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Structural response of fire-exposed cross-laminated timber beams under sustained loads

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ABSTRACT

Cross-laminated timber (CLT) is a popular construction material for low and medium-rise construction. However an architectural aspiration exists for tall mass timber buildings, and this is currently hindered by knowledge gaps and perceptions regarding the fire behaviour of mass timber buildings. To begin to address some of the important questions regarding the structural response of fire-exposed CLT structures in real fires, this paper presents a series of novel fire tests on CLT beams subjected to sustained flexural loading, coincident with non-standard heating using an incident heat flux sufficient to cause continuous flaming combustion. The load bearing capacities and measured time histories of deflection during heating are compared against predicted responses wherein the experimentally measured char depths are used, along with the Eurocode recommended reduced cross section method and zero-strength layer thickness. The results confirm that the current zero-strength layer value (indeed the zero-strength concept) fails to capture the necessary physics for robust prediction of structural response under non-standard heating. It is recommended that more detailed thermo-mechanical cross-sectional analyses, which allow the structural implications of real fire exposures to be properly considered, should be developed and that the zero-strength layer concept should be discarded in these situations. Such a novel approach, once developed and suitably validated, could offer more realistic and robust structural fire safety design.

1. Introduction and background

Cross-laminated timber (CLT) is an engineered mass timber product that is increasingly being used as a primary structural material in multi-storey construction. It is typically made from lamellae of softwood lumber, which are bonded one on top of another in a crosswise fashion using a polymer adhesive. The resulting alternating grain directions give CLT strength and stiffness in two directions, making it suitable for two-way spanning slabs, walls, and diaphragms. Cross-laminated timber falls within the "mass timber" family of engineered wood products, alongside glued-laminated timber, which has been widely used in buildings for decades. Construction using mass timber building systems is, however, becoming ever more popular due to various sustainability advantages, both real and perceived, alongside considerable benefits in terms of the speed and ease with which CLT buildings can be constructed in congested urban centres, the use of advanced offsite and modularised construction methods, and reductions in foundation size due to the reduced overall building mass. However, the use of mass timber as a primary structural material in multi-storey buildings is often limited due to the fact that timber is a combustible material, unlike traditional multi-storey building materials such as masonry, concrete, and steel. Before taller mass timber buildings can be designed with full confidence, particularly in cases where there is a desire to express (i.e. expose) the timber elements in the completed structure, the structural response of CLT elements during real fires must be better understood.

1.1. Current approach for fire resistance design

Structural fire design guidance for mass timber elements is available in design codes internationally, and takes many forms. The most advanced and rational guidance is likely that set out in Eurocode 5 [1], which can be used to determine the standard fire resistance of timber elements based on a simplified, notional charring rate and a reduced cross section calculation methodology

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Nomenclature

b_0	original breadth of structural element [m]
b_T	transformed breadth of structural element [m]
β_0	one-dimensional charring rate under a standard cellulosic fire exposure [mm/min]
$E_\parallel$	Young's Modulus parallel to the grain direction [N/m^2]
$E_\perp$	Young's Modulus perpendicular to the grain direction [N/m^2]
L	span length [m]
M	applied bending moment [Nm]
$M_{A,c}$	ambient temperature bending moment capacity established from control tests [Nm]
P	applied vertical load [N]
θ_n	free rotation at node n [rads]
v_n	free vertical translation at node n [m]
V	applied shear force [N]
Xa-*b*-c	specimen naming scheme (X=ambient temperature (A) or in fire (F), a=number of layers; b=load level; c=test number)

(described later). While CLT is not explicitly treated in the Eurocode, current practice in industry is to design CLT essentially as would be done for solid softwood timber; incorporating suitable modifications to account for CLT's crosswise lay-up. This approach takes advantage of so-called self-protection of the timber by surface charring and loss of an acceptable sacrificial depth of the surface timber, which protects and insulates the underlying (cool) timber.

Two specific, simplified methods are suggested in Eurocode 5 to determine the load bearing capacity of a mass timber (and, by extension, CLT) element during exposure to the ISO 834 [2] standard cellulosic compartment fire; (1) the reduced cross section method, and (2) the reduced properties method. The reduced properties method only applies to elements subject to fire from three or four sides, which is not typically applicable for CLT elements and is therefore not discussed herein (indeed, it is rarely used in practice even when applicable, and is slated for deletion from the upcoming revision to Eurocode 5).

The reduced cross section method assumes that timber will char at a notional charring rate during exposure to a standard fire, and then uses this notional charring rate to predict the depth of charred timber. The char is assumed not to contribute to the element's load bearing capacity and, to account for the presence of a zone of heated timber beneath the char, an additional 7 mm layer of 'zero-strength' timber is also assumed to make no contribution to strength or stiffness. The capacity of the timber structural element is then determined based on its ambient temperature mechanical properties, accounting only for the reduced cross section with the charred timber and zero-strength layer ignored.

The reduced cross section approach was originally derived in the 1980s based on numerical simulations of the fire behaviour of glued-laminated timber beams exposed to fire on three-sides by Schaffer [3]. Fig. 1 shows that this approach is fundamentally based on an assumed variation of mechanical properties of the timber below the char, which in turn is based on a small number of tests and on Monte Carlo analysis of the predicted responses. This is also for a specific North American timber species under specific, standard testing conditions (both heating and loading), rather than based on a rigorous assessment of mechanical properties from mechanical tests of the constituent timber materials and adhesives used. Based on his analysis and assumed mechanical inputs for heated timber below the char, Schaffer concludes that timber at depths below 0.3 in. (≈ 7 mm) from the base of the char layer can be assumed to be at full strength, with all other charred and heated timber ignored (as shown in Fig. 1(b)).

It is noteworthy that the 7 mm zero-strength layer approach has not been carefully experimentally assessed for application to CLT elements in bending, and that previous authors have criticised it as being inaccurate and physically unrealistic for solid timber or

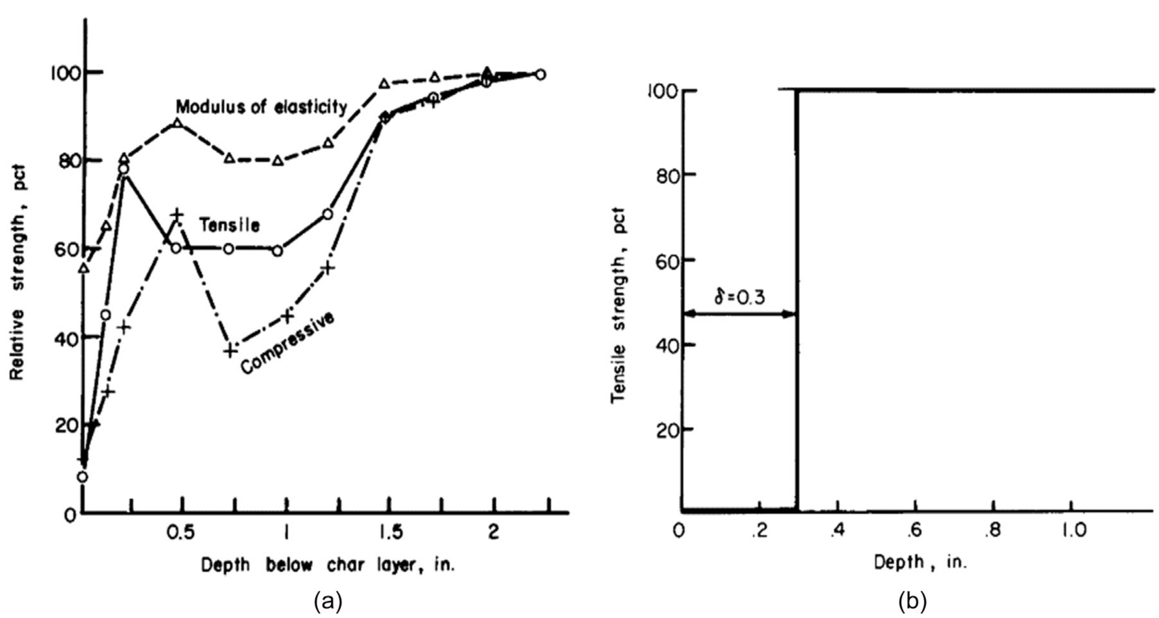

Fig. 1. The origins of the zero-strength layer in the work of Schaffer (after [3]) based on (a) variation of mechanical properties of timber beneath the char layer and (b) an assumed ambient temperature reduced cross section.