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Effects of exposed cross laminated timber on compartment fire dynamics

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ABSTRACT

A series of compartment fire experiments has been undertaken to evaluate the impact of combustible cross laminated timber linings on the compartment fire behaviour. Compartment heat release rates and temperatures are reported for three configuration of exposed timber surfaces. Auto-extinction of the compartment was observed in one case but this was not observed when the experiment was repeated under identical condition. This highlights the strong interaction between the exposed combustible material and the resulting fire dynamics. For large areas of exposed timber linings heat transfer within the compartment dominates and prevents auto-extinction. A framework is presented based on the relative durations of the thermal penetration time of a timber layer and compartment fire duration to account for the observed differences in fire dynamics. This analysis shows that fall-off of the charred timber layers is a key contributor to whether auto-extinction can be achieved.

1. Introduction

There is a global rise in the structural use of engineered timber, along with increasing demand for architectural expression of the timber structure, that is exposing the structural timber internally within buildings. Negative perceptions regarding fire safety in such buildings are one of the key barriers to realising current architectural aspirations. In most jurisdictions the use of combustible enclosures is restricted, and in some the use of a combustible material as an element of building structures is expressly prohibited for buildings of certain types and heights. These obstacles provide an opportunity to revisit compartment fire behaviour and to quantify the impact of these new construction technologies on the compartment fire dynamics.

Cross-laminated timber (CLT) is an engineered mass timber product formed from multiple layers (lamella) of timber, with adjacent lamellae bonded together with an adhesive such that the orientation of the grain is perpendicular. Cross-laminated timber has the advantage of reduced uncertainty in its bulk mechanical properties and can be produced to any desired size. In addition CLT offers significant construction advantages; it is both light and quick to construct, thus reducing the overall cost and duration of the construction programme.

Existing fire safety engineering design methods and correlations are principally based on the dynamics of fires within non-combustible enclosures. An understanding of the fundamental fire dynamics within an enclosure of combustible construction is essential to enable the safe fire design of compartments with exposed structural timber elements. This must be sufficient to enable the designer to predict key fire phenomena for building fire safety design, including the time to flashover, fire growth rate, and size and duration of the fire both within and external to the enclosure.

To understand the relevant challenges that exposed, combustible compartment linings present to fire engineering in multi-storey buildings, and the likely impact on the compartment fire dynamics, a series of large-scale compartment fire experiments have been undertaken. This series of experiments systematically varies the combustible surface configurations within the compartments to evaluate the compartment fire dynamics and material response of exposed CLT linings, and the performance of encapsulation methods for the unexposed CLT surfaces.

In a compartment with exposed structural CLT elements, the combustible timber linings have the potential to ignite and increase the heat release rate (HRR) of a compartment fire. The heat generated by this additional burning also has the potential to increase the burning rate of the compartment contents and other combustible surfaces, and thus the presence of exposed timber is likely to have clear effects on the compartment fire dynamics, and vice versa. Design of such compartments therefore must incorporate a strategy to achieve auto-extinction of the timber after the compartment contents have burnt out [1,2].

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1.1. Ignition and burning wood

Combustion of wood has been studied extensively. The processes of pyrolysis and char formation which control the burning of wood have been studied under a wide range of conditions [3–6]. The pyrolysis process produces a rigid, carbon-rich char in the solid phase and flammable, gas-phase pyrolysis products. The gas phase pyrolysis products can undergo flaming ignition if they are produced at a rate sufficient to form a mixture that reaches the lower flammability limit with surrounding air, and provided that there is an appropriate ignition source. In ambient oxygen environments, data from bench-scale experimentation consistently shows that the critical heat flux for piloted ignition of wood is 12 kW/m^2 and 28 kW/m^2 for unpiloted ignition [7]. The solid phase product of pyrolysis is a low density, porous char with a low effective thermal conductivity. The low thermal inertia and thermal diffusivity of the char layer results in high surface temperature and consequently high heat losses form the surface. This reduces the net heat flux into the virgin material, and consequently leads to a reduction in pyrolysis rate as the thickness of the char layer increases. Therefore, in order to support flaming combustion of timber, an external heat flux is required to overcome the heat losses from the surface. This has been shown to be on the order of 30 kW/m^2 [1,8], corresponding to a critical mass flux of between 3.5 g/m^{2}s [1] and 4.0 g/m^{2}s [8]; if the production of volatiles drops below this rate the flame will not be sustained. In the absence of a flame, oxidation of the surface char may occur leading to smouldering combustion.

1.2. Fire behaviour of cross laminated timber

This knowledge can be applied to cross laminated timber however there are two key differences. Firstly the laminated nature of these products introduces complexity as the properties of the adhesive will determine the mechanical properties of the timber. Commonly this has been associated with 'delamination' (fall-off of pieces of char and timber) as the timber burns. Although this phenomenon has been previously reported there is little information available to understand the governing physical mechanisms.

The second difference is that cross laminated timber products typically have a large dimensional thickness. Often this can be > 200 mm and as a result the temperature distribution within the timber will affect the burning behaviour and the mechanical properties.

2. Compartment fire behaviour

Compartmentation is a cornerstone of fire safety engineering design. However, the failure modes of common compartment construction systems and materials are relatively poorly documented from a scientific (rather than compliance testing) perspective. Failures can arise due to loss of material properties at high temperature and/or a system failure, as a result of the interaction or failure of one or multiple materials or components. In general failure of the compartment is defined by spread of the fire to an adjoining compartment (breach of compartmentation), or by excessive heating on the unexposed face of a fire-separating partition (inadequate insulation). In the context of compartments with exposed combustible linings, failure can be defined as the inability to reach auto-extinction, since this means that burnout has not been achieved. In both cases, failure modes are intrinsically linked to the characteristic timescales of the compartment fire.

Compartment fires have been the subject of extensive studies, with some key aspects summarised below. There are three phases commonly referred to during a fire in a compartment. First, a fuel-controlled growth phase until flashover is reached. Flashover has been studied extensively and numerous correlations exist to predict the necessary/sufficient conditions for it to occur, see e.g. Drysdale [7]. The subsequent post-flashover stage corresponds to a situation when all combustible surfaces are burning, and this fully-developed fire is typically referred to as a Regime 1, ventilation-controlled fire [7]. In this phase the burning rate and temperature in the compartment depend on the ventilation conditions rather than the fuel load, and can be approximated by Eq. (1), where A_V is the ventilation area, and H_V is the height of the ventilation opening. As the burning rate of the fuel decreases and extinction is approached, the fire will enter a decay phase, during which it will transition back to a fuel-controlled fire.

2.1. Burning rate and compartment heat release rate

The burning rate in a post-flashover compartment fire is commonly calculated using Eq. (1). The mass burning rate, $\dot{m}$ is dependent on the product $A_V\sqrt{H_V}$ and a coefficient based on the fuel (typically 0.09 for wood [7]). The origins of this correlation are based on the buoyancy driven flow and the stoichiometric burning of air inside the compartment and it is generally assumed to hold over a limited range of $A_V\sqrt{H_V}$ and fuel configurations [7]. If the opening is sufficiently increased relative to the fuel surface area, the burning rate will become independent of $A_V\sqrt{H_V}$, leading to a fuel-controlled burning regime [7].

$$\dot{m} = 0.09A_v\sqrt{H_v} \tag{1}$$

2.2. Compartment temperatures

The maximum temperatures achieved in post-flashover compartments have been extensively studied. Thomas [9] presents an analysis based on the opening factor, $A_T/A_V\sqrt{H}$. For low opening factors (< 15) the compartment temperatures increase as a function of opening factor. Beyond this limit, compartment temperatures decrease with increasing opening factor. The resulting curve is captured by the following expression [10]:

$$T_{\max} = \frac{6000(1 - e^{-0.1\Omega})}{\sqrt{\Omega}} \tag{2}$$

where

$$\Omega = \frac{A_T - A_V}{A_V\sqrt{H_V}} \tag{3}$$

and A_T is the total area of the compartment linings.

2.3. Effects of combustible linings

In general compartment fire testing has been carried out with inert compartment linings. Relatively few studies have investigated the effects of combustible linings on the resulting compartment fire dynamics. Butcher et al. [11] studied compartments with combustible fibre insulation board (FIB) linings on the walls and ceilings, and compared these to data gathered from cribs of equivalent fuel loading with inert compartment linings. The compartment with FIB linings reached higher temperatures faster than the compartment with wood cribs, and resulted in a fully-developed fire with flames filling the whole compartment and significant external flaming. No direct explanation for this behaviour was given; however it is logical to assume that the large surface area of fuel and the fixed ventilation conditions resulted in production of pyrolysis gases at a rate greater than they could be oxidised by the air inflow to the compartment. This suggests that the correlations provided above may not hold for compartments with significant areas of exposed combustible material.

Li et al. [12] carried out a series of 10 fire tests using compartments representative of common cross laminated timber constructions. Three of those tests had exposed CLT surfaces; one with one wall exposed, one with two opposite walls exposed (4.5 m×2.5 m), and one with two perpendicular walls exposed (4.5 m×2.5 m and 3.5 m×2.5 m). Both of the tests in which two walls were exposed experienced a secondary flashover, attributed to delamination of the charred CLT, whereas the compartment with only one exposed surface appeared to demonstrate