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A NATURAL FIRE TEST TO ASSESS THE BEHAVIOUR OF MODERN TIMBER CONSTRUCTION TECHNIQUES: LIGHT TIMBER FRAME VS. GLUED LAMINATED TIMBER

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1. INTRODUCTION

Wood, used as a building construction material, offers a range of advantages in terms of cost, time for construction, energy efficiency and sustainability. Modern timber construction is able to exhibit high anti-seismic and fire-safety performance, which is at least on a par with more “conventional” construction techniques (e.g. reinforced concrete). A full-scale natural fire test is performed with the aim to investigate the behaviour of modern timber construction techniques, namely the Light Timber Frame (LTF) and the Glued Laminated Timber (GLT) system, when exposed to realistic fire conditions.

The LTF system is used worldwide for the construction of load-bearing wall and floor assemblies, especially in the case of low-rise buildings. The LTF construction technique is based on timber structural members (studs, battens), which provide a stable frame to which interior and exterior walls, covered by a variety of sheathing materials (e.g. wood-based panels) are attached. The air cavities that are formed between the timber elements may be filled with thermal and acoustic insulation materials. In order to achieve the fire resistance requirements dictated by fire safety regulations, a fire protection cladding is commonly applied to the exposed side of the system, e.g. single or double layers of Gypsum Plasterboards (GP). The GLT technique, also known as Cross Laminated Timber, Glulam or XLam, is a relatively new timber construction system, which becomes increasingly popular, especially in certain European countries (e.g. Austria, Italy). The GLT system is based on prefabricated timber panels, consisting of 3 to 7 layers of timber layers glued together, that can be used to construct load-bearing wall or floor assemblies. The GLT system offers a range of advantages over the LTF system, such as higher stiffness and robustness, better air tightness and lower risk of fire spreading (due to the absence of air cavities). However, the GLT panels may increase the total fire load in the structure; similar to the LTF system, a fire protection cladding (e.g. single or double layers of GP) is required to be applied at the exposed side of the system.

2. EXPERIMENTAL METHODOLOGY

Standard fire resistance tests are conducted under rigorously controlled furnace conditions; it is well established that the obtained results are occasionally not representative of realistic fire scenarios, where wall assemblies are not heated in a uniform or continuous manner[1]. In this context, natural fire tests can be used to investigate the behaviour of wall assemblies when exposed to more “realistic” fire conditions; the obtained measurements can be a valuable tool for the validation of fire simulation tools. Despite the increasing number of experimental studies on large scale natural fire tests in compartments[2-5], there are scarce literature reports focused on the fire behaviour of load-bearing timber building elements. A series of fire experiments in a full-scale compartment has been performed by VTT[6], using both light and heavy timber construction techniques. It was demonstrated that when GP are used as a fire protection cladding, heat flux to the timber structure is dramatically (90%-97%) reduced and the onset of charring is significantly delayed (20-40 min). In addition, the use of GP cladding was found to result in higher compartment gas temperatures and lower probability of external flaming. More recently, BRE Global performed a series of large scale natural fire tests to evaluate the performance of GP protected timber floor systems[7]. A uniformly distributed load was applied to the investigated floor systems; it was found that properly installed cladding has a major impact on the overall fire behaviour of the system. A large-scale natural fire test on a three-storey GLT building has been performed by the group of CNR-IVALSA[8]. The 10 m high building was exposed to a typical residential fire scenario; GP protection was found to limit the observed charring depth in the GLT panels. In this context, the main scope of the current work is to comparatively assess the fire behaviour of the LTF and GLT construction systems when exposed to realistic fire conditions, by means of performing a natural fire test in a full scale test compartment.

2.1 Layout of the Test Compartment

The internal dimensions of the test compartment are 2220 mm x 2220 mm x 2110 mm; an open window, located on the S side and measuring 430 mm x 980 mm, provides the required ventilation (Fig. 1). The investigated timber construction systems are implemented in the test compartment using a symmetrical layout; LTF is used in two vertical walls (S, W) and the ceiling, whereas GLT is used in the remaining vertical walls (N, E) and the floor. The test compartment is built in accordance with the Eurocode 5[9] design guidelines.

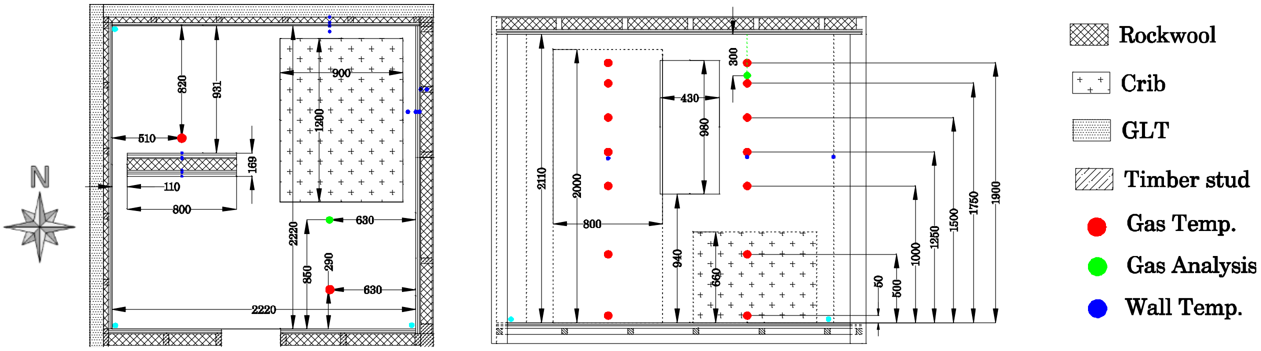

Figure 1. Top (left) and side (right) views of the test compartment; locations of main instrumentation.

Rectangular (85 mm x 40 mm) cross-section timber studs and battens are used to construct the frame of the LTF walls, with 10 mm plywood panels serving as the "sheathing" material; the closed cavities created by the timber frame are filled with an 85 mm layer of rock wool (Fig. 2, left). The GLT walls are formed using 95 mm pre-fabricated 5-layer GLT panels; rectangular (40 mm x 85 mm) wood studs on the indoor side provide a frame for a 40 mm layer of rock wool (Fig. 2, middle). In both cases, a final cladding layer, comprising two 12.5 mm fire-resistant GP panels, is installed on the indoor side to provide adequate fire protection. A double layer of fire-resistant GP panels is also used for the internal lining of the floor and the ceiling. In addition, aiming to investigate the fire behaviour of unprotected timber panels, a partially separating wall, measuring 2000 mm x 800 mm is constructed inside the test compartment, using multiple layers of fire-resistant engineered timber panels (Fig. 1). More specifically, from the N to the S side, the wall consists of two layers of 16 mm fire resistant (Euroclass B) chipboard, one layer of 10 mm plywood, 85 mm x 40 mm timber studs combined with 85 mm rock wool, one layer of 10 mm plywood and two layers of 16 mm (Euroclass C) MDF (Fig. 2, right).

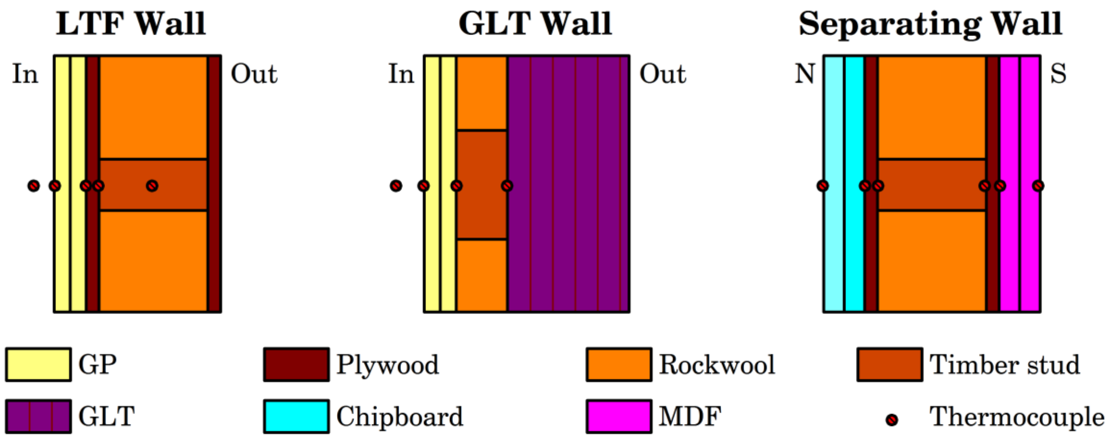

Figure 2. Main dimensions of the LTF (left), GLT (middle) and separating wall (right) assemblies and positions of the thermocouple devices.

The fire load density is estimated following the methodology described in Eurocode 1[10], assuming a typical office room (420 MJ/m^2). Aiming to achieve realistic natural fire conditions, a wood crib is assembled, using 105 kg of fir wood; its lower heating value was measured, using an oxygen bomb calorimeter (in accordance with the ISO 1716 standard), to be equal to 19.87 MJ/kg. The wood crib assembly, measuring 900 mm x 1200 mm x 660 mm, is located near the NE corner of the room, in order to provide uniform thermal exposure conditions to the adjacent LTF (E) and GLT (N) walls (Fig. 1).

2.2 Instrumentation

An extensive set of instrumentation is installed in the test compartment to allow the continuous monitoring of the temporal evolution of certain significant physical parameters (Fig. 1). Two thermocouple trees, recording the gaseous temperature distribution in 7 different heights, are installed near the SE (close to the opening) and NW (on the N side of the partially separating wall) corners. Wall surface temperatures and temperatures at the interfaces between the various wall layers are monitored using 15 K-type thermocouples; an infra-red camera, aimed through the window at the northern GLT wall, is also used. Flame shape and position variations are recorded using 3 video cameras installed at the corners of the test compartment. A gas analyser is also used to monitor the chemical composition of the gaseous environment. The velocity of the gaseous products emanating from the upper part of the window is measured using a Pitot tube. The obtained measurements provide a detailed physical description of the main characteristics of the developing turbulent, reactive and multi-component flow-field.

3. RESULTS AND DISCUSSION

3.1 Fire Development and Gas Temperatures

The fire is initiated by igniting a paraffin soaked fabric located under the wood crib. A rapid increase of the fire power is observed during the initial fire growth stage (Fig. 3); the gaseous temperature quickly reaches 750^{o}C (Fig. 4, left). Approximately 9 min after fire initiation, there is a sudden decrease in the gas temperatures; a local minimum (420^{o}C) is reached at the 11 min mark. A sudden drop in oxygen concentration is also recorded at the same time period (9 - 11 min). This behaviour suggests that under-ventilated fire conditions are temporarily established in the compartment, owed to the rapidly increasing concentrations of combustion products; however, the ambient air entrainment through the window results in a gradual increase of the indoors oxygen concentration, thus allowing gas temperatures to regain their previous levels, roughly 13 min after fire initiation. Approximately 17 min after fire initiation, the fire growth stage is completed, as gas temperatures reach their peak values (830^{o}C). Fully developed fire conditions are established, until the end of the test, 45 min after fire initiation. At the 21 min mark, the thermocouple tree installed near the SE corner failed; in addition, the S side of the separating wall, built using engineered timber panels, partially collapsed approximately 35 min after the fire initiation.

Figure 3. Stills from indoors video recording cameras, 3 min after fire initiation.

The temporal evolution of the recorded gaseous temperatures is found to agree reasonably well to the standard (e.g. EN 1991-1-2[10] and ISO 834) time-temperature curves (Fig. 4, left). The vertical distribution of the gas temperatures, measured at the thermocouple tree located near the partially separating wall, are depicted in Fig. 4 (right). A thermally stratified flow is quickly established; temperatures at lower heights (50 - 500 mm) are significantly lower than the respective temperatures at the upper hot layer (1000 - 1900 mm). Once more, the characteristic stages of a typical compartment fire are observed; the initial fire growth stage (0 - 17 min) is followed by a fully-developed fire stage (17 - 45 min), where steady-state conditions are established in the upper layer gas and the corresponding temperatures remain practically constant. Combustion products are locally accumulated near the NW corner of the test compartment, due to the partially separating wall that restricts the flow; as a result, gas temperatures at lower heights (50 - 500 mm) are steadily increasing. The sudden drop in the upper hot layer temperatures, which is observed after the initial rapid growth stage (9 - 11 min), is owed to the local oxygen starvation due to the development of strong under-ventilated fire conditions. The modest drop in all temperatures observed at the 35 min mark is owed to the partial collapse of the separating wall supporting the thermocouple tree.

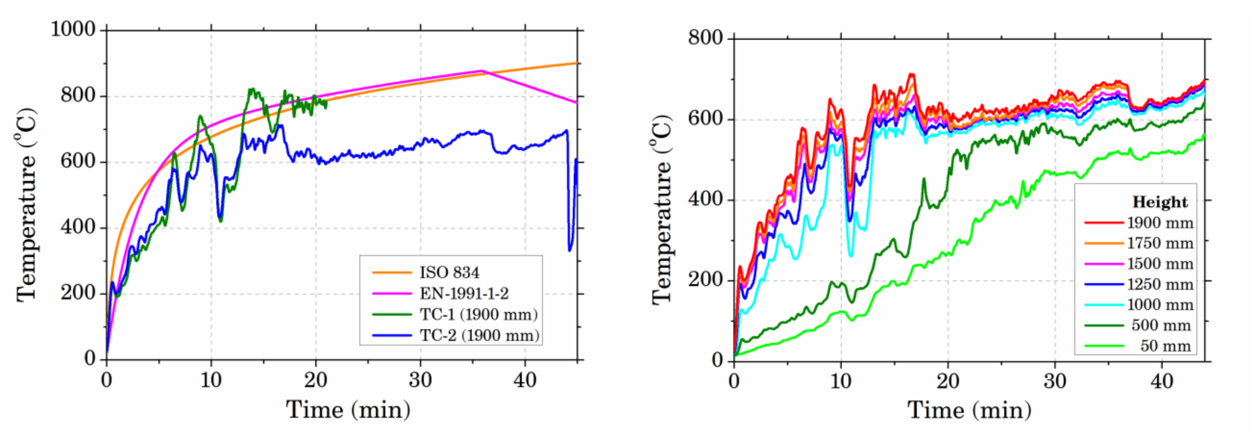

Figure 4. Temporal evolution of temperatures at the upper gas layer (left) and at the partially separating wall thermocouple tree (right).

3.2 Thermal Behaviour of the Building Elements

The temporal evolution of surface temperatures across the LTF and GLT wall assemblies is depicted in Fig. 5. In order to properly characterize the thermal exposure of each wall assembly, measurements of gas temperatures, at a distance of 10 mm from the exposed wall surface, are also obtained. Despite the fact that gas temperatures exceed 500°C, the recorded temperatures at the exposed GP surface are kept below

300ºC. Due to the very good fire-resistance characteristics of the GP[11], temperatures at the unexposed GP side are constantly lower than 150ºC. The presence of the plywood sheathing in the LTF wall further impedes the heat flow, thus resulting in temperatures that never exceed 60ºC or 30ºC, at the exposed side and the middle span of the timber studs, respectively. As expected, the presence of the rock wool layer at the GLT wall assembly results in low temperatures (less than 90ºC) at the exposed side of the GLT.

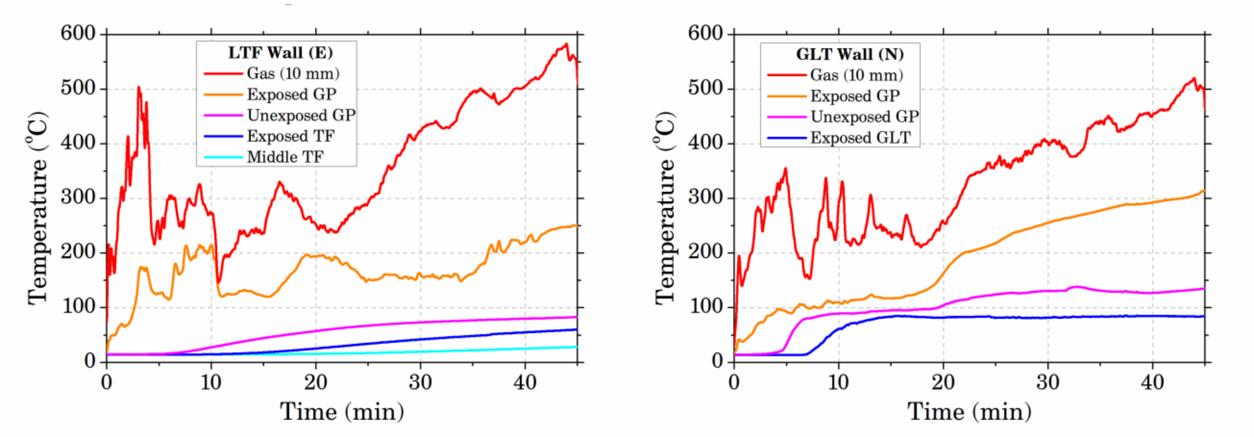

Figure 5. Temporal evolution of surface temperatures across the LTF (left) and the GLT (right) wall assemblies.

The overall behaviour of the LTF and GLT wall assemblies is comparatively assessed in Fig. 6 (left), where the temporal evolution of gas and timber element temperatures are depicted. Comparison of the gas temperatures suggests that due to the carefully selected positioning of the wood crib fire source, both wall assemblies are exposed to thermal environments that exhibit very similar characteristics. It is evident that the presence of the double GP fire protection layer and, additionally, of the plywood sheathing and rock wool insulation layers, results in recorded temperatures at the exposed side of the timber elements that never exceed 90ºC. According to optical inspection both during and after the fire test, no charring or cracking has been observed in the timber elements.

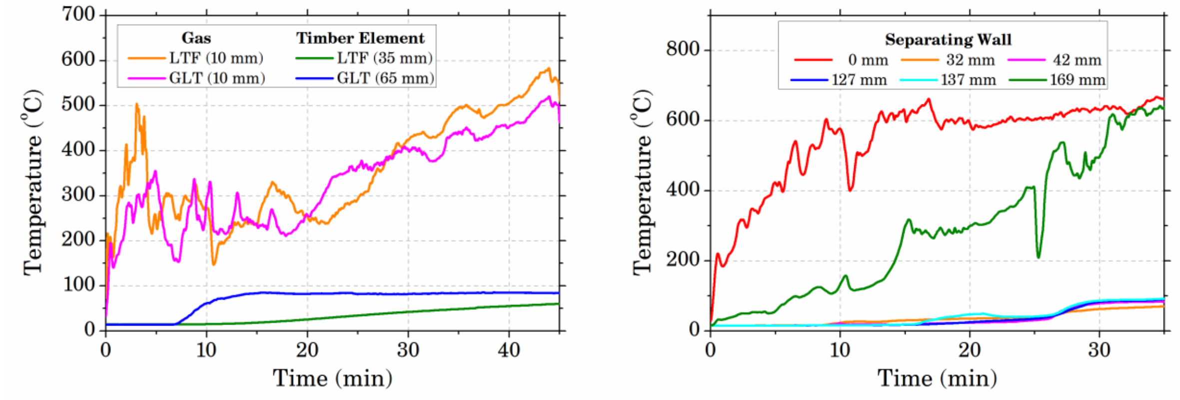

Figure 6. Comparison of gas and timber element temperatures at the LTF and GLT wall assemblies (left); temporal evolution of surface temperatures across the separating wall assembly (right).

The absence of fire protection GP layers is evident in the recorded temperatures at the separating wall assembly (Fig. 6, right). As expected, high temperatures are observed at both the exposed sides of the wall; temperatures at the N side (0 mm), facing the wood crib and the NW corner of the test compartment where combustion products are accumulated, increase faster than the respective temperatures at the S side (169 mm). However, temperatures at the unexposed sides of both the chipboard (32 mm) and the Medium

Density Fibreboard (137 mm) layers never exceed 100°C. Due to the high thermal stresses imposed on the separating wall, a partial collapse of its S side is observed approximately 35 min after fire initiation.

4. CONCLUSIONS

Aiming to comparatively assess the behaviour of two modern timber construction techniques, namely the LTF and the GLT system, a natural fire test was performed in a full scale compartment. The gas temperatures achieved in the test compartment reproduced well the EN 1991-1-2[10] and ISO 834 time-temperature curves for compartment fires. The measured wall surface temperatures, combined with information obtained by optical inspection after the conclusion of the test, suggested that the fire protection GP cladding did not fail and no charring occurred either in the LTF or the GLT walls. Both timber building elements were found to retain, for the 45 min duration of the test, their separating and load-bearing functions. In contrast, recorded temperatures and optical evidence (significant charring, partial collapse of the wall) suggested that the separating wall, constructed using unprotected fire-resistant engineered timber panels, failed thus corroborating the need for adequate fire protection cladding (e.g. GP layers). The obtained set of measurements, corresponding to the temporal evolution of a large variety of physical parameters, such as gas temperatures, wall layer temperatures, gas species concentrations, flame shape and location, can be used for validation of relevant fire simulation tools, appropriate for modelling the fire behaviour of timber construction systems.

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