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Review article

# Cross laminated timber (CLT): Design approaches for dowel-type fasteners and connections

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ABSTRACT

Within the last 20 years, cross laminated timber (CLT) has become one of the most important building products in contemporary timber engineering. By the end of this decade, its annual worldwide production volume is expected to exceed 1,000,000 $m^3$. The industry, engineers, architects and constructors have a strong interest in implementing CLT in European product, design and execution standards. The design of CLT is part of the currently ongoing revision of Eurocode 5. In this context and in addition to the verification of CLT panels in respect of ultimate and serviceability limit states, guidelines on the design of connections in CLT with dowel-type fasteners are of the utmost importance.

In this article, we review approaches for calculating characteristic values as provided in literature for single dowel-type fasteners and connections in CLT. We also compare these approaches, with focus on withdrawal and embedment strength of dowels, nails and self-tapping screws, with the current regulations on dowel-type fasteners for solid timber and glulam as formulated in Eurocode 5. These comparisons are made in order to identify the need and potential for revision of current EC 5 equations and state-of-the-art regulations. We summarise regulations on connection design, i.e. minimum spacing, edge and end distances, other additional geometrical conditions, regulations on the effective number of fasteners in a group and minimum penetration depths. Finally, we draw conclusions in respect of the single fastener properties withdrawal and embedment strength and suggest some execution guidelines, which ensure the integrity of CLT structures. Overall, we aim to present a compilation of the current state-of-the-art knowledge on dowel-type fasteners in CLT as a basis for implementing design guidelines for CLT in the new connection chapter of Eurocode 5.

## 1. Introduction

Cross laminated timber (CLT) is a planar, large-dimensioned engineered timber product, designed for structural purposes and capable of bearing loads in-plane and out-of-plane. CLT, with dimensions $t_{CLT} \times w_{CLT} \times \ell_{CLT}$, is usually composed of an uneven number of $N$ layers, laid orthogonally to each other ($t_\ell \times w_\ell$), of finger-jointed laminations or wood-based panels. Adjacent laminations within the same layer may also feature narrow face bonding; without narrow face bonding, gaps between the laminations may occur. The orthogonal layers are typically bonded at their side face forming rigid composite elements. Flexible composites with layers connected by nails, staples or other fasteners are also on the market but are beyond the scope of this article. Current approvals and assessment documents of European CLT products allow gaps in width ($w_{gap}$) up to 6 mm. Some CLT products feature also laminations with one or more stress reliefs, usually 2.5 mm wide; see Fig. 1 and EN 16351 [1].

CLT has been used in many different applications but mainly as large dimension wall, floor and roof elements in single and multi-storey buildings, halls and bridges. Although this type of product has only been on the market for 20 years, it has been changing the timber engineering sector in many ways, e.g.:

- by allowing architects to think in planes and volumes rather than in lines;
- by supporting the timber engineering sector with a stand-alone structural element enabling extremely rapid, dry, clean and high-precision construction;

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- by providing all subsequent crafts conditions for easy and fast assembly and installation, e.g. of additional layers (e.g. insulation as well as service layer and facade) and building services in general; and
- by offering end-users and investors the highest building quality and a sustainable, natural living and working environment.

CLT is in the process of catching up two very important steps: standardization (e.g. of layer thicknesses ($t_\ell = 20, 30, 40$ mm), layups, base material quality and design approaches) and development of optimized connection techniques; the latter area still offers a lot of room for further developments and improvements.

When considering how to create versatile and practicable connection solutions for CLT structures, a first step is to differentiate between the basic types of connection lines; see Fig. 2.

With this in mind and looking at structures as a whole, the possibilities for realizing integer, i.e. box-like, CLT structures also depend on the overall construction system being used. Detached houses, residential, office and school buildings of up to three to five storeys are commonly built as platform-frame structures (indirect vertical load transfer between wall elements of vertically adjacent storeys via soft floor elements). Higher or heavily-loaded buildings are commonly designed as balloon-frame systems (direct vertical load transfer between wall elements of vertically adjacent storeys).

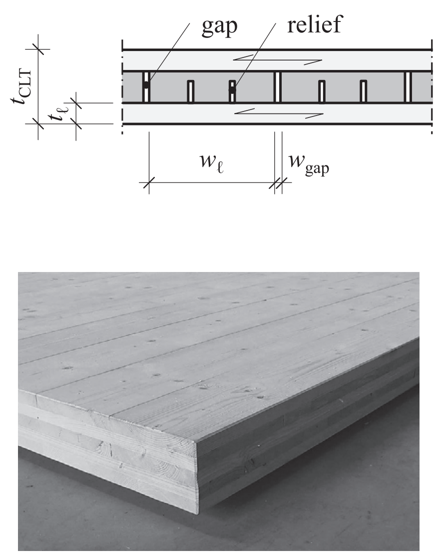


**Fig. 1.** (above) Principal CLT layup and some definitions of geometry and execution; (below) typical five-layer CLT element.

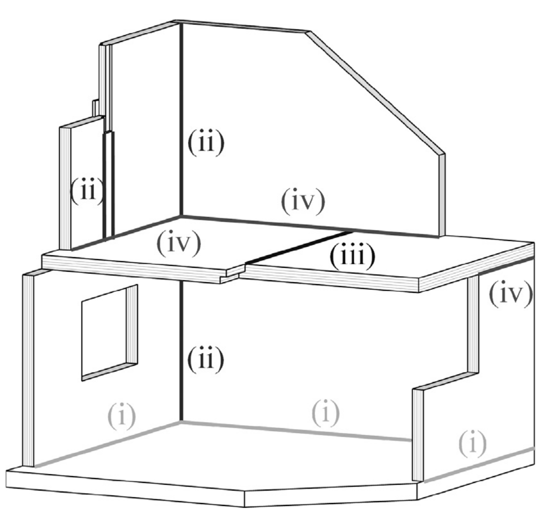


**Fig. 2.** Definition of connection lines exemplarily for a CLT platform-frame structure (Brandner et al. [2]; adapted): (i) wall-to-foundation, (ii) wall-to-wall, (iii) floor-to-floor, (iv) wall-to-floor.

Although CLT is currently used for structures that were hardly feasible in timber one decade ago, a connection technique that underpins the possibilities of building with CLT is still largely missing. Some current commonly applied fastener and connection solutions, like angle brackets and hold-downs, have been adopted from light-weight timber constructions (illustrated for a wall-floor-wall connection line in a typical platform-frame CLT structure in Fig. 3). To optimize angle brackets for CLT structures, a first step would be to adapt the geometry to resist both shear and uplift forces, combining the functions of current angle brackets (shear load transmission) and hold-downs (transmission of uplift forces) in one connector [3].

Apart from angle brackets, hold-downs and connection lines realized using self-tapping screws (partially-, fully- or double-threaded, see Fig. 3), there are some more specialized connection solutions and systems: e.g. solutions with (self-drilling) smooth dowels/tight-fitting bolts and inner metal plates (e.g. Bernasconi [5]), the X-RAD connector system [6,7,9] or the SHERPA CLT Connector [8,10] and others, such as embedded steel tubes in combination with glued- or screwed-in steel rods [4].

What all these solutions have in common is a connection between metal elements and CLT based on single dowel-type fasteners, e.g. profiled nails (annular ringed shank nails or helically threaded nails), fully-, partially- or double-threaded self-tapping screws, smooth dowels or tight-fitting bolts as well as screwed- or glued-in steel rods, which are loaded either axially, laterally or combined. Suppliers such as Rothoblaas, Simpson Strong Tie, etc. support engineers with comprehensive (software) design tools and tables of characteristic connection performance values; a detailed verification of the single dowel-type fasteners, for fixing angle brackets, hold-downs or system connectors to CLT, is thus not required. However, the anchorage potential of single fasteners in CLT, as described e.g. by the embedment strength and the withdrawal strength, are essential parameters for the development of CLT connectors and for verification of connection lines made with self-tapping screws or (self-drilling) dowels as well as individual connection solutions.

Connections decisively affect the behaviour of CLT structures. In light-weight timber structures wall and floor diaphragms are relatively flexible, but CLT diaphragms (walls and floors) are characterized by high stiffness and high resistance to shear, tension and compression in-plane. Therefore, in CLT structures, the CLT itself does not contribute significantly to ductility and energy dissipation, so that these characteristics have to be provided by the connections. This means that CLT needs a different conceptual approach to develop adequate connections and arrive at suitable combinations of resistance, stiffness and ductility.

In view of ongoing harmonization and standardization processes and the upcoming new version of the European Timber Design Code, Eurocode 5 (series of standards EN 1995-x-x), it is intended to reorganize the chapter on connections by providing a toolbox, supporting the engineer step-by-step with required basic characteristic values for different anchoring materials. To do this, we need to move from models limited to specific timber products towards generic approaches. We will consider how to achieve this in the following sections.

In the rest of this article, we will begin by providing some general notes on dowel-type fastener behaviour in CLT; noting similarities and differences to solid timber and glulam and reviewing potential failure modes. Then we will summarize and discuss the state-of-the-art of axially and laterally loaded dowel type fasteners anchored in CLT, focussing especially on withdrawal and embedment behaviour. We make some proposals for harmonization of current regulations on solid timber and glulam with CLT. And finally, we review current proposals and regulations on connection design and requirements for ensuring structural integrity.

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