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Numerical simulation of fire integrity resistance of full-scale gypsum-faced cross-laminated timber wall

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ABSTRACT

Fire design requires three fire resistance criteria, namely integrity, insulation and load-bearing. In particular, repartition wall systems used in residential and commercial buildings are required to provide certification of insulation and integrity fire resistance and have to be analysed in the context of the characteristic time scales of a fire. This paper presents a numerical methodology to simulate the fire integrity resistance of full-scale timber-based wall systems exposed to fire. The main contribution of this paper, with regard to the existing literature, is the presence of cross-laminated timber (CLT) panel in the central part of the wall system, where the pyrolysis of timber was modelled explicitly in the energy balance equation system. For this end, a user-subroutine, called UMATHT, is developed and successfully implemented in the Abaqus finite element code for thermal analysis. The falling off of the gypsum boards under fire was considered implicitly in the FE model based on experimental observations. The obtained results show clearly the need to take into account explicitly the cracks and falling off of the gypsum boards for an appropriate prediction of the integrity fire resistance in order to reduce expensive experimental procedures.

1. Introduction

Fire Safety is the superposition of three different types of events occurring simultaneously. Two of these events, egress and structural behaviour, are reactive events while the rate of fire growth is the driving process. The structure will be designed and it will respond to the fire. Some passive fire protection systems (detection, alarm) are designed and implemented to warn of the fire, and others are designed to affect the rate of growth (suppression). People within a building are located according to the general use of the premises but will change their behaviour in response to the fire. Occupants will have mostly a passive role, while fire fighters will have an active role attempting to control the growth of the fire.

Building design and fire fighter intervention procedures are defined on the basis of one or more fire growth scenarios. In the case of prescriptive design (codes and standards) the fire growth scenarios are implicit, while in the case of performance based design (engineering based methods) they are explicitly defined and are referred to as "design fires". Prescriptive design rules use knowledge on fire dynamics and empirical data to bind the fire growth for the specific conditions of the implied scenarios. Fire safety systems are designed to operate within these bounds and are deemed adequate for a range of buildings. But given that there are unavoidable and significant differences between buildings, there is a risk of extrapolating codes and standards outside its range of applicability. Therefore, to know the extent of the extrapolation of prescriptive solutions requires understanding the parameters that govern and bound the fire growth scenario. In the case of performance based design, knowledge on fire dynamics is used to predict fire growth under the particular conditions of the building. Thus the link between fire safety objective and understanding of the physical parameters controlling fire growth is important and explicit.

There are three fire resistance criteria for fire design, namely: integrity, insulation and load-bearing. The integrity failure which results in flame and/or smoke leakage from the fire compartment can result in significant loss of life [1]. Light non-load-bearing partition wall systems used in residential and commercial properties are required to provide a certified insulation and integrity fire resistance rating. In Europe, certification for fire resistance rating involves subjecting such walls to a standard fire according to the standard fire curve ISO 834-1 [2] as given in the EN1991-1-2 [3].

The fire rating of partition walls are subjected to certification before they can be used in construction. The certification process is quite costly and could involve repeated experimental attempts, using accredited fire testing facilities which are very limited, to achieve the required fire rating with additional cost and loss of time [1]. It is, therefore, of primary importance to develop numerical tools to simulate

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Nomenclature

T	temperature [K]
t	time [s]
x,y,z	location coordinates [mm]
c_i	specific heat of components i [J/(kg.K)]
ρ	density [kg/m^3]
Q_r''	energy source [kW/m^3]
h_{conv}	convection coefficient [W/(K.m^2)]
ε_{emis}	emissivity
R	gas constant [J/(K.mol)]
k	reaction rate [1/s]
E	activation energy [J/(mol)]
H	moisture content [%]
A	pre-exponential constant [1/s]
Δh	reaction heat [J/kg]

Subscript

λ	thermal conductivity [W/(m.K)]
0	initial
c	char
g	gas
l	liquid
t	tar
v	vapor
w	wood

the behaviour of full-scale structural (or non-structural) components under fire.

Timber has an explicit role within the context of fire growth. Timber is a flammable material that when exposed to a fire will ignite contributing to the growth of the fire. Thus, it will affect the rate of growth of the fire and thus alter the times to reach untenable conditions. If burning or pyrolyzing it will generate combustion products, thus will introduce toxic and irritant species. Timber, if part of the structure (load bearing or non-load bearing) will have a significant impact on structural integrity but also will help define heat transfer through the infrastructure boundaries, thus will affect compartment temperatures. It is therefore clear that the presence of timber has the potential of dramatically affect fire safety. Nevertheless, the real question that needs to be addressed is how significant is this effect. The significance of timber in fire is intimately related to the characteristic times involved in the degradation, burning and loss of mechanical properties of the material relative to all the characteristic times for egress.

Timber structures have traditionally been built using heavy timber frames, with the walls being constructed of various materials such as interwoven branches and split logs in the very early versions of these types of structures, and later using plastered panels and bricks [4]. The coming of the industrial revolution marked the appearance of industrially built planks, boards and nails which spawned the appearance of new and modern construction techniques, especially in the Europe and USA, where new framing methods reduced labour costs, increased the flexibility in construction and allowed for prefabrication [4]. These light frame construction methods are nowadays the predominant form of construction in residential and low-rise buildings. During the last decade, prefabricated cross-laminated timber panels (CLT) for load bearing wall and floor assemblies have become increasingly popular not only for residential but also for office, retail and industrial buildings [5,6] in particular in the actual context of multi-storey timber

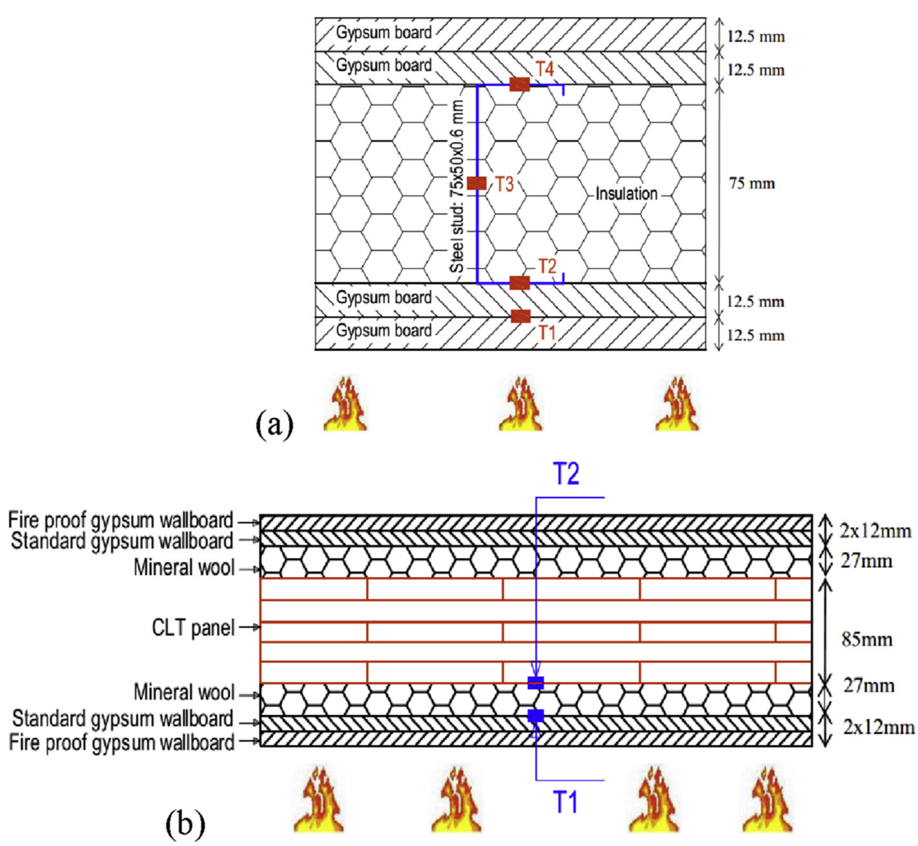

Fig. 1. Geometrical illustration of the studied wall systems and location of thermocouples: (a) steel-stud gypsum-faced partition wall and (b) gypsum-faced CLT wall.