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Structural response of cross-laminated timber compression elements exposed to fire

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ABSTRACT

A set of novel structural fire tests on axially loaded cross-laminated timber (CLT) compression elements (walls), locally exposed to thermal radiation sufficient to cause sustained flaming combustion, are presented and discussed. Test specimens were subjected to a sustained compressive load, equivalent to 10% or 20% of their nominal ambient axial compressive capacity. The walls were then locally exposed to a nominal constant incident heat flux of 50 kW/m^2 over their mid height area until failure occurred. The axial and lateral deformations of the walls were measured and compared against predictions calculated using a finite Bernoulli beam element analysis, to shed light on the fundamental mechanics and needs for rational structural design of CLT compression elements in fire. For the walls tested herein, failure at both ambient and elevated temperature was due to global buckling. At high temperature failure results from excessive lateral deflections and second order flexural effects due to reductions the walls' effective cross-section and flexural rigidity, as well as a shift of the effective neutral axis in bending during fire. Measured average one-dimensional charring rates ranged between 0.82 and 1.0 mm/min in these tests. As expected, the lamellae configuration greatly influenced the walls' deformation responses and times to failure; with 3-ply walls failing earlier than those with 5-plies. The walls' deformation response during heating suggests that, if a conventional reduced cross section method (RCSM), zero strength layer analysis were undertaken, the required zero strength layer depths would range between 15.2 mm and 21.8 mm. Deflection paths further suggest that the concept of a zero strength layer is inadequate for properly capturing the mechanical response of fire-exposed CLT compression elements.

1. Introduction

Engineered mass timber products are experiencing a rapid increase in popularity and utilisation, as structural elements for both residential and commercial developments globally. Cross-laminated timber (CLT), in which timber layers (lamellae) are built up in alternating orientations and bonded using polymer adhesives, offers multidirectional mechanical properties and is increasingly being used in load bearing floor and wall applications in multi-storey buildings. The use of engineered timber such as CLT offers many benefits in construction. Prefabricated off-site manufacturing enables rapid, accurate assembly on site, and timber's high strength-to-weight ratio enables lighter structures to be built, thus saving on site preparation and foundation costs [1] and permitting construction above pre-existing buildings or buried infrastructure. However, timber is combustible and its application for structural frames in tall buildings is heavily constrained by strict fire safety regulations and the approvals process in many jurisdictions. Building a knowledge-based, rational structural fire engineering approach for CLT is therefore a key hurdle for advancing the engineered timber construction sector, particularly for multi-storey buildings in which there is an architectural aspiration for some of the CLT to be expressed within the finished building.

Fire compartment boundaries in buildings are typically required to fulfil three criteria to meet conventional 'fire resistance' design requirements. These are maintenance of: (1) sufficient insulation from the fire for the neighbouring spaces, (2) integrity to prevent the passage of hot gases or flames, and (3) load bearing capacity to prevent local or global collapse or the spread of fire. Each of these requirements must be maintained during exposure to a standard fire, the duration of which is based on local building code requirements. Required standard fire resistance times were originally derived based on an equivalency argument related to the equivalent duration of a real building fire that continued until burnout of the combustible contents within a fire compartment without intervention [2]. For a load-bearing CLT wall under sustained compression, structural failure during fire could

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Nomenclature

d_0	zero strength layer
e	eccentricity due to deflection
h	residual cross-section
K	stiffness matrix
M	bending moment
P	applied load
subscripts	
c	charring
s	deflections

compromise all three of the above criteria, with adverse consequences for both life safety *and* property protection. Thus, a proper physical understanding of CLT's mechanical response and failure modes in fire is needed to enable confident structural fire design and analysis of ever taller CLT buildings.

2. Background

As early as 1967 Malhotra & Rogowski [3] proposed an empirical model for predicting the fire resistance of glued laminated timber columns of different species, adhesives, shapes, and load levels. This was based on full scale standard fire resistance tests undertaken in fire testing furnaces. Their model could be used to predict fire resistance based on assigning experimentally-derived input parameters for each of their investigated parameters; these were then multiplied in series, to extend their data and empirically predict fire resistance. However, the application space of this model is extremely restricted and it cannot be applied to CLT wall elements, which may make use of novel adhesive types, raw timber with varying mechanical properties, and with a crosswise (rather than unidirectional) lay-up of timber lamellae.

2.1. The reduced cross section method and zero strength layer

The most common fire resistance design verification and analysis method currently used for mass timber structural elements is the reduced cross section method [4]. The RCSM assumes the formation of an insulating sacrificial char layer at the fire-exposed surfaces of timber structural elements; this provides an insulating layer and partially protects the underlying timber from fire, thus slowing the increase of internal temperatures and deterioration of the elements' load carrying capacity. In the RCSM method the timber is assumed to char at a nominal rate during exposure to standard fire conditions (or, more precisely, one of a number of prescribed nominal charring rates depending on the specific circumstances) [5]. The sacrificial char layer is assumed to have zero mechanical strength. In addition, a certain depth of 'thermally affected' timber beneath the char also has reduced mechanical properties due to heating and moisture transport effects. In the classical RCSM method, the mechanical consequences of the thermally affected timber beneath the char are treated by lumping a portion of the affected zone into a 'zero strength layer' (ZSL). The ZSL is typically assumed to be 7 mm [4,6], and this further reduces the size of the effective cross section; this reduced cross section is then used to predict the remaining load capacity in fire, assuming that the reduced cross section retains its full ambient temperature mechanical properties.

For fire safe design of common (i.e. low-rise) timber buildings the above approach is widely considered sufficiently accurate, since the temperature gradients in timber elements exposed in a standard fire resistance test are relatively steep and changes in the timber's strength and stiffness are concentrated close to the char [7]. However, the constant 7 mm ZSL depth currently suggested in design codes [4] is based largely on models calibrated from a relatively small number of flexural standard furnace tests on glulam beams undertaken in the 1980s [8]. The applicability of the current ZSL value to CLT in general [9], and to engineered timber compression elements more specifically [10,11] is doubtful.

The reductions in mechanical properties experienced by heated timber are substantially different when considering tensile or compressive response, and these are also heavily grain dependent [12,13]. The ZSL determined from computational models validated using flexural furnace tests is unlikely to apply to elements under uniform compression or combined compression and bending, as noted by König [6]. Furthermore, it has previously been shown – using both computer simulations and standard furnace tests – that the constant 7 mm ZSL used in design should actually vary for loading in bending, compression, or tension. For flexural compressive loading (i.e. hogging moment with heating from below) Schmid et al. showed that the ZSL should be increased to between 12.5 and 18.9 mm with a mean of 14.8 mm [10].

Schmid et al. [11] performed tests on compressively loaded CLT wall elements exposed to fire from one side, and postulated that a minimum residual depth of 3 mm should be imposed when considering CLT, in which the cross layers have negligible strength and stiffness in the primary loading direction, particularly considering the propensity for buckling of compression elements and the comparatively fine margins of residual cross section depth that could result in instability failures. Schmid et al. also state that the precise depth of the ZSL is potentially irrelevant to the fire resistance time if the ZSL penetrates into a weak layer, since only the load bearing function of the strong layers is critical. From analysis of a series of furnace tests on flexural CLT elements, Schmid et al. [9] have suggested that the 7 mm ZSL for CLT should be replaced with a ZSL depth that varies depending on the total depth of the remaining cross section. For example, for a CLT structural member in hogging with fire exposure on the compression face, Schmid et al. [9] propose a ZSL, d_0, from Eq. (1), where h is the reduced cross section depth (in mm).

$$d_0 = \frac{h}{20} + 11 \tag{1}$$

Goina [14] has used computation and experimental results to show that the above approach conservatively predicts fire resistances for compressively loaded CLT walls in standard furnace tests, by 45–47%.

2.2. Fire-induced delamination

Notwithstanding the complexities of proposing a more conservative ZSL depth for use with either glued laminated or CLT compression (rather than flexural) elements, another potentially important issue in determining the structural fire response of laminated timber products is fire-induced delamination; sometimes alternatively called 'loss of stickability' or 'falling off'. Delamination is the detachment of charred lamellae at in-depth glue-lines, which can expose the underlying uncharred timber to direct heating and increase the effective rate of charring. It is noteworthy that delamination may also contribute additional fuel to a fire compartment, thus altering the resultant fire dynamics and further influencing the structural fire response (and fire resistance). While delamination has previously been reported as an important issue to consider for CLT floor slabs in fire [15,16], it has been suggested that it is less likely in furnace tests of vertically oriented elements, presumably due to reduced separation forces from gravity [17,18]. Delamination should not be confused with debonding, which describes loss of composite mechanical action between lamellae, with both plies still theoretically capable of performing a significant load bearing function [19].

2.3. Thermal deformations in fire

Unlike steel or concrete structural elements, which experience structurally significant thermal deformations during heating [20],

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