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Review article

Seismic behaviour of Cross-Laminated Timber structures: A state-of-the-art review

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ABSTRACT

Cross-Laminated Timber (CLT) structures exhibit satisfactory performance under seismic conditions. This is possible because of the high strength-to-weight ratio and in-plane stiffness of the CLT panels, and the capacity of connections to resist the loads with ductile deformations and limited impairment of strength. This study summarises a part of the activities conducted by the Working Group 2 of COST Action FP1402, by presenting an in-depth review of the research works that have analysed the seismic behaviour of CLT structural systems. The first part of the paper discusses the outcomes of the testing programmes carried out in the last fifteen years and describes the modelling strategies recommended in the literature. The second part of the paper introduces the *q*-behaviour factor of CLT structures and provides capacity-based principles for their seismic design.

1. Introduction

Timber constructions have undergone a revival of popularity over the last years; this positive trend is associated to a combination of several factors. Firstly, wood-based structural products generate fewer pollutants compared to the mineral-based building materials (e.g. steel and concrete) because are obtained from sustainable and renewable resources. Secondly, timber structural elements are prefabricated off-site and transported to the building location, where they are quickly assembled. Finally, the high strength-to-weight ratio of wood is a great advantage for structures erected in seismic-prone areas, because it limits the total mass of the buildings.

The seismic performance of multi-storey timber structures has been the focus of several research projects. Tests firstly examined the behaviour of light-frame buildings, which were the most common timber structural systems all over the world. Results of full-scale shaking table tests showed a highly dissipative behaviour, with most of the plastic deformations concentrated in the sheathing-to-framing joints and the anchoring devices (hold-downs and angle brackets) still in the elastic phase [1–5]. More recently, the increasing interest in high-rise structures (the so-called 'tall buildings') required a higher level of seismic performance. Therefore, the focus has shifted to massive and more effective systems, such as Cross-Laminated Timber (CLT) [6]. Compared to light-frame buildings, CLT structures have a higher in-plane stiffness and a greater load-carrying capacity; differences are attributed to both the physical parameters of the timber panels and the mechanical properties of the connections used (hold-downs and angle brackets, stronger and stiffer than the connectors used in lightweight structures). In particular, full-scale tests of CLT structures highlighted that the CLT panels act almost as rigid bodies, while the connections provide all the ductility and the energy dissipation [7,8].

CLT structures are generally divided into two groups, depending on their dissipative capacity. The first group refers to buildings assembled using large monolithic walls, i.e. panels with high length-to-height ratios. The second group refers to buildings assembled using segmented walls, i.e. systems of narrow panels fastened together with vertical step joints. In the first case, the energy dissipation takes place only into the anchoring connections used to prevent the rocking (hold-downs) and sliding (angle brackets) of the CLT walls. Therefore, such structures have a low to medium capacity to dissipate the seismic energy. In the second case, if properly designed, the vertical step joints enhance the ductility of the buildings, thus resulting in a high capacity to dissipate the seismic energy.

Nowadays, the use of CLT structural systems in Europe is codified only into the European Technical Assessments (ETAs) issued for the specific building products, while design principles have not yet been

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included either in Eurocode 5 [9] or in Eurocode 8 [10]. General design principles for CLT structures have been included in the Austrian National Annex to Eurocode 5 [11], while similar pieces of information are not yet available for any other European country. Based on the current situation in Europe, the COST Action FP1402 'Basis of Structural Timber Design - from research to standards' was established in 2014, as part of the initiatives dedicated to the development of the new Eurocodes.

This paper summarises a part of the activities conducted by the Working Group 2 of COST Action FP1402; it presents a state-of-the-art review of the studies that focused on the seismic performance of CLT structures and recommends principles for the design practice. The first section discusses the outcomes of the testing programmes that have examined the seismic behaviour of CLT structural systems. The second section shifts the focus to the modelling approaches recommended in the literature to predict the seismic performance of CLT structures. The third section introduces the *q*-behaviour factor (denoted as the 'seismic reduction factor' in some structural design codes) of CLT buildings, necessary in the seismic design to scale down the elastic response spectrum to the design spectrum. Finally, the fourth section proposes capacity-based design principles for CLT structures. Results of past testing programmes are used as a basis to develop provisions capable of ensuring that all plastic deformations occur in selected ductile components and no other part (less ductile or brittle) exhibits any anticipated failure.

2. Testing of CLT structures

The seismic performance of CLT buildings has been the central topic of several testing programmes. The experiments have been carried out on single connections, monolithic and segmented wall systems (i.e. CLT walls and connections), and full-scale buildings featuring different numbers of storeys and layups. In this section, the outcomes of the testing programmes are discussed; further information is also available in Pei et al. [12].

2.1. Testing of connections

Mechanical connections used in CLT buildings are typically divided into two groups. The first group refers to the connections used to prevent the rocking and sliding of the walls, i.e. the hold-downs and the angle brackets. Such metal connectors are fastened to the CLT walls using threaded nails or screws with a small diameter, and have been developed based on the connection systems used in light-frame structures [13]. The second group refers to the step joints used to prevent the relative sliding between contiguous walls or between a floor panel and the underlying wall. Those joints are usually assembled using self-tapping screws made of carbon steel, with partially or fully threaded shank [14].

The hysteretic behaviour of the connections with hold-downs and angle brackets has been the focus of several research projects. Gavric et al. [15] and Flatscher et al. [16] carried out the most complete testing programmes as part of the SOFIE and SERIES Projects, respectively. Results highlighted a dissipative behaviour and ductile failure mechanisms, with the only exception of the situations where the angle brackets, designed to resist primarily in shear, were loaded in tension. In such situations, they exhibited some inappropriate failures caused by either withdrawal of the nails from the floor panels or pull-through of the anchoring bolts (Fig. 1a–b). However, those connectors proved to have good mechanical properties under lateral and axial loads. Conversely, the hold-downs showed high strength capacities when loaded in tension and a weak mechanical behaviour if subjected to lateral loads, due to the buckling of the metal flanges. Furthermore, tests of connections with hold-downs conducted by Tomasi and Sartori [17] pointed out two additional failure mechanisms that may occur if high tension loads are transferred along the connections, i.e. tensile failure in the net cross-section of the metal flange and buckling of the anchoring to the foundations (Fig. 1c–d).

Shear tests of panel-to-panel joints, performed by Gavric et al. [18] on half-lapped and spline joints with partially threaded screws, led to a good hysteretic behaviour. However, some brittle mechanisms occurred in cases where the requirements for end and edge distances were not satisfied. More recently, Hossain et al. [19] conducted similar tests on panel-to-panel joints with double-angled fully threaded screws. Results showed significantly higher strength and stiffness capacities than those obtained with partially threaded screws, although the loads transferred along the joints caused some brittle failures with splitting of the timber members.

The experimental activities finalised at the cyclic characterisation of the connections used in CLT structures are still ongoing, with special attention to the applications in mid- and high-rise buildings. Tests have been carried out on a large number of connections, by varying the thickness and geometry of the connectors [20–23]. Furthermore, several hold-downs [24], angle brackets [25] and screws [26] have been examined by considering the simultaneous presence of lateral and axial loads. This proved that the coupled shear-tension action influences their mechanical properties and dissipative capacity. In addition, great effort has been devoted to investigating the performance of some innovative connection systems. Polastri et al. [27] analysed the hysteretic behaviour of X-RAD connectors, which showed great potentials to resist the coupled effect of shear and tension loads with a good level of ductility and high dissipative capacity. Loo et al. [28] developed a slip-friction connector, composed of a central plate of abrasion resistant steel and two lateral plates of mild steel between which it slides. Kramer et al. [29] proposed an energy dissipation system for self-centring wall systems, based on the concept of the steel buckling-restrained braces, composed of a milled element designed to yield and a steel pipe in which it is enclosed. Similarly, Sarti et al. [30] investigated the performance of a replaceable dissipater, composed of a mild steel bar confined by a steel tube filled with grout or epoxy. Finally, Hashemi et al. [31] introduced a slip-friction connector that allows for the self-centring of the wall without requiring the adoption of post-tensioned tendons. Compared to traditional connections with hold-downs and angle brackets, these systems attain large ductility ratios while limiting the residual drift and peak accelerations.

2.2. Testing of wall systems

Racking tests of monolithic and segmented wall systems (i.e. CLT walls composed of narrow panels, fastened together with vertical step joints) further explored the hysteretic behaviour of CLT structural systems. For this purpose, several testing programmes have been conducted in Europe [7,8,32–34], Canada [20] and Japan [35,36].

In Europe, Gavric et al. [32] carried out cyclic racking tests using monolithic and segmented walls. In the first case, tests considered a square wall and the layout of the anchoring connections was varied; in the second case, the wall was composed of two narrow CLT panels and tests investigated the influence of the screws in the vertical joint. Hummel et al. [33] conducted similar racking tests to those reported above and extended the investigations to walls with an opening. Dujic et al. [34] examined the racking behaviour paying particular attention to the effects of the boundary conditions; three situations were investigated: shear cantilever mechanism (rocking response), restricted rocking mechanism (coupled shear-rocking response) and pure shear mechanism. Finally, Hristovski et al. [7,8] performed shaking table tests on monolithic and segmented wall systems; compared to the investigations reported above, which were carried out under quasi-static loading conditions, the shaking table tests were performed under dynamic conditions and provided a detailed insight into the seismic performance of the systems.

In Canada, Popovski et al. [20] investigated the racking behaviour of monolithic walls with three aspect ratios, segmented walls with