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The lateral load resistance of unclassified cross-laminated timber walls: Experimental tests and theoretical approach

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ABSTRACT

This paper focuses mainly on the mechanical behaviour of unclassified cross-laminated timber walls under lateral loading (seismic and wind loads). Unclassified wooden planks were used to construct the wall unit with an odd number of layers (three) for each wall, with the planks in each layer in a perpendicular relative orientation. In this research, an experimental study of large-scale timber walls was carried out with a view to determining the lateral load resistance. Diagonal struts, under tension and compression were employed on the cross-laminated walls to investigate the effects of these elements on the lateral resistance of the wall. A theoretical approach has been developed to describe the overall behaviour of the cross-laminated wall and to investigate the internal forces on the fasteners. The present work is then compared to Oriented Strand Board (OSB) panel designs. Based on the data and results obtained from the experimental tests, this study confirms, firstly, that cross-laminated walls without a diagonal strut have approximately double the horizontal strength of (OSB) panels, secondly, that diagonal strut significantly increases the lateral load resistance of cross-laminated walls, particularly under compression conditions, and thirdly, the proposed theoretical approach shows similar performance to the average experimental test up to 100 mm of overall lateral displacement of cross-laminated timber wall.

1. Introduction

Wood is commonly associated with lightweight structures, it has ubiquitous uses as a building material in many around the world. The pros of wood lie mainly its abilities in ductile joints, its physical properties and being environmentally friendly [1]. Timber walls are the frequently used structural system in the buildings designed to withstand lateral loads and transfer these forces to the foundations with ductile behaviour [2]. According to the European Norm EN 594, [3] a timber shear wall consists of a timber frame and sheathing board, connected by fasteners. The sheathing board may be made of a variety of materials, such as Gypsum, Plywood, Fibre board or OSB [4]. Two different methods for calculating the lateral resistance of timber walls are presented in Eurocode 5. The first is a very simple analytical approach, based on the assumption that the fasteners transmit the same ultimate force along the perimeter of the panel, and the second is an experimental approach based on the test procedures set out in EN 594. The two methods in Eurocode 5 are not clearly expressed, leading to unsafe and imprecise structural design [3–7]. Some of the obvious limitations of Eurocode 5 are that it does not consider the horizontal displacement of the wall, and assumes that fasteners under shear stresses are entirely within lower bound of the plastic state, which may lead to unlimited displacement and an overestimation of the wall's racking strength. Furthermore, the underlying assumption of Eurocode 5 is that the wall is blocked, the role of the layout of the fastenings is not taken into account. Clearly, Eurocode 5 has many design conflicts, and it is not advisable to consider its guidance absolute in terms of design.

A number of studies have been conducted by various authors, to investigate the load-carrying capacity of a timber frame wall, based on modelling and experimental tests. Most of these studies have been carried out on OSB walls, as these walls are very widely used. However OSB walls have lower in-plane stiffness than fibre-plaster boards (FPB) [8]. An elastic analysis model is presented by Girhammar and Kallsner [9] to investigate the lateral load resistance and determine the horizontal displacement at the top of the timber wall against static forces, this model pertains to fully anchored sheathed timber frame. Vogrinec et al. [10] proposed another model based on static and dynamic analysis to investigate horizontal loads on timber walls and study the effect of openings and the diameter of the diagonal strut on the load-carrying capacity. Gattesco et al. [11] examined the effect of different base

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Nomenclature

$F_{l,Rd}$	design racking load-carrying capacity
α	rotation angle of the board in OSB
γ	rotation angle of vertical studs in OSB
h	height of timber wall
K_{ser}	slip modulus of the fastener
n	total number of fasteners in the wall of OSB
x_i	x-coordinate of fastener number i
y_i	y-coordinate of fastener number i
F_d	design capacity of the fastener.
Δ	horizontal displacement of a timber unit
OSB	oriented strand board
CLT	cross-laminated timber
F	external horizontal force applied on the top of cross-laminated wall
$M_{y,Rk}$	characteristic value of the yield moment for the fasteners
$F_{ax,Rk}$	characteristic axial withdrawal capacity of the fastener
t_1	headside thickness in a single shear connection for nails
t_2	pointside penetration in a single shear connection for nails
H	external horizontal force applied on the top of oriented strand board
N	total number of layers in cross-laminated wall
N_v	number of layers with vertical planks
N_H	number of layers with horizontal planks
N_{px}	number of vertical planks
N_{py}	number of horizontal planks
e	width of plank
y	thickness of plank
a	width of timber wall
b	thickness of timber wall
d	diameter of fastener
N_{m1}	number of meshes in two layers of the wall
S_h	distance between fasteners in OSB
N_m	total number of meshes in the whole cross-laminated wall
$F_{v,Rk}$	characteristic load-carrying capacity per shear plane per fastener
β	ratio between the characteristic embedment strengths
$f_{h,1,k}$	characteristic embedment strength in plywood elements
$f_{h,2,k}$	characteristic embedment strength in timber elements
r	distance from the fastener to the centre of the intersection plane

connections of timber walls on the stress distribution of the fasteners in sheathing board, their model and experimental study confirm that different types of base arrangement influence the shear distribution on sheathing nails. Another analytical model was devised by Casagrande [12] to study the elasto-plastic behaviour of shear walls, on the one hand, and to find a genuine relation between the properties of the structural elements of the wall, such as fasteners, and the structural properties of the whole wall, on the other hand.

Many parameters have been investigated experimentally in timber shear walls which play a crucial role in the overall behaviour of the wall, such as the connections between the wall and foundation [13], the type of fasteners used and the effect of openings. The aforecited studies confirm that increasing the opening size in OSB timber shear walls will create concentrated stresses at the corners points of the opening, with resultant shear cracks which decrease the strength and stiffness of walls [14,15]. Also, the strength of ring shank nails connections is 1.75 greater than that of smooth nails in timber shear walls, also staples exhibited brittle behaviour in Italian OSB panels [16,17].

Other approaches are used by authors to improve the lateral resistance of timber frame walls, such as using stones and earth infill [18], or the addition of diagonal steel strips fixed to the timber frame, which increase the lateral resistance by 77% [19] or adding concrete core with cross laminated timber for skyscraper applications [20].

Cross-laminated timber (CLT) is a prefabricated solid timber wall made of at least three orthogonal layers and bonded using adhesive material or fasteners such as nails. These walls were introduced in the early 1990s in Germany and Austria, and have been recently been gaining increased popularity for multi-story timber construction in North America and Europe in form of roof, floor, or wall applications. CLT has many benefits as a structural element. The first benefit is that it provides excellent in-plane strength. The second benefit is that it decreases the time of construction [21]. Some studies have been carried out recently by various authors to study the structural behaviour of cross-laminated timber (CLT) and these studies have focused mainly on the mechanical properties of CLT and also fire resistance [22].

Wiesner et al. [23] examined the structural response of cross-laminated timber compression elements exposed to fire. Wiesner tested eight walls of two different configurations and exposed them to thermal radiation sufficient to cause sustained flaming combustion. The lateral and axial deformation of the wall was investigated and compared with predictions calculated using a finite Bernoulli beam element analysis. Wang et al. [21] investigated the mechanical properties of laminated stand lumber and hybrid cross-laminated timber (HCLT), this study confirms that HCLT has better bending and shear properties compared to generic CLT. Shen et al. [24] studied the hysteresis behaviour of brackets connection in cross-laminated timber walls, with three kinds of connection for CLT shear wall subjected to cyclic and monotonic loading protocol used in this study to investigate its structural performance. The test results have been compared to two hysteretic models (saws model and Pinching4 model). The study confirms that the Pinching4 model has a better performance than the saws model, while using Simpson bracket as a connection shows the best connector with excellent seismic behaviour and ductility. Tomasi proposed a new connection system between wood frame shear wall and foundation under cyclic loads with high values of strength and stiffness and also confirmed that using a hold down connector does not induce differences in terms of stiffness. By contrast, angle brackets have some differences in performance depending on the type of fasteners used [25]. Vaivade et al. [26] verified experimentally the design procedures for elements subjected to flexural forces in cross-laminated timber under static load, using K-method, gamma method, shear analogy method and transformed section method all compared analytically. The deflection was calculated using the transformed section method and compared with the experimental results, the differences did not exceed 7%.

It is obvious from literature review that the design procedures of Oriented Strand Board have been covered in detail in Eurocode 5 and also a number of models have been proposed by many authors. The main aspects of previous studies focused on the modelling and experimental tests of Oriented Strand Board walls [27,28]. The modelling studies concentrated on the theoretical approaches related to the lateral displacement and the total horizontal force applied on the wall. The experimental studies focused on the effect of many parameters such as base connections and opening on the lateral resistance of the wall.

By contrast, there is a gap of knowledge in Eurocode 5 and state of the art for the design procedures related to cross-laminated timber walls especially subjected to lateral loads. For this purpose, an analytical prediction has been proposed in this present study to describe the performance of CLT walls subjected to lateral loads, which also could be used in the design recommendations. This present paper also examines the feasibility of using unclassified timber for constructing timber frame-walls in cross-plank form, and the lateral resistance of these walls to horizontal loads without the addition of extra, expensive, materials.