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Lateral Stiffness of Timber frames with CLT Infill panels

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Abstract
In recent years timber infill panels have been proposed for multi-story column-beam frame structures with the aim to substitute the stabilizing function of column-beam moment connections. The preliminary study reported in this paper considers a column-beam timber frame where stability is assured by cross-laminated timber (CLT) infill elements. The performance of the system depends on frame-panel connections as well as the dimensions of the CLT panel. The desk research focused on the behavior of such an assembly using high performance reinforced frame-panel connections comprising steel tube fasteners. The numerical investigation is aimed at optimizing the interaction between frame and infill as a function of CLT panel stiffness in addition to the number and location of the connections. It is shown that the overall lateral stiffness of timber infill frames compares well with concrete infill steel frames.

Keywords
Connection, cross laminated, portal frame, infill, racking, reinforced, tube.

1 Introduction
1.1 Infill elements
Portal frame structures are well known and used in many multi-storey buildings, particularly steel structures. Since timber, as structural material, gains more and more credit being an environmental friendly material with low carbon footprint, feasibility studies are carried out to show what the conditions are for successful application. Although structural timber is well known and mainly used for residential and low rise apartment buildings, new innovative timber products may offer new opportunities. In particular CLT- Cross
Laminated Timber is such a product that becomes increasingly popular in Europe. In particular its structural properties open new horizons in structural design. In this desk study CLT is being proposed as stability element in a timber portal frame. If the stability of portal frames is assured by only column-beam connections, so-called sway structures, the demands on the connections to achieve the required lateral stiffness are high. Alternatively, diagonal bracing can be applied without much effort, resulting in an easier and highly effective way to satisfy the demand, Figure 1. Since partition walls are often located between the beams and columns, the opportunity to let them contribute to the lateral stiffness is evident. These partitions are designed to resist fire and should satisfy sound transmission demands and therefore usually made of masonry or concrete. To speed up the erection of the building, partition walls can be prefabricated; however, the connections are crucial in the structural frame behavior. These prefabricated elements are called infill elements. Apart from the connections, the structural behavior depends on the interaction between the infill element and the portal frame. The interaction is complex and involves many parameters. Over the years research was mainly focused on steel portal frames with masonry infills that were not purposely fixed to the frame [1]. Infill elements of in-situ cast concrete and prefabricated concrete infill elements followed [2]. With respect to the connection between the frame and the partition walls, three types of connections can be distinguished: not connected, fully connected along the wall perimeter and discreetly connected, Figure 2. Assuming the same infill element for these cases, the case where no connections are used leads to the stiffest and strongest portal frame provided no clearance is left between the infill and the frame. However, this option is difficult to achieve from a builders perspective. The discreetly connected infill element takes position between the continuously and non-connected elements. In contrast to masonry and concrete infills no study is known to the authors that investigates timber infill elements. Traditional timber frame elements, studs with top and bottom rail, are not suitable for this application because of the low racking stiffness and strength compared to what the portal frame demands. In this respect the performance of CLT elements is much
better. For this reason it is interesting to investigate the potential for successful application.

2 Cross Laminated Timber

Cross-laminated timber (CLT) is produced from softwood (Spruce) lamellas that are stacked in crosswise layers and glued together, Figure 3.

The crossways arrangement of the longitudinal and crosswise lamellas reduces the swelling and shrinkage in the board plane to a minimum - static strength and shape retention increase considerably compared to conventional timber construction products. Cross-laminated timber offers new possibilities when it comes to load transfer. Not only can loads be transferred in one direction (as is the case, for example, with supports, girders, etc.) but on all sides (referred to as "genuine plate and sheet action").

Figure 3: Cross-Laminated-Timber

The CLT product finds application as wall, ceiling, floor and roof element throughout Europe. The commercially available maximum dimensions are 4.8×20m. The overall thickness depends on the thickness and number of the individual layers. The maximum thickness is 500mm. In the analyses the thickness of the CLT is taken to be 216mm, which means about 5 to 7 layers. As usual in timber, structural connections are essential as they usually are the weakest link. For connections between CLT panels normally long self-tapping screws are used. An example of what can be accomplished with CLT panels is demonstrated by the 8 storey high City Hall, Marray Grove building in London (UK). It took an assembly team of four people to erect this structure in 27 days.

3 Steel-to-timber connections

For the application as infill elements screws and threaded rods are not considered suitable to adequately connect CLT to portal frames. In addition, the requirements for stiffness and strength are high and no clearance is allowed to limit storey drift. Especially, the latter requirement disqualifies traditional fasteners such as bolts or dowels (drift pins) that require hole clearance for easy assembly. For this reason the high capacity DVW reinforced connections with hollow steel tubes as fasteners have more potential and therefore have been selected for this study [3]. The DVW stands for densified veneer wood, which is commercially available high density beech plywood with strength properties between tropical hardwoods and mild steel. This commercial plywood product has a thickness ranging from 6 to 80 mm thickness. However, for this investigation 18mm thick sheets suffice. The bearing or embedment strength (120 N/mm²) is approximately six times as large as the embedment strength of timber. It is applied by gluing it to the timber surface where high bearing stresses are expected. The DVW material not only enhances the bearing capacity, it also prevents premature splitting of
the timber. Instead of bolts, hollow mild steel tubes are inserted in over-sized holes. The tubes are loaded in lateral direction like bolts. The tubes are expanded in diameter after assembly to remove any hole clearance. The maximum tube diameter ever tested is 38mm. This connection has been successfully applied in many heavy timber structures, especially in statically indeterminate portal frames as column-beam connection, [4]. Although originally designed as timber-to-timber connection, later studies have shown that steel-to-timber connections are also possible [5]. Figure 4 shows a built-up connection with two side members and one middle member. The middle member in Figure 4, between the DVW plywood reinforced sheets can be exchanged for a steel plate, resulting in a timber-to-steel connection. The minimum end and edge distances are 3.5 times the fastener dimension.

**Figure 4:** DVW reinforced timber-to-timber connection with expanded tubes.

### 4 Starting points of the FEM study.

The storey height and the distance between the beams of the frame is 3.4m. This allows a free space between ceiling and structural floor for sound isolation purposes and other facilities. The distance between the columns is the same as for the beams, so a square infill element is foreseen. The beam-column connection of the frame is assumed to be pinned, which is a safe approximation.

#### 4.1 Connection strength and stiffness

In order to evaluate the performance of the frame with CLT infill elements the strength and stiffness properties for the connection are required. Compared to a bolted connection the strength and stiffness capacity of the DVW reinforced expanded tube fastener is four and eight time larger, respectively [3]. The tube diameter chosen for the analyses was 21.3mm. This choice is based on the requirements regarding the minimum edge spacing and the available space to accommodate the connection. The characteristic strength per shear plane per tube is 55 kN and a stiffness of 53 kN/mm/shear plane per tube [1]. However, these values are reached after considerable plastic deformation. For the purpose of this analysis only the linear part of the load-slip curve is considered, and therefore the strength and stiffness are set to 29kN and 48 kN/mm per shear plane per tube, respectively.

Summary of the properties used in the numerical simulation:

Calculation method: 2D - 1e order linear elastic, infill element: 3.4×3.4m, portal frame beam and columns, hinged, dimensions beams and columns 400×400mm, strength class GL28, MOE parallel= 12600N/mm², MOEperp = 420N/mm², infill panel CLT 216mm thick, MOE parallel = 8250 N/mm², MOE perp = 2750 N/mm², G parallel = 518 N/mm², G perp = 173 N/mm². The CLT structural properties...
are taken from the technical data sheet of Finnforest.

4.1 The Numerical Model

The aim of the FEM is to assess the strength and stiffness of the frame with CLT infill elements, and to gain insight into the parameters that affect this behaviour. The frame is build up with beam elements, B23 and B22 beam elements of Abaqus. This element allows significant shear deformation to be taken into account, which for timber is high and influences the total deformation of the frame. Based on sensitivity analyses regarding the dimensions of the four node plane stress element (CPS4R), used to simulate the CLT infill, a mess of 80×80mm is chosen. The connection between the infill and the frame is represented by linearly elastic translation springs. Figure 5 shows three load transfer Types. Type A represents shear load transfer in every in-plane direction. In the other two cases, Types B and C, a slotted steel plate with elongated holes prevents shear load transfer to the frame in perpendicular and parallel direction, respectively.

4.2 Interaction of frame and infill

The most advantages location for the connections is investigated by comparison of four alternatives, Figure 6 and 7.

Figure 6: Option A

The only difference between the alternatives is the number of, and the load transfer direction in the connections. In the application of
connection Type A, B and C in Options A, B, and C, respectively, 2×2 connections are situated at every corner. The last alternative applies a total of 64 connections of Type B to Option D, Figure 7. The comparison focussed on differences in stiffness and load transfer by the infill element to beam and column. For a given racking load of 250 kN the horizontal deformation is given Table 1.

<table>
<thead>
<tr>
<th>Option</th>
<th>Horiz. Def. [mm]</th>
<th>Number connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6.0</td>
<td>16</td>
</tr>
<tr>
<td>B</td>
<td>6.6</td>
<td>16</td>
</tr>
<tr>
<td>C</td>
<td>16.6</td>
<td>16</td>
</tr>
<tr>
<td>D</td>
<td>3.8</td>
<td>68</td>
</tr>
</tbody>
</table>

Having noticed the number of connections and differences in horizontal deformation Option B was considered the best for a number of reasons. This option is most effective in that the shear forces at the column beam connection are much less than in the other alternatives. Because of the vertical elongated holes in the connection of Option B the storey floor load that rests on the beam will not be transferred to the infill element. A high normal force in the beam is not considered as a problem.

5. The parameters that affect the stiffness

To optimize the stiffness of the assembly, the contribution of each element in Option B is evaluated. For this reason the influence of the thickness of the CLT panel, the dimensions of the beam and columns of the frame, the location and number of connections are assessed in more detail. To combine all results of the parameter study into Figure 8 the horizontal axes contains normalized values,
while the vertical axis represents the horizontal deformation. The horizontal racking load is set at 250 kN. The steepest curve represents the CLT thickness. This indicates that the stiffness of the infilled structure is mainly governed by the CLT thickness. The steepest but one represents the stiffness of the connections. As expected the two almost horizontal curves, representing the beams and column dimensions of the frame, hardly show any influence. To optimize the structural behavior clearly the attention should focus on the stiffness of the CLT infill element and the connection. In addition, the numerical model was also applied to determine the properties of a 3×7.2m CLT infill, which makes comparison with experimental results from previous studies possible, Figure 9. These studies comprise steel frames with infill elements, varying in dimensions, of brickwork and concrete.

*Figure 8*: Summary of the parameter study results.
Figure 9: Comparison of performance

6 Conclusions
The application of connection Type B in assembly Option B is preferred. It allows only load transfer parallel to the infill edges, while the horizontal stiffness is close to the stiffest of Options A, B and C. In comparison with other type of infill panels the performance of CLT compares well to other tested options with steel and concrete infill elements. However, confirmation by experiments is required before any definite conclusions can be drawn.

7 Acknowledgement
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References