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DEVELOPMENT OF NOVEL STRUCTURAL CONNECTIONS – INSPIRATION FROM FURNITURE INDUSTRY

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ABSTRACT: The presented project aims to develop prototypes for building connections inspired by the furniture and interior industry and explore them with representatives from the timber construction industry. The long-term vision is that actors from furniture and building industry together develop a smart system for assembly of building elements, which provide higher precision, faster and more efficient assembly than what is available today. The prototype connection developed in this project shows that the idea is ripe for full-scale investigation. Laboratory tests showed promising results due to the high failure loads obtained with very high stiffness.

KEYWORDS: assembly, connections, CLT

1 INTRODUCTION

There is a lack of affordable housing in Northern Europe and the construction industry cannot keep up with the demands, primarily due to scarce of available resources [1]. One of the bottlenecks is related to efforts required on-site to assemble prefabricated building elements. Therefore, new solutions are continuously sought to improve efficiency on the construction site, thereby reducing delivery times and costs. Such innovative ideas might come from industries that have a higher level of industrialisation than traditional building construction.
The furniture industry and timber construction have common traditions. However, today's furniture industry has a larger share of industrial production, which means production at a lower cost. By borrowing ideas from industrial furniture production, there is an opportunity to renew and transform the structural timber design and streamline the construction process. Historically, cross-sectoral spin-off effects have been shown to generate success factors.
This paper reports about a demonstration project with the aim to develop prototypes for building connections inspired by the furniture and interior industry and explore them together with industry actors. The success of the demonstration led to the initiation of a larger project, together with industry actors with the aim of developing systems for assembly of building elements, which provide higher precision and enable a faster and more efficient process than what is used today.
The main focus is on joints used to assemble cross laminated timber (CLT) elements at the construction site as this is a building system that is currently undergoing strong development, yet connections are somewhat underdeveloped. Based on the ideas developed in this study, a full-scale investigation is underway in the continuation project.

2 CARPENTRY JOINTS VS MODERN TIMBER CONNETIONS

A simple way to adjust and align parts of furniture to fit together is provided by (wooden) dowel pins. Slide connectors and hook connectors allow control along the length. Connecting bolts in combination with cam lock nuts allow for detachable mounting solutions; however, other types of connectors are also available with the same feature.
There are several types of joints to consider when assembling a CLT building frame. Standard connections used in building can be categorized into (1) walls to foundations joints, (2) walls to floors/roofs joints and (3) walls to walls and floors to floors joints.
Long self-tapping screws or brackets together with anchor nails/ screws are common for connecting the structural elements. There are also slotted-in plates with dowels, glued rods and other systems for load transfer.

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Traditional woodworking joints are also applied such as sliding dovetail, tenon and dovetail joint. There are also special connections, many of which are based on different metal brackets, of steel or aluminium, screwed onto the wooden boards. Several of the systems are based on the CLT panels being processed with a high degree of prefabrication in a CNC machine with a high degree of accuracy. [2] presents some innovative system for connecting CLT elements in combination with different mounting brackets: (1) Knapp® connection system and (2) Tube connection system.

The dowel pins of the furniture and interior industry are similar to the dowels used in construction. Historically, wooden dowels have been used to keep logs in place. In today's timber structures dowel type connections are still popular. The dowels are made of steel and transfer forces between elements primarily through shear, often with the help of reinforcing steel plates.

Steel dowels can experience plastic deformations especially if they are loaded in bending which gives ductility and helps reducing the risk for brittle failure. Different hook connectors and angle brackets are also found in both industries. In older house designs there are several types of joint that are common in traditionally manufactured furniture.

3 THE NOVEL CONCEPT

3.1 MODEL

The system under development is somewhat similar to the tube connection presented in [3] and [4], with the main difference that the proposed system is made similar to joints common in ready-to-assemble furniture. The self-centring circular coupling bracket is placed in a hole in the CLT panel and attached to the next element with the help of a screw hidden inside the panel. The project started with exploring different geometries as shown in Figure 1.

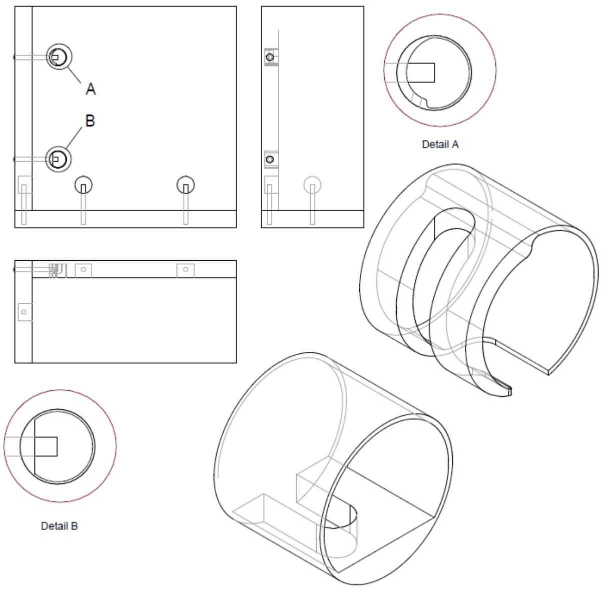

Figure 1: *Corner and connectors*

3.2 FE-ANALYSIS

As a next step, a preliminary finite element (FE) model (Figure 2) has been developed by importing the 3D CAD-models into Ansys [5]. Deformations and stresses both in the wooden and steel element have been calculated for various loading situations (i.e. tension and shear transfer).

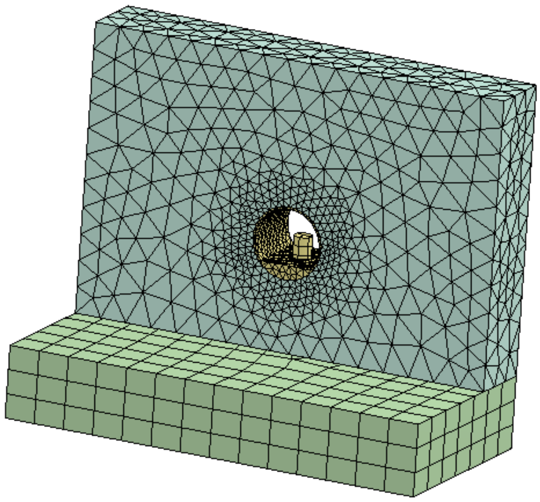

Figure 2: *FE-model model showing the mesh*

The main purpose of the modelling was to prepare and test a digital workflow to be applied in later stages of the project for numerical experiments testing various geometries and dimensions. However, before that, the numerical model needs to be refined and verified based on laboratory tests.

In the first phase the main concern was to study the feasibility of the solution. Therefore, a simplified FE-model was applied with effective properties of the CLT panel as an orthotropic material, see Table 1.

Table 1: *CLT material properties in the preliminary model*

Description	Notation	Value [GPa]
Young's modulus	E_x	11.0
	E_y	5.5
	E_z	0.6
Shear modulus	G_{xy}	0.7
	G_{yz}	0.5
	G_{xz}	0.07
Poisson's ratio	ν_{xy}	0.40
	ν_{yz}	0.40
	ν_{xz}	0.04

For different loading conditions, such as tension and shear in the dowels, the magnitude of stresses and deformations where calculated and subjected to a qualitative assessment. This study gave good insights about how the order of the forces that could be transferred with this type of connection and which parts could be sensitive.

As an example, Figure 3 shows the deformations in the timber part calculated for a 80 kN tensile load applied at the top of CLT element.

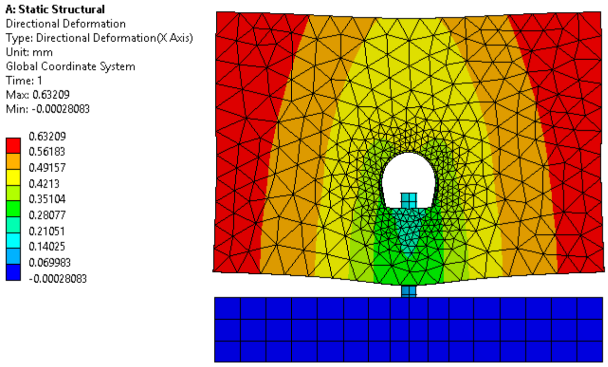

Figure 3: *Example of calculated deformations in the timber*

Besides the stresses and deformations in the timber, the effects of the loads on the steel bracket were assessed as well (see Figure 4), which could be useful to optimize the dimensions of the bracket.

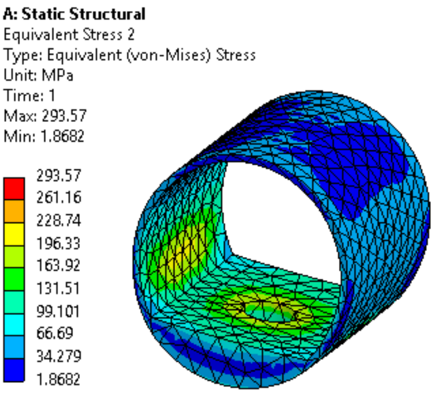

Figure 4: *Example of stresses in the steel bracket*

3.3 PROTOTYPE

The next step in the project was to manufacture and assemble a physical prototype. The CLT panels were machined with high precision in a CNC machine. The round coupling bracket from the early models as seen in Figure 1 was replaced by a washer made of birch plywood with a shape like an extruded segment of a circle with the same diameter as the round bracket.

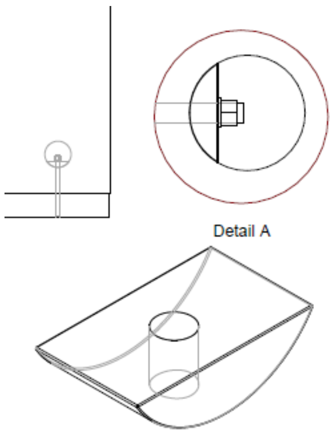

Figure 5: *The modified joint for the prototype*

The assembly was easy as expected and the prototype appeared to be robust (Figure 6). However, in discussions about the test specimen some changes were proposed (see next section). It was concluded that in the further developments the brackets should potentially be combined with dowels to ensure better resistance to shear forces.

Figure 6: *The assembled prototype*

3.4 TESTING

3.4.1 Test setup

The final step in this phase of the project was to carry out laboratory tests in order to characterize the load-carrying behaviour of the connections.

For practical reasons, the design was further simplified and the previous cylindrical holes in the CLT panels were changed to rectangular ones with filleted corners. A rectangular steel washer was then added to ensure a relatively large bearing area as shown in Figure 7.

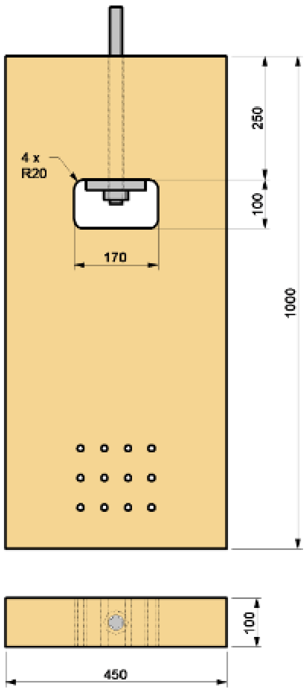

Figure 7: *Dimension of test sample*

The CLT panel consisted of three layers of spruce laminations with a strength class of C24. The thickness of the layers was 30, 40 and 30 mm. The middle layer was oriented perpendicular to the other two layers, the last mentioned being oriented in the direction of the applied load. The size of the rectangular washer was 130 mm (length) × 100 mm (depth) × 22 mm (thickness). Thus, the effective depth of the washer according to the layer orientation was 60 mm when estimating the failure load. The dimensions were chosen so that tensile tests would primarily result in shear failure in samples and damage due to compression under the washer. Three samples were tested in a tensile testing machine. Local displacements were measured with linear variable differential transducers (LVDT) placed adjacent to the openings (Figure 8).

Figure 8: *Test setup*

3.4.2 Results

Figure 9 shows the load-displacement curves for the three tests, concerning both local and global deformations. For Test 2 and 3 the load-displacement relationship was largely linear until failure, whereas for test 1 reduction in the global stiffness of the assembly was observed early in the loading process. This is mainly attributed to a failure in the loading system as one of the metal chain eyelets holding the tensioning rod turned out to be too week and started deforming during testing. Thus, the deformations of the steel are included in the measurement data for the global deformations (green curve in Figure 9). The local deformations (dashed curves in Figure 9) shows that the local behaviour around the connection was similar is all three tests.

For all 3 tests, typically until up to 20 kN the initially low stiffness increased as all load transferring mechanisms became gradually activated (no prestressing was applied). For test 2 and 3 linear behaviour lasted up until approximately 110 kN.

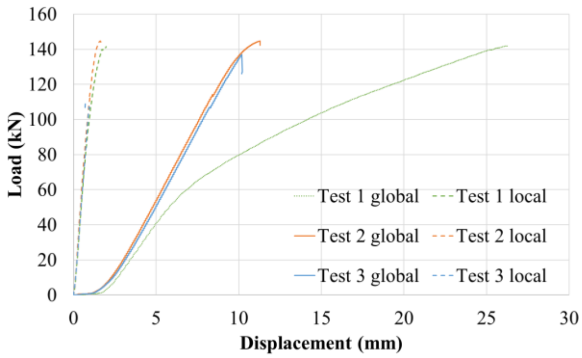

Figure 9: *Load displacement curves from the tests*

All three samples failed as expected. Damage due to shear between the timber laminations as well as due to compression under the steel plate washer was observed, see Figure 11-Figure 17.

Figure 10: *Test 1 shear failure*

Figure 11: *Test 1 local damage under the washer*

Figure 12: *Test 1 rolling shear failure in mid-layer*

Figure 13: *Test 2 shear failure of outer layer*

Figure 14: *Test 2 local failure under the washer*

The outer layers being stronger parallel to the load application (due to their grain direction) were pushed out from the assembly as the wood within the layer and the interface between the adjacent layers failed in shear. The transverse (inner) layer experienced damage due to compression perpendicular to the grain and could accommodate most of the deformations. However, the middle layer could partly fail in tension and rolling shear as well, i.e. in a block shear like failure mode (Figure 12 and Figure 15). In test 3 the failure of the finger joints was also observed, see Figure 16.

Figure 15: *Test 3 failure in middle layer*

Figure 16: *Test 3 shear and finger joint failure*

Figure 17: *Test 3 local damage under the washer*

The average of the maximum load was approximately 141 kN and the local deformation was about 0.7 mm at 80 kN load (see Table 2).

Table 2: *Max load and local deformation at 80 kN*

Test	Max load (kN)	Def. at 80 kN (mm)
1	141.9	0.73
2	144.7	0.66
3	137.0	0.70
Average:	141.2	0.70

The measured deformations are similar to those obtained from the preliminary FE-model, although the geometry was quite different. Updating of the numerical model based on the testing seems to be a straightforward task. It would probably involve a refinement through modelling each layer individually.

4 CONCLUSIONS

The paper provided an overview about the progress in the development of a novel CLT connection system enabling an easy and fast installation of the panels on-site. The preliminary numerical model and the physical prototype indicated a potential to scale up the proposed solution. The prototype was easy to dismantle and rebuild, which is well in line with responsible and circular construction with the environmental aspects in focus.
Empirical tests showed promising results due to the high failure loads obtained with small deformations. The order of the deformations was comparable with the results of the preliminary numerical model (with a different geometry). Further studies regarding the structural performance of the connection, the calculation model needs to be refined and validated by further lab experiments. The verified model will be used to perform parametric studies to investigate the effect of different variants and configurations on the load-carrying capacity.

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