviour in tension and have a comparatively low stiffness and strength, Fig. 6. The tensile strength for the Simple Gooseneck joint was about 70% higher than that of the Thick Gooseneck joint.

The Simple Gooseneck joint failed because the node head and/or protruding area sheared off (Table 2). Failure occured either in the shear planes of either the beam or the node. This behaviour is best visualised by a rope with a plate at the end, the rope -in this case the slender node neck- will align in the direction of the resulting force at the protruding areas of the node head and compensate for small eccentricities. The compensation for eccentricity explains why the tensile strength is almost twice that of the Thick Gooseneck joint (Table 1).

In the Thick Gooseneck joint, failure occurred in two stages. First, one of the beam protruding areas sheared off, and thereafter the other protruding area of the beam or LVL sheared off (Table 2). Under load, the joint of the Thick Gooseneck node tended to open up due to the bending moment introduced by the eccentricity of the contact area relative to the centre axis between the timber and LVL. This bending moment leads to an increasing eccentricity and ultimately to failure of the joint. The slip moduli of the two joints differ, but the difference is small. The slip modulus of the Simple Gooseneck joint is 18.44kN/mm and this is approximately 14% higher than that of the Thick Gooseneck joint.

Table 2
Number and location of shear failure in tensile testing of Simple Gooseneck and Thick Gooseneck joints

Shear failure in:	*Simple Gooseneck joint*	*Thick Gooseneck joint*
Timber	2	3
LVL	2	-
Timber and LVL	1	2

Overall, the strength in tension of a steel-to-timber connection was approximately twice that of the Simple or Thick Gooseneck joint and this shows the necessity for further improvement (Fig. 5). The abrupt failure due to brittle shear failure also shows the need for possible improvements.

The beam could be improved by adding materials, by changing the joint geometries or by wood modification. By adding material e.g. reinforcement with surface-glued veneers or timber or dowels welded into the protruding area of the beam with the grain in the direction of the resulting forces, the tensile strength of the joint could be increased. Another option is to change the joint geometry to strengthen the weak axis or increasing the shear plane length. A possible method of increasing the shear strength and therefore the tensile strength of the joint would be pre-stressing of the shear area by densification perpendicular to the grain.

Furthermore the node could also be improved by using a higher strength or higher grade material e.g. beech LVL (DIBt 2013). Increasing the area moment of inertia to stiffen the protruding area and to reduce the deformation in the Thick Gooseneck joint connection is also an option.

CONCLUSION

The tensile and compressive strengths of two different timber joints of the new Makerjoint timber engineering concept have been studied. The joint was of a splicing joint type with nodes of laminated veneer lumber (LVL) and beams of sawn timber. The results show that joints with a high strength in both tension and compression can be achieved, but the brittle failure under a tensile load is problematic due to the risk of abrupt failure. Alternative designs of the tension-relevant part of the joints have therefore been presented.

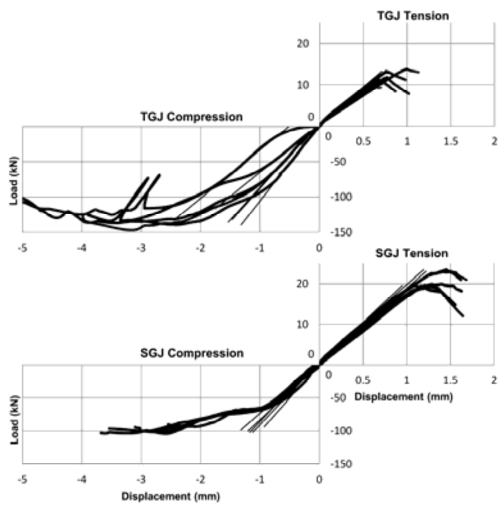

Fig. 6.
Load-displacement plots in tension and compression of the Simple Gooseneck (SGJ) and Thick Gooseneck joint (TGJ) specimens

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