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„Fire Safe Use of Bio-Based Building Products“

Proceedings of the 1st European Workshop Fire Safety of *Green* Buildings

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Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

Internet: www.shaker.de • e-mail: info@shaker.de

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Preface

With the 1st European Workshop "Fire Safety of Green Buildings" the COST Action FP1404 continues the way started with the successful working group meeting, held in Barcelona, Spain on 20th – 21st April 2015, to provide a common understanding about the fire safe use of bio-based building products and a more harmonized and stronger market for these products.
The aim of this Workshop is to present the state of the art, with recent developments in fire safety of bio based building products and construction. The Workshop provides experts and practitioners a chance to present and discuss their research activities and work at European level and establish collaborations. Within the Workshop the following topics have been covered: *material properties, modification and assessment methods for bio-based materials, contribution of bio-based materials to fire scenarios, overall structural fire behaviour under standard and natural fire conditions, fire safe detailing and execution, risk methods and safety concepts, fire statistics and intervention, application of structural fire engineering, best practice examples.*

This book contains the proceedings of the 1st European Workshop and includes the extended abstracts of the 3 keynote speakers, 17 oral presentations and 20 posters and is supplemented by a full colour pdf file, which can also be downloaded from the COST FP1404 website: www.costFP1404.com.

This proceedings has been subdivided into three themes following the technical working groups of the COST Action FP 1404:

WG 1: Contribution of bio-based materials to the fire development

WG 2: Structural elements made of bio-based building materials and detailing

WG 3: Regulations for fire safety of bio-based building materials

The standard of the extended abstracts received was excellent and challenged the committee during the selection process. Finally, we would like to thank all members of the scientific committee who reviewed all the extended abstracts in a very short time, the members of the organising committee of TUM who organised this workshop, the authors and the sponsoring organisations for their contribution to the success of this Workshop.

Joachim Schmid, chair of FP1404

Massimo Fragiacomo, vice-chair of FP1404

Norman Werther and Stefan Winter, host of the workshop

August 2015

Working Group 1

Timber Behaviour in Fire: the role of Pyrolysis and Smouldering Combustion

Guillermo Rein

Department of Mechanical Engineering, Imperial College London, SW72AZ, UK, g.rein@imperial.ac.uk

Keywords: heat transfer, structure, chemistry, char, burning.

Wood is a construction material with two seemingly antagonistic characteristics; it is sustainable and it is flammable.

Modern engineering timber products create the possibility of designing tall and more sustainable buildings. Architectural trends already include the design of tall buildings in excess of 20 storeys with structural timer elements (engineered wood). However, as a flammable material, the single biggest market barrier to tall timber construction is the fire risk borne from the structural material. This differs from the more traditional risk borne from the contents or insulation of the building. Because of this unique risk, timber high-rises are severely restricted by regulation in many countries. However, a close inspection of the scientific literature on the behaviour of timber in fire shows that the perceived risk is not well informed. In fact, there is very little research on the topic when compared to other construction materials like steel or concrete.

When a fire breaks, the resulting smoke and flames heat up the exposed structural elements. Heating starts at the surface but penetrates in-depth with time.

The initial response of wood to heat is drying and thermal expansion. If heat continues, the temperature rise leads to the onset of pyrolysis (Fig. 1), which initiates the loss of mass and char formation. Char has negligible mechanical strength and it is brittle; hence its formation reduces the load-carrying capacity of timber and damages the structural response. The ability to predict the initiation of mass loss and the growth of the char layer is important for structural engineers (Fig. 2).

This presentation will review the thermochemical processes unleashed during fire that are important to timber, like heat transfer, drying, pyrolysis, charring, mass loss and smouldering [1]. These processes ultimately determine the evolution of the char layer in the short and long terms, and thus explain the transient loss of strength of timber elements.

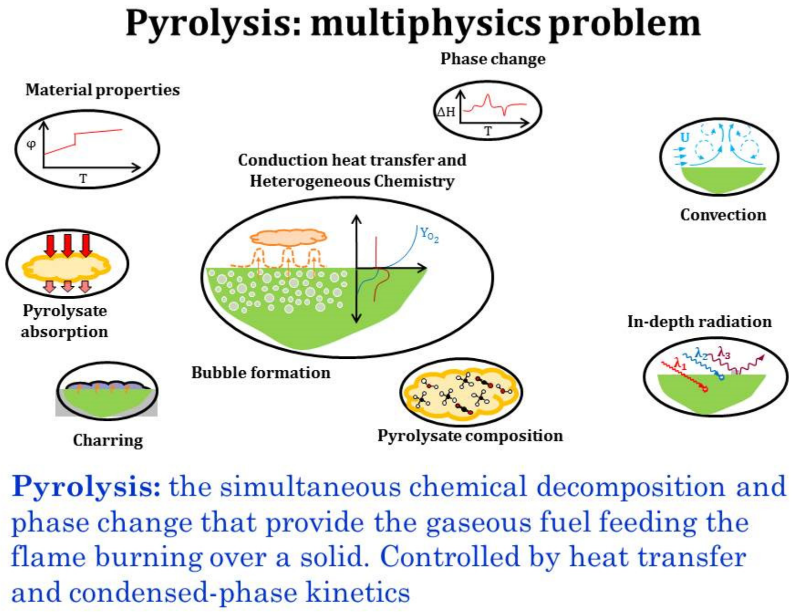

Figure 1. Pyrolysis is a multiphysics process involving heat and mass transfer

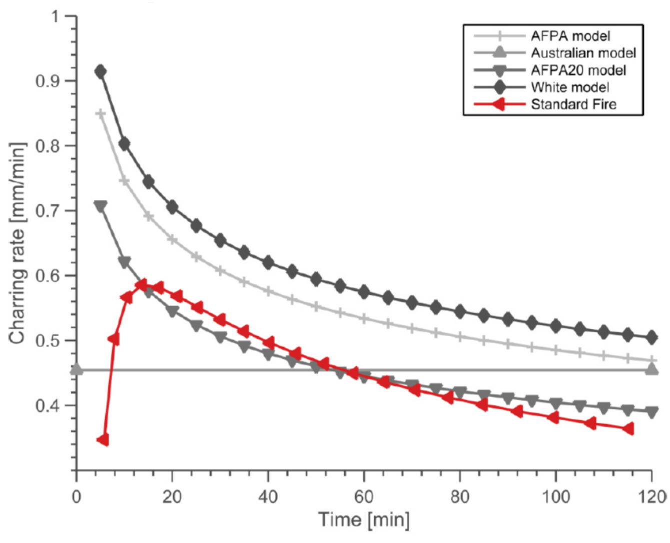

Figure 2. Predicted charring rates with a pyrolysis model of timber for a range of possible fire scenarios [2]

References

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[2] Richter F, Rein G, 2015, Numerical simulation of the charring of timber structures under non-uniform fires, 1st Workshop on Fire Safety and Bio-Based Building Products in Berlin, October, COST F1404.

Properties of bio-based polyurethane coatings with intumescent flame retardants

Vladimir Yakushin, Irina Sevastyanova, Dzintra Vilsone, Andris Avots

Dzerbenes 27, Riga, Latvian State Institute of Wood Chemistry, Latvia, yakushin@edi.lv

Keywords: intumescent flame retardant, polyurethane coating, flammability

Introduction

To decrease the flammability of bio-based polyurethane coatings, halogen-free intumescent flame retardants (IFRs) have been in common use in recent years [1]. Typical intumescent coating systems, besides a film former, usually contain three synergistic ingredients: an acid source, which acts as a charring catalyst; a char forming agent and a blowing agent, which dilute the volatile pyrolysis gases [2]. The database on the properties of IFRs is rather broad. However, the choice of IFRs for a definite polymer remains individual, because the synergistic effects at thermal decompositions and combustion of intumescent polymer systems depend on the chemical structure of the polymer itself [3]. The aim of the present study was the choice of the most efficient IFRs and their combinations for polyurethane coatings based on triethanolamine esters of tall oil fatty acids.

Materials and methods

Ammonium polyphosphate (APP), grade Exolit® AP 422, was purchased from Clariant International Ltd., BU Additives (Switzerland). Melamine 99% (MEL) and Pentaerythritol 98 % (PER) were obtained from Sigma-Aldrich Chemie GmbH (Germany). Melamine phosphate (MP) was purchased from Tianjin Aokatet Chemical Co., Ltd. (China).

Polyol, synthesized from triethanolamine and tall oil fatty acids [14] and Polyisocyanate Voratec SD 100 from Dow Deutschland GmbH (Germany) were used for polyurethane coating preparation. APP, Mel and PER were preliminary mixed in polyol, and MP was mixed in polyisocyanate. The content of single IFRs was varied in the range from 0 to 30 wt.%. On varying the weight ratio in combinations of two or three IFRs, the total amount of the introduced IFRs was constant - 25 wt.%. For the thermal and mechanical test, polyurethane coatings were prepared in the form of free films [14]. For the cone calorimeter test, polyurethane coatings, 250-300 μm in thickness, were applied on 100×100×16 mm wood (pine) samples.

TGA/SDTA 851e METTLER TOLEDO was used for thermal gravimetric analysis (TGA) of polyurethane coatings. The test was carried out at a heating rate of 10°C/min, in the airflow of 20 cm^3/min. FTT Cone Calorimeter (Fire Testing Technology Ltd.) was used for the combustibility test of wood samples with applied coatings. The heat flux was 35 kW/m^2. All samples were arranged in a horizontal position. Test duration was 30 min.

TGA of intumescent polyurethane coatings

With increasing content of single flame retardants (FRs), the initial temperature of decomposition of filled polyurethanes, in comparison with the case of neat polyester urethane (PEU), changed slightly (Fig. 1). However, the temperatures of the maximum rate of weight loss for the final steps of decomposition and char yield at 600°C (m_{600}) changed considerably (Fig. 2). They increased to a greater extent at loading of APP, in which, among all FRs, the content of phosphorus was the highest. MP with a lower content of phosphorus, in terms of those parameters, was inferior to APP. MEL and PER, in contrast to the phosphorus-containing FRs, accelerated the thermal decomposition process.

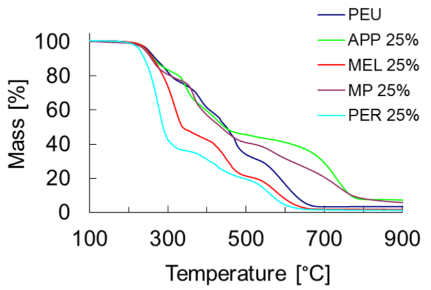

Figure 1. TG curves of neat PEU and polyurethanes with single FRs.

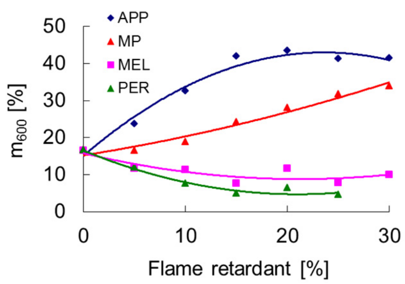

Figure 2. Char yield at 600°C for polyurethanes versus FRs' weight content.

However, at loading of MEL or PER combined with APP, due to synergism, the thermal decomposition of filled polyurethanes in APP/MEL and APP/PER retarded and the temperatures of the maximum rate of weight loss for the final steps of decomposition increased (Fig. 3). In this case, the char yield approximated the value of the char yield of polyurethane, filled with APP, and exceeded the value of the char yield of polyurethane, filled with MP (Fig. 4).

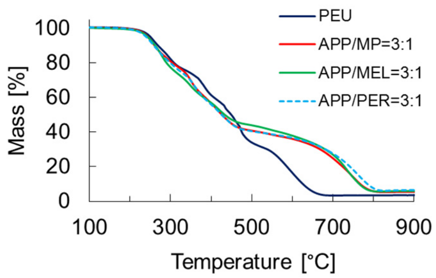

Figure 3. TG curves of neat PEU and polyurethanes with combinations of two FRs

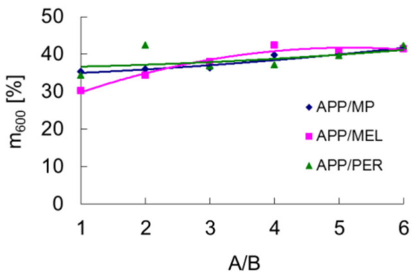

Figure 4. Char yield at 600°C for polyurethanes versus FRs' weight ratio

An analysis of all the presented data reveals that the content of phosphorus, which, in particular, was higher by the factor of 2.6 in APP than in MP, has the greatest effect on the value of the char yield of intumescent polyurethane coating systems. The summary content of nitrogen in the coating system does not have such an effect, although in MP and MEL, the content of nitrogen was 2.9 and 4.6-fold, respectively, higher than in APP.

Cone calorimeter test of wood samples with intumescent polyurethane coatings

The flammability parameters of wood samples with polyurethane coatings in the cone calorimeter test were measured in terms of time to ignition (t_{ig}), heat release rate (HRR), peak heat release rate (PHRR), total heat release (THR), mean mass loss rate (MLR) and total smoke release (TSR). Additional parameters, which characterised better the flame resistance of materials such as maximum average rate of heat emission (MARHE) and fire growth index FGI = PHRR/t_{ig} [4], were also determined.

A comparison of the behaviour of polyurethane coatings with the addition of single FRs in this test showed that, in terms of most of the mentioned indices, the efficiency of APP and MP as a FR was the same. Thus, with increasing content of both APP and MP up to 25 %, PHRR for the samples with a polyurethane coating decreased 2.3 times (Fig. 5). The decrease of the FGI of the samples with polyurethane coatings, containing 25 % MP or APP, was still greater, namely, 2.8 fold. In this case, the mentioned parameters characterised to a greater extent the behaviour of the coating itself. The parameters, characterising the behaviour of wood samples with polyurethane coatings for the full time of the test, such as MARHE and THR at loading of 25 % MP or APP, decreased much less, namely, 1.8 and 1.2 fold, respectively.

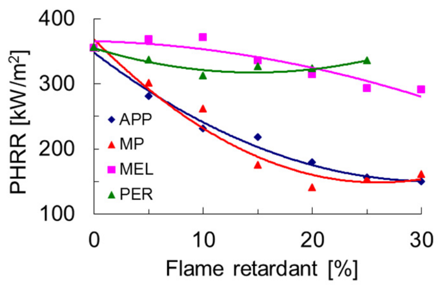

Figure 5. PHRR versus FRs' weight content for wood samples with coatings.

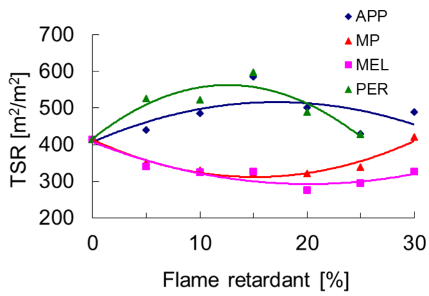

Figure 6. TSR versus FRs' weight content for wood samples with coatings.

MP, despite the much lower content of phosphorus, demonstrated the so high efficiency as a single FR owing to the much higher content of nitrogen and phosphorus-nitrogen synergism. Owing to the high content of nitrogen, in this case, MP had one clear advantage. TSR of samples with polyurethane coatings, containing additions of MP, were much lower than for the same ones with the addition of APP (Fig. 6). With increasing content of MP up to 20%, TSR of the samples decreased similarly as for the samples with polyurethane coatings, containing additions of MEL. With the further increase of the MP content, TSR of the samples with a polyurethane coating increased, probably due to the formation of MP agglomerates.

Loading combinations of APP/MEL, APP/PER and APP/MP in polyurethane, weight ratios of FRs were varied from 1:1 to 6:1. The tests of the samples with such coatings revealed that, owing to the presence of APP, most of the flammability indices with addition of APP/MEL and APP/PER were lower than the flammability indices with addition of single MEL and PER as, for example, PHRR (Fig. 7). However, in this case, the coatings with additions of APP/PER were inferior to the indices of the coatings with addition of single APP and MP. Hence, the presence of an additional char forming agent (PER) in the coating system did not give any additional effect. In the given system, the polyurethane itself acted as a char forming agent. These conclusions were testified in the tests of the coatings, containing combinations of three IFRs (APP/RER/MEL) at different weight ratios.

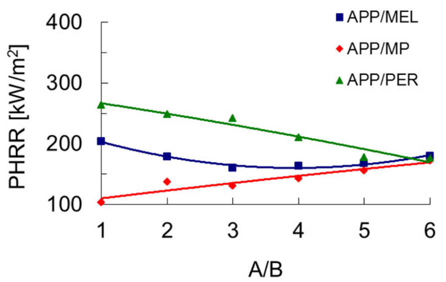

Figure 7. PHRR versus FRs' weight ratio for wood samples with coatings.

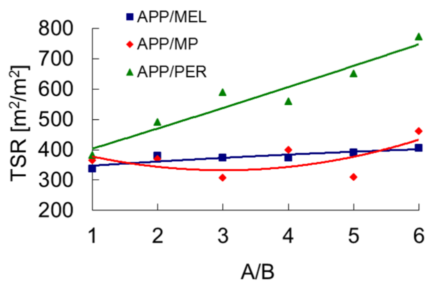

Figure 8. TSR versus FRs' weight ratio for wood samples with coatings.

The combination APP/MEL was more efficient and, at weigh ratios ≥ 3:1, in terms of a range of the indices of the coating with such an additive, approximated the indices of the coatings with addition of single APP and MP. In this case, the TSR of the coatings with the addition of APP/MEL was much lower than for the coatings with the addition of single APP (Fig. 8). Thus, on the whole, by the combination APP/MEL at definite weigh ratios, the same flammability parameters for samples with polyurethane coatings can be reached, as in the case of the samples with the addition of MP. The PHRR and THR of the samples with coatings, containing a combination of APP/MP in the range of the ratios from 1:1 to 3:1, were lower by 10-20% than the analogous parameters of the samples, containing single APP or MP.

Acknowledgments

The present study was supported by the State Research Program 4.1 "Forest and earth entrails resources: research and sustainable utilization – new products and technologies" (ResProd).

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Determination of Fire Performance of Reinforced Plywood Construction With Woven Glass Fiber

Eser SOZEN[1], Ali Naci TANKUT[2]

[1]Faculty of Forestry, Bartin University 74200, Turkey, esozen@bartin.edu.tr

[2] Faculty of Forestry, Bartin University 74200, Turkey, nacitankut@bartin.edu.tr

Keywords: Plywood, Fire performance, Woven glass fiber

Aim of this study to determine effect of woven E-glass fiber (WGF) on fire performance and bonding quality of plywood. For this reason, 1.5 mm thick beech veneers were used with urea formaldehyde (UF) glue resin which contains 64% solid content. Plywood panels with five plies and 7.2 mm thick were manufactured from both control and reinforced by woven glass fiber material. All veneers used in plywood manufacturing were used 7% moisture content before the gluing process. Approximately 170 g/m² adhesive mixture was spread on single surfaces of veneers by using roller brush. Hot press time and pressure were used 5 min and 15 kg/cm² respectively. Press temperature was 120 °C in the manufacturing of plywood panels. Plan of layers utilized in plywood board manufacturing and shear strength samples are shown below Fig. 1.

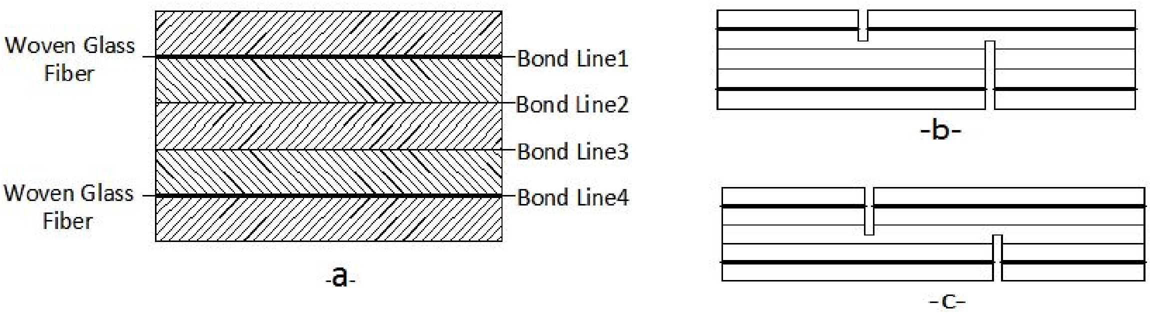

Figure 1. Plan of layers utilized in reinforced plywood board manufacturing. (a) cross section (b) shear strength sample for bond line 1 (c) shear strength sample for bond line 2

Densities of control plywood (CP) and reinforced plywood (RP) were averaged 0.68 gr/cm³ and 0.72 gr/ cm³ respectively. Fire performance tests were performed according to ASTM E69 by fire tube test. Bonding quality tests (shear strength) of plywood's were carried out TS EN 314-1. Before the shear strength tests, samples obtained from the panels were immersed for 24 hours in water at 20 ±3 °C. The results of shear strength tests were showed below (Table 1).

Table 1. Results of shear strength tests (N/mm²)

	Control Plywood (CP)[a]		Reinforced Plywood (RP)[a]	
Glue line	Air Dry	24 hours in water	Air Dry	24 hours in water
Bond line 1	2.60	2.17	2.43	2.12
Bond line 2	2.86	1.78	2.61	2.70

[a]Mean values of the results of shear strength tests are from12 replicates

In bond line 1, CP samples have showed 7% higher shear strength properties than RP samples in air dried samples. This rate for samples immersed for 24 hrs in water was determined as 5%. It has been shown that the WGF reinforcement has decreased the bonding strength of samples by 23% [1]. However, in bond line 2, RP samples have showed higher about 50% shear strength than CP samples immersed for 24 hrs in water. It can be said that WGF has prevented the transfer of water to the inner layer. In fire tests, similar curves were obtained until 3rd minute time duration which carried out surface combustion. After 3rd time duration, WGF has slowed down the combustion rate. Mass loss (Fig. 2) and temperature curves (Fig. 3) of the CP and RP were given below.

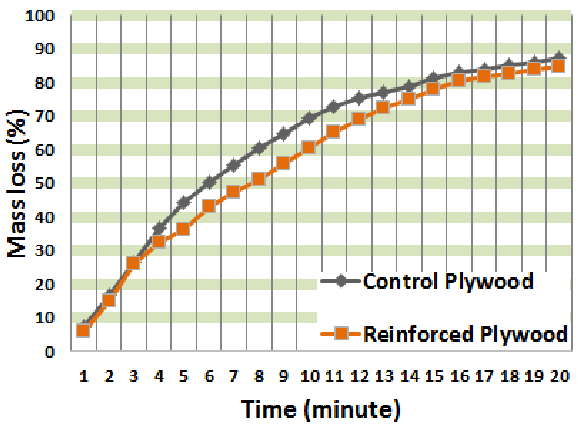

Figure 2. Mass loss curves of the CP and RP.

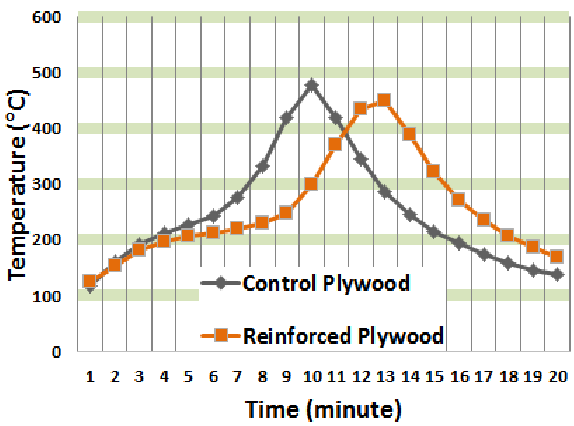

Figure 3. Temperature curves of the CP and RP.

According to Fig. 3, RP has increased in reach to maximum temperature approximately four minutes (from 10 to 14). This four minute is very important time during fire for evacuating people from inside of building. It is possible to say that WGF can be used as fire retardant such chemical compounds provided that by using stronger adhesive.

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Wood char of fire retardant coated Norway spruce (Picea abies L.)

Wilfried Beikircher[1], Hanspeter Gasser[2]

[1] University of Innsbruck – Unit forTimber Engineering, Technikerstr. 13, 6020 Innsbruck, AUSTRIA, wilfried.beikircher@uibk.ac.at

[2] University of Innsbruck – Unit for Timber Engineering, Technikerstr. 13, 6020 Innsbruck, AUSTRIA

Keywords: intumescent coatings, cone calorimeter, Norway spruce (Picea abies L.), wood char

Introduction

Fire retardants and intumescent coatings are effective in reducing different reaction to fire parameters of wood such as the ignitability, the heat release, the burning rate and the flame spread. These parameters are relevant for the classification of materials with regard to the reaction to fire behaviour according to European or international Standards. For timber constructions, especially for the refurbishment, more and more important is also to protect the material from burning and increase the fire resistance. This paper discusses the charring of Norway spruce (*Picea abies L.*) coated with transparent and pigmented intumescent coatings in comparison to uncoated wood as reference material. The tests were performed by using the cone calorimeter test according to ISO 5660 [1].

Materials and methods

One uncoated reference series and two intumescent fire protective coated test series made of defect free Norway spruce (Picea abies L.) were cutted into 100 mm by 100 mm squares with a thickness of 40 mm. For all tests three replications were performed. The underlying wood was selected in that way to have twin samples made out of three different boards (A, B and C) for generating comparable results. The samples were prepared for testing perpendicular to the grain orientation in the tangential direction.

Commercial intumescent fire retardant coatings were chosen instead of model formulations so that the effects of single chemicals and other additives are included in the fire performance results. Previous investigations on products of different manufacturers showed, that the behavior under fire load of different applied products behaves similar. The products were selected in that way, that both fulfil the reaction to fire class B according to European standard EN 13501-1 [2].

Experiments were performed according ISO-5660 the cone calorimeter test at a heat flux of 50 kW/m² and the simplified ISO 834 test curve [3] with the adapted Conical Heater from Fire Testing Technology (FTT). In this study the focus was to determine the development of charring within the substrate. The tests were performed in the horizontal orientation, with the conical radiant heater located above the specimen. The distance between the cone heater and the specimens were 2.5 cm for the uncoated reference series and 6.0 cm for the coated samples. The irradiance was adapted for the different distances.

Results

The charring depth shows clearly the protection effect of the fire protective intumescent coatings. The results in the diagrams show the average of the charring depth in the samples for the different testing time s. Figure 1 and Figure 2.

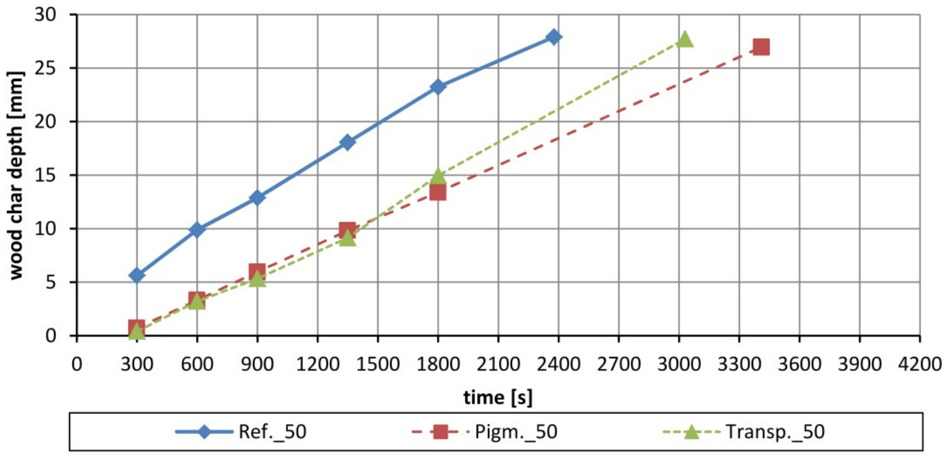

Figure 1. Wood char depth after 50 kW/m² exposure

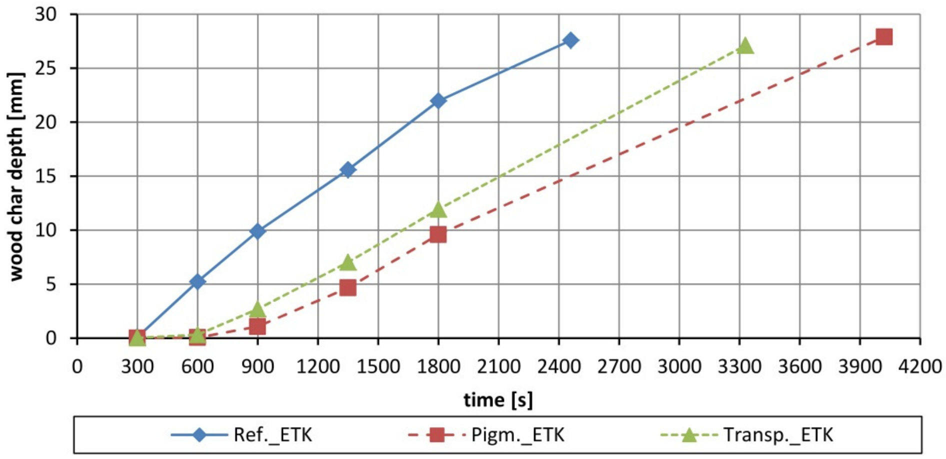

Figure 2. Wood char depth after ISO 834 test curve exposure

Conclusion

The results show, that Intumescence coatings on wood protect effective the substrate to burn in comparison to uncoated reference material. The behaviour of the tested transparent and pigmented intumescence coatings is similar. Standard products of fire protective intumescent coatings reduce the charring layer for about 10 mm by the applied irradiance of 50 kW/m² and the ISO 834 test curve exposure within the testing time of 30 min.

Acknowledgments

This work was partially supported by the "Innovative Wood Protection" project, which is funded by the Tyrolean Government and the European Regional Development Fund (ERDF).

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[2] EN 13501-1:2002, Fire classification of construction products and building elements – Part 1: Classification using test data from reaction to fire tests. Brussels: European Committee for Standardization

[3] ISO 834-1:1999, Fire-resistance tests - Elements of building construction - Part 1: General require-ments

Reaction to fire performance of cellular wood materials

Edgars Buksans[1], Janis Iejavs[2], Edgars Rudzitis[3]

[1,2,3] Forest and Wood Products Research and Development institute.

Dobeles street 41, Jelgava, Latvia, LV-3001, edgars.buksans@e-koks.lv

Keywords: Reaction to fire, cellular wood material, fire resistance.

Introduction

Light weight building systems are actual topic in building industry now. It gives possibility to decrease building costs and to improve energy efficiency of building. Cross-laminated timber (CLT) product is well known product and it has stable market in building industry. Lot of ideas of light weight panels for building industry has been developed, but only some of them has been realised in life. Some of light weight panel ideas were described by Skuratov (2010). In October of 2010 the manufacturing of the cellular wood material DendroLight® started in Latvia and this product now is available in market. The product was invented by Johann Berger (Berger 2006) and first industrial plant was built in Latvia. Cellular wood material is new product in global market and its performance in fire fundamentally is not known. The reaction to fire performance of cellular wood material is presented it this paper.

Production process of cellular wood material starts from four side calibration of sawn timber and grooving with 3 mm groves from both sides of the board (see Fig. 1a). Then these grooved boards are glued together in cross-laminated timber (see Fig. 1 b). These panels can be used in building systems and they are called as parallel orientation cellular wood material panels. Parallel orientation cellular wood panels can be cut in lamella by band saw and glued together. This is called perpendicular orientation cellular wood material panel (see Fig. 1c).

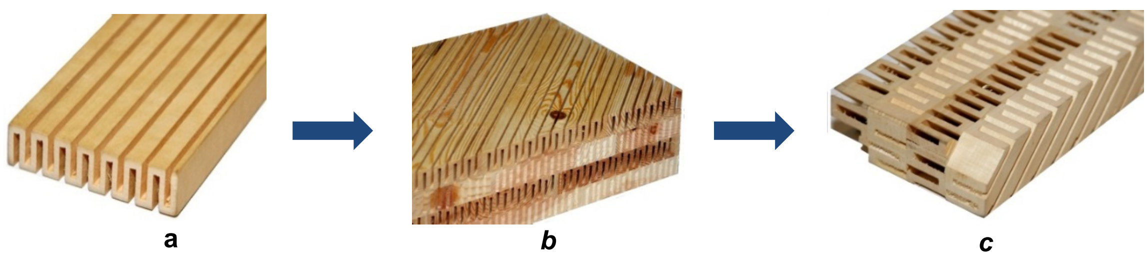

Figure. 1 Production technology of cellular wood material.(Buksans et al. ,2013)
a- grooved board; b- cross-laminated boards; c- perpendicularly cut and glued panel.

Materials and methods

The reaction to fire performance of the cellular wood material and its different compositions was investigated as well as reaction to fire and fire resistance improvement methods. Two different scale fire tests were used to evaluate reaction to fire performance of developed prototypes. Single burning item test according EN 13823 and cone calorimeter test ISO 5660-1 were used.

Fire growth rate and total heat release of burning material was analysed as well as heat release dynamics during the test. Material description and test methods used in this research are identified in Table 1. All specimens were conditioned according standard EN 13238 to reach target moisture content of wood. Five specimens from each product variation were tested in cone calorimeter method and three specimens in single burning item test.

Table 1. Material identification

Marking	Product description	Test method
Reference	Cellular wood material in perpendicular orientation without any treatment	ISO 5660-1
D+A1	Cellular wood material treatment with fire retardant TENTS, treatment done by immersion method with total consumption 95 $kg \cdot m^{-3}$	ISO 5660-1
D+A2	Cellular wood material treatment with fire retardant FAP, treatment done by immersion method with total consumption 76 $kg \cdot m^{-3}$	ISO 5660-1
D+A3	Cellular wood material treatment with fire retardant Antipirens RS, treatment done by immersion method with total consumption 85 $kg \cdot m^{-3}$	ISO 5660-1
D+A4	Cellular wood material treatment with fire retardant Unitherm AWR, treatment done by coating method with total consumption 1000 $g \cdot m^{-2}$	ISO 5660-1
D+A5	Cellular wood material cells filled with special fire retardant mastic prepared on basis of Unitherm AWR	ISO 5660-1
Spruce	Solid spruce Picea abies L. wood as reference, 25 mm thickness.	EN 13823
D	Cellular wood material parallel orientation, 55 mm (type b in Fig. 1)	EN 13823
Dp	Cellular wood material perpendicular orientation, 50 mm (type c in Fig. 1)	EN 13823
D-MDF-25	Cellular wood material with 4 mm thick medium density fibre board facing, 25 mm thickness	EN 13823
D-MDF-60	Cellular wood material with 4mm thick medium density fibre board facing, 60 mm thickness	EN 13823
D3L	Three layer cellular wood panel 100 mm with 20 mm thick spruce wood facing and cellular core 60 mm.	EN 13823
D-Mg	Cellular wood material 40 mm with 6 mm thick magnesite board facing	EN 13823

Results and discussions

Cellular wood structure has reduced density up to 40 % from solid wood density – about 300 $kg \cdot m^{-3}$. This factor changes the normal charring rate of solid wood. Small air cavities decrease fire performance of this building material due other physical factor phenomena takes part in combustion process. Additional study was done to investigate heat convection effect on burning rate of cellular wood and it was found that air channels weakly promote fire development at early stage of fire and increase several times during fire development. This effect was observed also in SBI test (Fig. 2) where the first test minutes run similar as solid wood but later starts fast fire development. Solid spruce wood developed up to 40 kW heat release rate peak at the beginning but cellular wood panel goes up to 100 kW in parallel (D) orientation and up to 400 kW in perpendicular orientation (Dp). Test of cellular wood panel was early stopped at moment of 400 kW due to safety reasons. Increasing convection effect has very important effect to fire performance of cellular wood materials. Different performance was observed for products laminated with different type of facings. Due to high dimensional stability cellular wood core was found as good solution for fire resistant doors. Cellular wood panels faced with 4 mm MDF panel showed much better performance in fire tests see Fig. 3;7;8, but it still has higher total heat release.

Figure 2. SBI test of product "D"

Figure 3. SBI test of product "D-MDF-25"

Figure 4. Intumescent fire retardant effect on cellular wood combustion "D+A5".

Different fire retardants available in local market were used for improvement of reaction to fire performance of cellular wood material. Test results are shown in Fig. 5-6. All of them showed reasonable decrease of peak heat release rate and total heat release, but the best performance for this material was achieved by intumescent type fire retardant which blocks the air cavities during combustion process and protects wood from heat transfer (Fig. 4). Usage of fire retardants for cellular wood treatment is problematic due to further need for lamination with different type facings. Gluing of panels is not possible after usage most of fire retardants.

Very good fire performance was achieved by cellular wood material combination with mineral type panels. 40 mm thick door panel with 6 mm magnesite board facing showed potential to pas 60 min requirement for fire resistant doors. Reaction to fire parameters for this combination was close to 0. If Cellular wood is laminated with solid wood boards (D3L), then panel reaction to fire performance is the same as for solid wood panel (Fig 7-8). Theoretically fire resistance will be affected by increased charring rate in cellular structure.

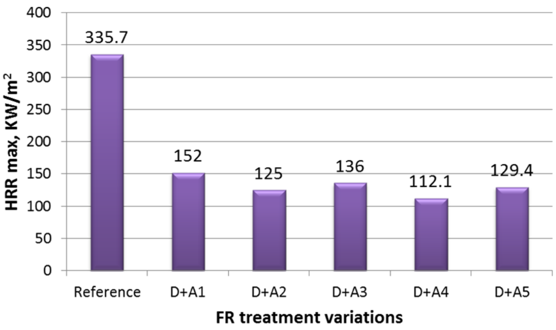

Figure 5. Peak heat release rate.

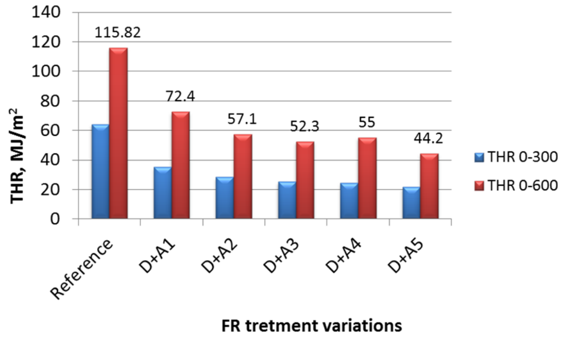

Figure 6. Total heat release in 300 s and 600 s.

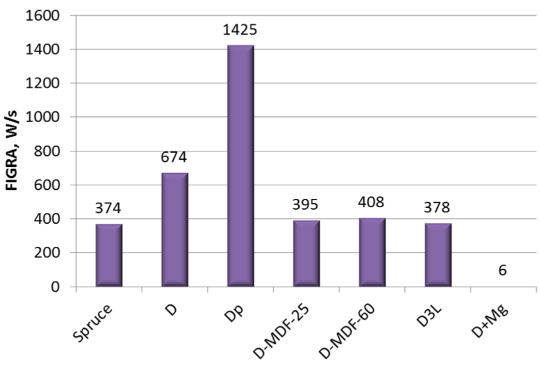

Figure 7. Fire growth rate index.

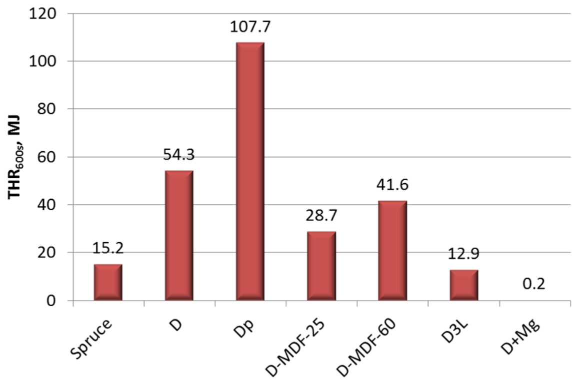

Figure 8. Total heat release in 600 s.

Conclusions

- Cellular wood material in parallel orientation shows two times larger fire growth rate index and 3.5 times larger total heat release rate comparing to solid wood but it still pass reaction to fire D class criteria.
- Cellular wood material in perpendicular orientation shows 3.8 times larger fire growth rate index and fulfil only E reaction to fire class criteria.
- Due to cellular structure it's easy to perform deep impregnation of material with fire retardants, but it can be problematic for further technological operations like gluing.

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Fire-Induced Delamination of Cross-Laminated Timber

Alastair Bartlett[1], Kuba Gajewski[1], Rory Hadden[1], Neal Butterworth[2], Luke Bisby[1]

[1] School of Engineering, University of Edinburgh, Kings Buildings, Mayfield Road, Edinburgh, EH9 3JL, United Kingdom alastair.bartlett@ed.ac.uk

[2] Arup, Rose Wharf, 78 East Street, Leeds, LS9 8EE, United Kingdom

Keywords: delamination, extinction, flame spread, radiant heating, charring

Background

Cross-laminated timber (CLT) is an engineered timber product formed of several timber lamellae glued together with a polymer adhesive, typically such that the grain of the adjacent lamellae are perpendicular to each other. This offers key structural advantages over traditional timber materials which, coupled with aesthetic and environmental considerations, means that CLT is rapidly gaining popularity with architects, engineers, and designers. A major factor preventing widespread uptake of CLT in multi-storey buildings is uncertainty as to its performance in the event of fire. Much of the available research on engineered timber products has focussed primarily on determining effective charring rates in fire; these are well known to depend on factors such as density, moisture content, species, geometry, oxygen concentration, and heating scenario [1]. However, additional factors such as flame spread, fire dynamics, reductions in mechanical properties, and delamination during heating require detailed, quantitative consideration to enable rational, optimised, fire safe design.

Delamination

Delamination can be defined as a phenomenon in which the fire-exposed lamella(e), or part(s) thereof, detach from the main mass of timber. This may have adverse effects on the burning of the timber, since the presence of a charred timber layer is well known to protect the underlying virgin wood [2, 3]. When the charred layer falls off, the layer beneath is suddenly exposed to the fire and it has been observed that this results in faster burning and pyrolysis until the char layer has been re-established [4]. The specific causes of delamination are not yet fully understood. Thermal expansion coefficients across the grain are typically 5 to 10 times more than those along it [5], potentially inducing differential stresses at the glue-line between adjacent lamellae due to differential thermal expansion. However shrinkage due to drying will also occur [5] such that the net effect during heating to 300°C is one of shrinkage rather than expansion. Frangi et al. [4] have previously tested otherwise identical cross-laminated timber and glued-laminated timber (in which the grain structure of adjacent lamellae were parallel) specimens and observed no significant differences in delamination behaviour between the two lay-ups. They did note, however, that specimens manufactured using a polyurethane (PU) adhesive were vulnerable to delamination when the char front reached the glue-line, whereas specimens bonded with a melamine urea formaldehyde (MUF) adhesive were did not delaminate. However due to a lack of additional data, the reason for this, as well as to which testing setups, geometries, and heating rates this conclusion may be applicable, remain unknown.

Experimental Setups

Two sets of independent experiments were undertaken to interrogate the delamination process in CLT. The first setup was a modified BS 476-7 test [6], shown in Fig. 1 to examine flame spread behaviour along combustible surfaces. The sample was setup at an angle of 25° to the radiant panel array, achieving an external heat flux varying from 35kW/m^2 at the leading end to around 2kW/m^2 at the trailing end. Thirty eight type K thermocouples were embedded in the sample at regular intervals up to a maximum depth of 36 mm and at various positions along the flame spread axis to examine temperature profiles at arrival of the flame front as well as flaming extinction. Samples were 885mm long, 270mm high, and 220mm thick, consisting of 7 lamellae of thicknesses 20mm, 40mm, 30mm, 40mm, 30mm, 40mm, and 20mm, and bonded with a polyurethane (PU) adhesive. The front two and back two lamellae were parallel rather than perpendicular to each other.

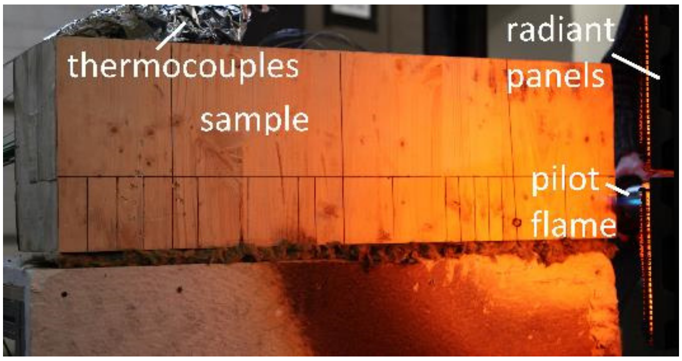

Figure 1. Flame spread test setup

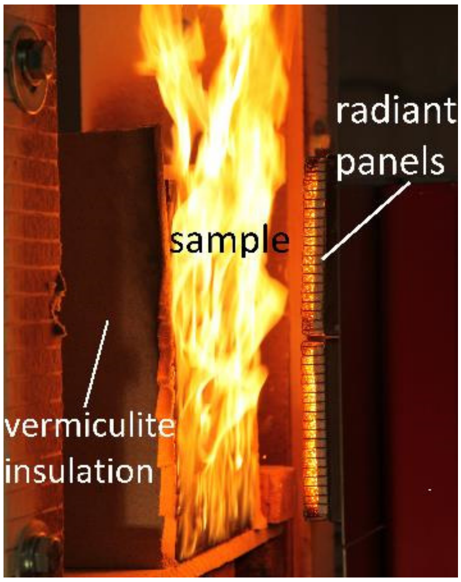

Figure 2. Constant HF test setup

The second setup, shown in Fig. 2, consisted of a smaller sample, set opposite an array of radiant panels and subjected to a constant incident heat flux (HF) of 100kW/m^2. Twenty eight Type K thermocouples were embedded in the samples to record temperature profiles, allowing estimation of the charring rates and the temperature at the glue line when delamination occurred. The samples in this case were 300mm wide, 400mm high, and 100mm thick, and consisted of three uniform lamellae bonded with a melamine formaldehyde (MF) adhesive. Samples were wrapped in foil and protected with vermiculite insulation on their sides so as to reduce heat losses through the sides and to promote one-dimensional heat transfer within the samples. Because the two setups used both different adhesives and lay-ups, quantitative analysis is limited however detailed qualitative comparisons between the two cases were still possible.

Experimental Observations

Causes of Delamination

In all tests, and in agreement with observations from previous researchers, it was observed that delamination occurred not by entire lamellae falling off at once, but rather by small pieces of charred timber, generally 2 to 5 centimetres in length, actively detaching from the lamella below. A representative sample of these pieces from a constant HF test is shown in Fig. 3.

Figure 3. Delaminated pieces from H-TRIS test H3-100-1

Figure 4. Extent of flaming prior to delamination in flame spread test, 235s into test

Figure 5. Flaming between lamellae in flame spread test, 2380s into test

In the flame spread tests, in addition to the “minor delamination” discussed above, “major delamination” was also observed, which commenced by visible movement of the front lamella away from the second lamella. This occurred without complete detachment of the front lamella, since, due to the variable heat flux, char thicknesses along the sample varied; i.e. further down the sample the two lamellae remained bonded. This typically occurred around 30 to 40 minutes into the test, by which point the char layer had limited the pyrolysis rate such that flaming was reduced, as shown in Fig. 4. The newly exposed second lamella, receiving heat from the detached first lamella then began to pyrolyse. The pyrolysis gases were ignited by the small flames established on the timber, and the flaming then proceeded between the two lamellae, as shown in Fig. 5, until a large piece of the detaching lamella fell off and flaming reduced considerably due to the elimination of cross-radiation between the lamellae. This confirms that delamination can occur for parallel as well as perpendicular lamellae. Within two to four minutes of the first visible movement of the front lamella, increases in temperature of several hundred degrees were observed behind the glue-line.

In the uniform HF tests, three thermocouples were placed (notionally) at the first glue-line. The first delaminations typically occurred after about 20 to 25 minutes, at which point the glue line temperature was in the range of 90 to 120°C – i.e. significantly before the char front had reached the glue-line. Furthermore, more 'explosive' delamination occurred later in the tests.

Effects of Delamination

For two of the flame spread tests, the heat release rate was recorded through oxygen consumption calorimetry. An increase in heat release rate of about 5kW was observed at the onset of "major delamination". This was not due to the burning of the delaminated layer itself, but rather due to the burning of the newly exposed underlying lamella. The potential consequences of this additional heat release should not be ignored with respect to compartment fire dynamics in CLT buildings where the CLT is partially or totally exposed. Additionally, in the constant HF tests rapid increases in charring rates, to around 2mm/min, were observed upon delamination, due again to the increased pyrolysis as virgin timber was exposed to the high heat flux.

Conclusions and Further Work

This work has shown initial steps for identifying the conditions under which delamination of CLT will occur. It has been shown that delamination may occur for both formaldehyde and polyurethane based adhesives, however no general conclusions can be drawn regarding the underlying physical/controlling mechanisms. Future work will concentrate on identifying the conditions and mechanisms that may control the delamination processes, through detailed experimental studies under a range of conditions. To quantify the effects of the adhesives, samples will be tested under identical fire exposure conditions to determine key reactions, phase changes, and how and when losses in adhesion and/or shear strength occur.

Acknowledgments

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Development of new fire retardant varnish for improving the fire reaction classification of wood derivatives by cone calorimeter and SBI validation.

Aitor Barrio[1], Paco Santos[2], Javier Torre[2], Izaskun Garmendia[1], Idoia Etxeberria[1]

[1]Area Anardi 5, 20730 Azpeitia, SPAIN; TECNALIA R&I, aitor.barrio@tecnalia.com

[2]Ctra. de Tolosa, s/nº Apartado 30 – 20730 Azpeitia, SPAIN; IRURENA group.

Keywords: varnish, cone calorimeter, SBI, fire retardancy, wood

IRURENA GROUP and TECNALIA R&I, under the frame of SUGABER project have developed a new transparent varnish for the treatment of wood substrates capable of improving the classification of reaction to fire of an untreated wood substrate (D-s2,d0) to reach B-s2,d0 euroclass classification [1].

The main objective of the project was the development of a clear varnish that improves the reaction to fire classification according to Euroclasses (EN 13501-1: 2007) of a lignocellulosic substrate. As specified by this standard (part 6.3), coating products can be applied on any substrate but their classification and scope is linked to that substrate and the specific application is limited. The method used by the majority of the companies for classifying the coatings as B-s2, d0 is directly using a substrate already classified as B-s2,d0. The possibility of using a standardized substrate (UNE-EN 13238: 2011) increases the field of application to any cellulosic materials. The classification given by these standard substrates would apply to all wood products collected by this substrate. Hence, a coating applied to a D-s2,d0 substrate that reach a better classification is a “true” fire retardant coating.

Method:

For the development of the coatings, a bench scale approach was carried out and different formulations of coatings were studied changing the fire retardancy system (FR) and the substrates (hardboard, fibreboard and plywood). Due to the number of formulations and the range of variables, a first screening was carried out in cone calorimeter and only the best formulations were tested according to SBI test. After an extensive study that evaluated different aspects such as the influence of the substrate, different reagents, a wide range of flame retardants, use of primers, finishes, etc. three candidates were selected for testing in SBI. In this paper, the results of the final formulations are included (Table 1):

Table 1. Formulations selected for SBI test

Specimen	Substrate	Solvent	System
Ref	Hardboard	-	-
P1[a]	Plywood (poplar)	PUR	Primer+Coating+Topcoat
P2 [a]	Hardboard	PUR	Coating
P3 [a]	Hardboard	Aqua	Coating+Topcoat

[a] *Formulations based on two components acrylic-aliphatic polyurethane.*

Substrate:

Hardboard was the best substrate reaching the lower values of heat release rate (HRR) of all the substrates (Plywood, hardboard and fibreboard). However, for the use of fire retardant primer systems, plywood was used due to the best permeability of the system.

Solvent:

The developments were carried out in parallel in solvent and water based.

Systems:

After the development of the fire retardant system (phosphorus based FR), different finishes were evaluated. The application of a fire retardant primer and the protection of the fire retardant system by a topcoat were evaluated. These formulations were tested in cone calorimeter and SBI for comparison.

Results:

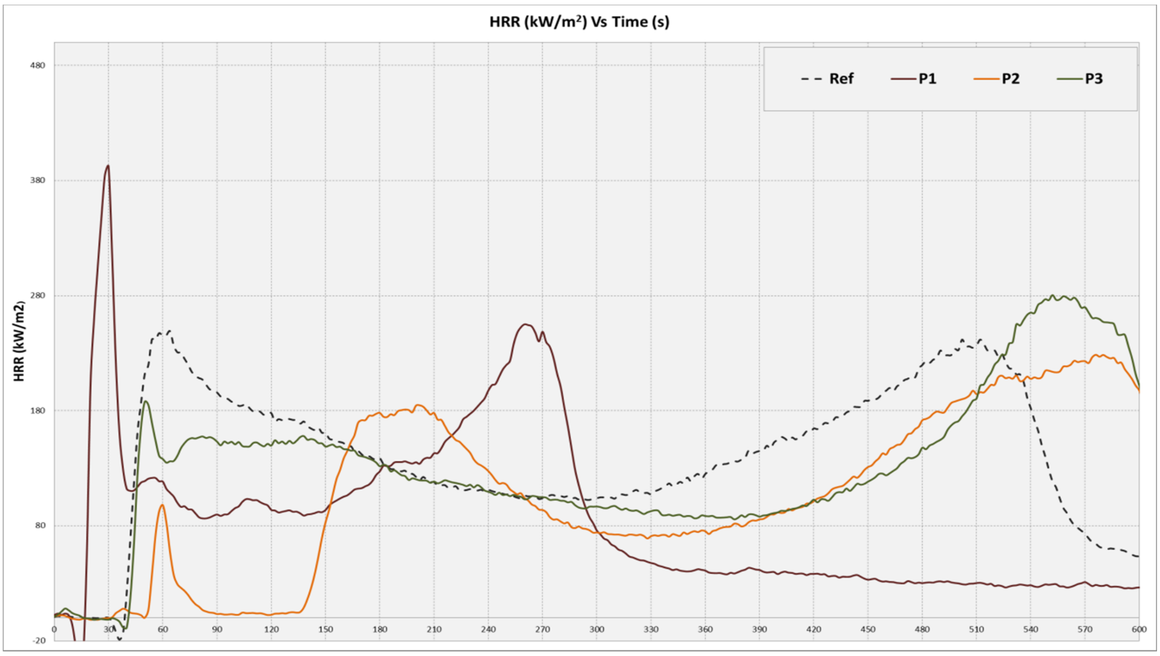

Figure 1. Cone calorimeter HRR curves of the prototypes.

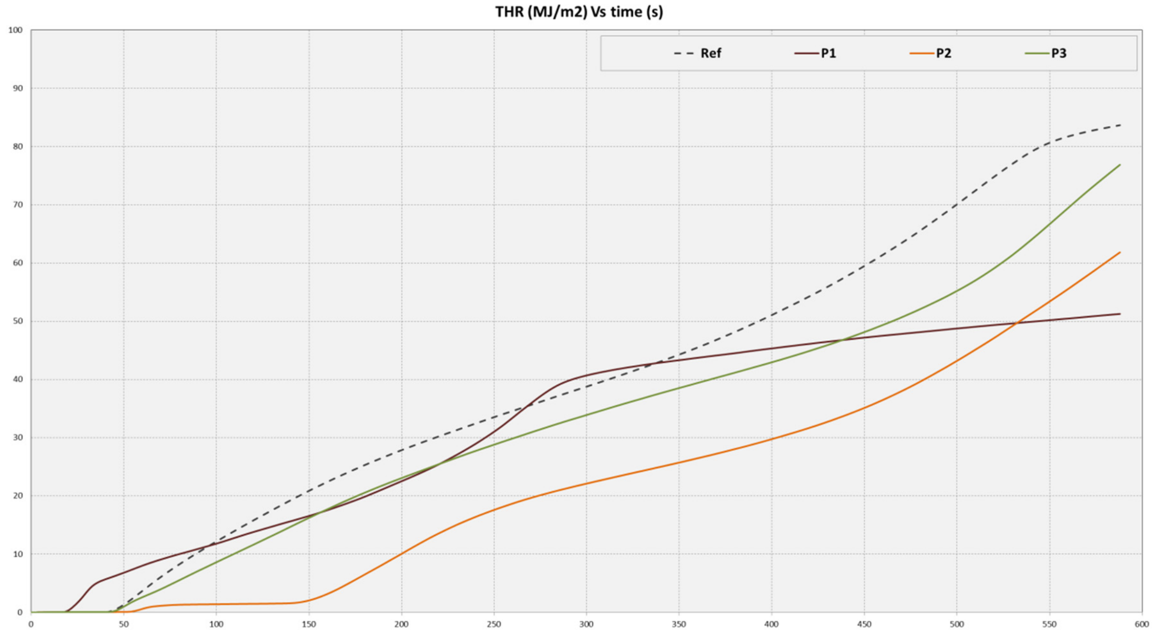

Figure 2. Cone calorimeter ARHE curves of the prototypes.

As it can be observed, P1 released a significant amount of heat at the beginning of the test so it is expected to obtain a bad classification in SBI. The water based system (P3) showed a similar behaviour than the reference material, slightly improving the HRR values. P2 showed a very good result forming a protective layer that extinguished the flame reducing the heat emitted by the substrate.

The same samples were tested in SBI to corroborate the results obtained in cone calorimeter.

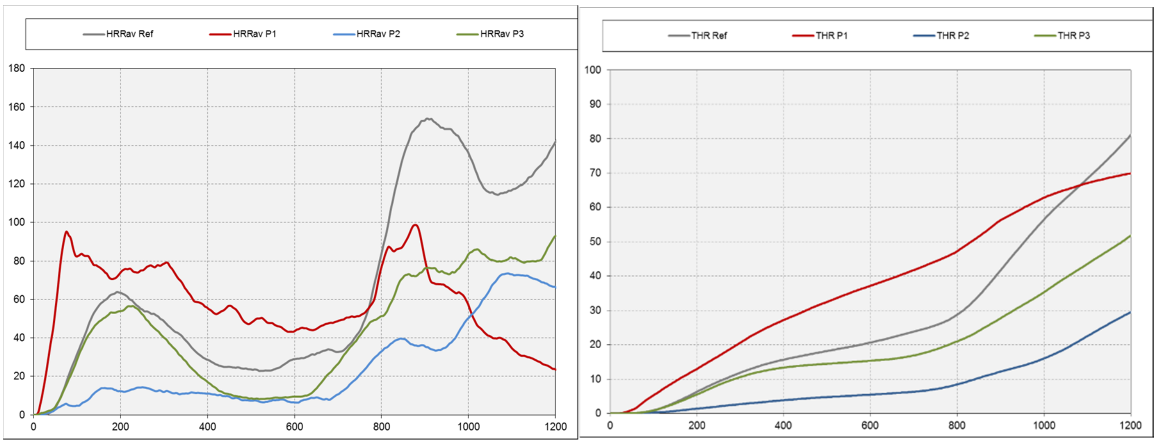

Figure 2. SBI HRR and THR curves of the prototypes.

The samples showed similar behaviour than obeserved in cone calorimeter and the prediction of the classiffications matched perfectly with the final results. The following graph shows the summary of the classification parameters (FIGRA and THR) of the SBI tests.

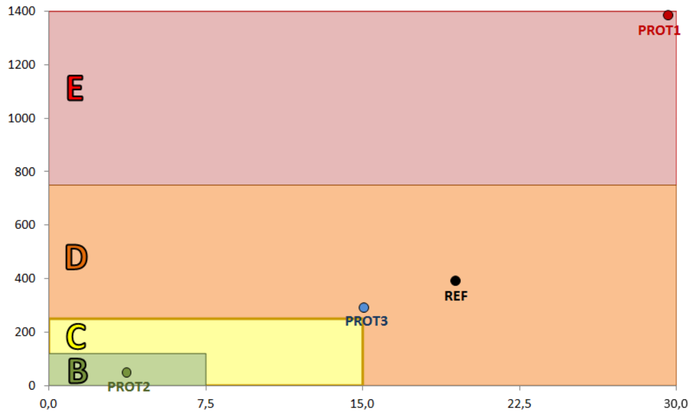

Figure 3. SBI classification of the prototypes.

Therefore varnish developed (P2), under the conditions described, improved fire reaction classification of a lignocellulosic standard substrate (hardboard) from D-s2, d0 to B-s2, d0.

CONCLUSIONS:

A new fire retardant varnish has been developed for improving the fire reaction properties of untreated lignocellulosic substrates to B-s2, d0.

The development has been carried out at bench scale level in cone calorimeter and validated by SBI test for the best fire reaction candidates.

Acknowledgments

The authors acknowledge Gobierno Vasco (Gaitek program 2012-2014) for financial support.

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Combustion Performance of treated wood by tannin-based formulation advanced with montmorillonite

Jin-Bo HU[1, 2], Gianluca TONDI[3], Marie-France THEVENON[1]

[1] TA/B 114/16, 73 Rue Jean-François Breton, 34398 Montpellier Cedex 5, Research Unit BIOWooEB, CIRAD, France, hjb1999@hotmail.com

[2] Shaoshan South Road, No. 498, Changsha, Hunan, 410004, College of Material Science and Engineering, Central South University of Forestry and Technology, China

[3] Marktstraße 136a, Kuchl, 5431, Forest Product Technology & Timber Construction Department, Salzburg University of Applied Sciences, Austria

Keywords: Wood modification; Tannin-boron; Montmorillonite; Combustion

The combination between tannins and boric acid was and still is a very interesting solution in wood protection. The very low amount of boron and its limited leaching renders these formulations in compliance with EU restrictions [1] while maintaining its biological resistances and its fire-proof [2-3]. The properties shown promote the tannin-boron formulations as one of the most environmentally friendly wood protection systems.

Montmorillonite (MMT) which is one of expandable layered silicates has received considerable attentions to composite in recent three decades. Some studies focus on impregnating MMT into solid wood via water-soluble resin. The properties of modified timber (such as tensile strength, heat distortion temperature, fireproofing, etc.) were greatly improved with low MMT content [4-6]. The present study combines the tannin-boron formulations with the organo-MMT and it aims to investigate their fire performance using cone calorimetry tests and long-exposure tests.

Wood samples were impregnated with tannin-boron-montmorillonite formulations (10% tannin, 0.5% boric acid and 3% montmorillonite) at 8 mbar vacuum for 30 min at room temperature (treated wood abbreviated WTNC). Then treated samples were left in solution for 24 hours and put in an oven at 103 °C for at least 12 hours in order to allow the polymerization of tannin resin.

The Scots pine and beech specimens of dimensions 100×100×10 mm^3 (L, T, R) were performed the combustion properties in a cone calorimeter at an external heat flux of 50kW/m^2.

The cubic samples of Scots pine and beech (25×25×25 mm^3) were exposed to direct flame in a simply lab-made instrument. The mass loss of the sample was registered every 30 seconds until completing wood combustion.

The fire behavior observed with the cone calorimeter was summarized in Table 1. The peak heat release rate (PHRR) and total heat release of beech WTNC was lowest among all testing formulations. However, these improvements were not shown with pine WTNC. The addition of complexes of tannin-hexamine-boron and OMMT had effectively increased the time to ignition (TTI) and time to flame out (TTF) of beech WTNC in contrast to only tannin-hexamine-boron formulation. For pine WTNC, TTI had been prolonged by the nanoclay and tannin resin, which could not be increased TTF. TSR value of treated pine was reduced compared with that of control, but it is contrary that TSR of control beech was suppressed instead of an increment TSR of treated beech. Compared with control samples, the treated pine and beech wood showed little effect on CO and CO_2 production level. These resultants of wood combustion possibly were connected with the homogeneously dispersed or even intercalated/exfoliated clay structure in the WTNC.

Table 1 Data recorded in cone calorimeter experiments

Samples	PHRR (kW/m^2)	THR (MJ/m^2)	TSR_{whole} (m^2/m^2)	SEA_{peak} (m^2/kg)	TTI (s)	TTF (s)	CO_{peak} (kg/kg)	$CO_{2,peak}$ (kg/kg)
Pine WTNC	366.8	61.6	239.2	230.1	34	410	0.3612	4.79
Tannin-boron treated pine	493.5	68.9	355.3	345.2	26	384	0.2608	4.69
Pine control	321.1	60.1	366.4	381.7	22	424	0.5801	9.95
Beech WTNC	517.2	75.3	247.7	149.2	36	460	0.1819	3.37
Tannin-boron treated beech	635.4	78.1	221.4	134.5	34	452	0.1952	7.62
Beech control	717.3	82.5	167.8	113.0	31	444	0.9607	10.35

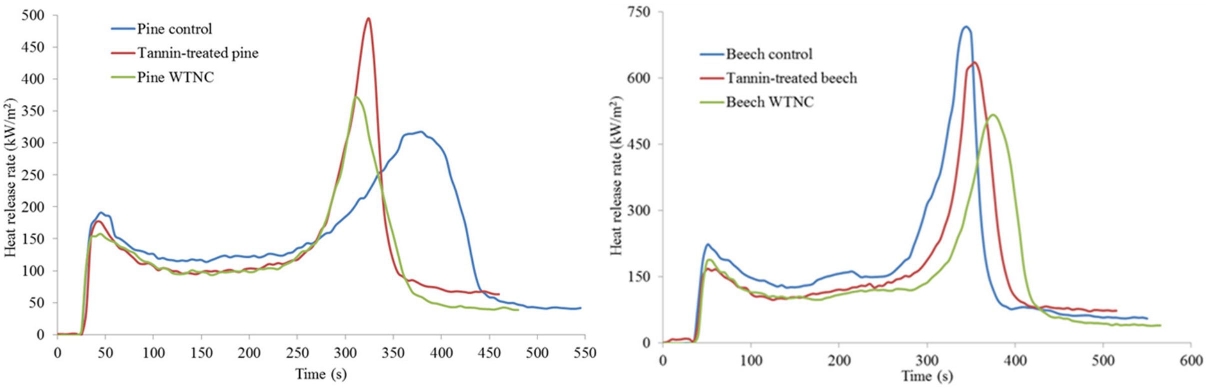

Figure 1 Heat release rate history of pine (a) and beech (b) WTNC

Average heat release rate (HRR) during WTNC combustion was arranged in Fig. 1, which was computed over a fixed around 10-min period. The HRR curve indicated that treated pine WTNC presented better combustion behaviour than control, but beech wood conducted the treatment decreased HRR than control. Possibly the better dispersal of OMMT in beech wood resulted in this phenomena, because of the barrier for heat created by OMMT [7]. In the cone calorimeter measurements of wood at the beginning of burning showed a sharp peak. As the burning proceeds and a char layer were formed on the surface of wood, the HRR value decreases. The increasing uptake of tannin and OMMT had an influence on lowering the first HRR. Both the middle range of the HRR curve as well as the second peak decreased in intensity with increasing tannin and OMMT in beech wood. However, the middle HRR figure of pine WTNC was placed below that of control and was nearly same trend with that of tannin-treated wood; as unexpected, especially the second peaks HRR of treated pine wood were higher than control. These results suggested that the treated formulations as improving flame retardant had an effect to beech wood only.

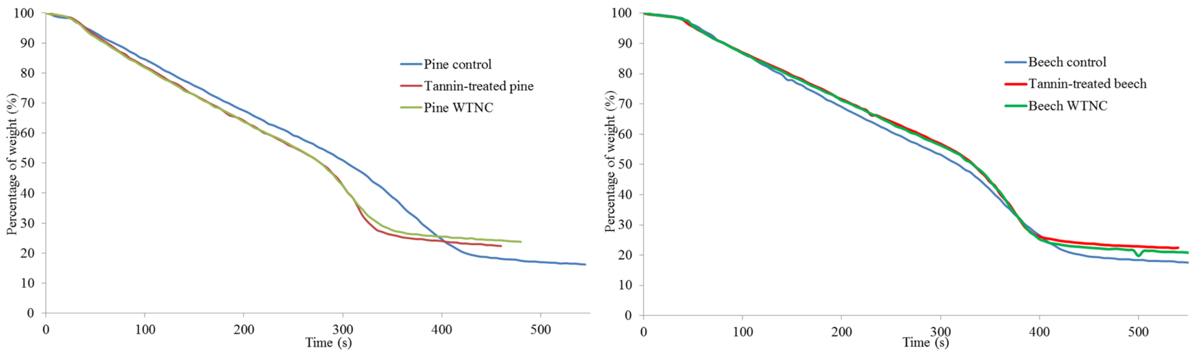

Figure 2 Mass loss of samples (Pine-left, Beech-right) in the cone calorimeter

Fig. 2 showed the mass loss curve for the samples during combustion in the cone calorimeter at 50 kW/m^2. The weight decreasing trend of sample during the combustion followed with a well-defined slope of the curve. To pine wood, the residual weight of control always remained more than the treated samples, which presented a little difference between two protected formulations. To beech wood, mass loss rate of treated samples seemly indicated a better fireproofing effect than control, but there was nearly no difference between two treated formulations.

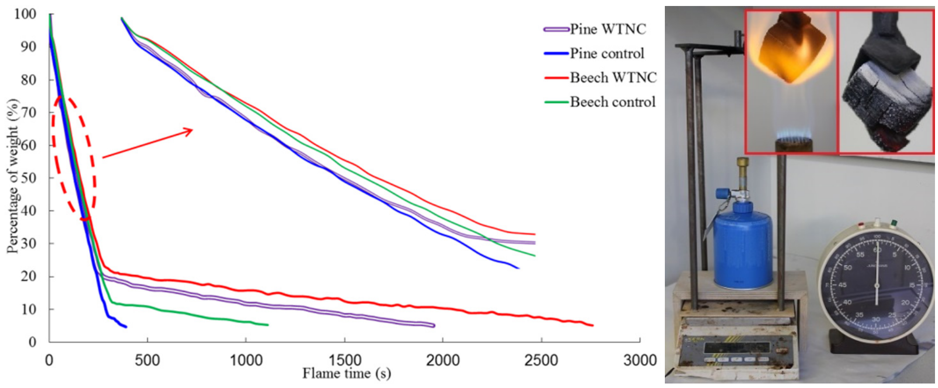

Figure 3 Mass loss of samples for long-fire exposure in a simply lab-scale tested apparatus

Longer-fire exposure in a simply lab-made apparatus also presented a little sensible effect on treated wood. The mass loss for wood samples is shown in Fig. 3. The constant monitoring of these long-term exposure tests produced curves with the same tendency. From the start up to 80% weight loss, the difference between treated and control samples were barely noticeable. The slope of curve for pine WTNC was nearly same prior to that of the relative control sample; but that of beech WTNC was slightly mitigatory with comparison to one of the relative control sample. After 80% weight loss of the samples, the flame time was always longer for the treated samples. Furthermore, even if this shift happened when the weight loss was already substantial (around 80%), it still allowed the sample to resist the burning process for at least twice the time required to complete the burning. At the end of combustion experiment, it was to be expected that formulations with amount of inorganic additives resulted in greater residue values.

From the analysis of the combustion parameters discussed in this study, which give an overview on burning behaviour of WTNC, we can conclude that the presence of nanoclay in treated wood can affect wood degradation pathway, resulting in more or less improved fire retardancy properties (it depended on wood species). Whereas treated pine showed a higher flame spread with respect to control, beech WTNC appeared to be an effective fire retardant, resulting in lower HRR. The behaviour was probably due to different distribution of nanoclay in hardwood and softwood, promoting inorganic shell-like to hinder the combustion.

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Fire behaviour of a plaster base plate with the basic material "moulded fibre"

Josef Kögl[1], Anton Kraler[2]

[1]Technikerstraße 13, 6020 Innsbruck, Innsbruck University, Austria, josef.koegl@uibk.ac.at

[2]Technikerstraße 13, 6020 Innsbruck, Innsbruck University, Austria, anton.kraler@uibk.ac.at

Keywords: plaster base plate, moulded fibre, cross laminated timber, clay, facing shell

Introduction

The research objective of this project was to develop a plaster base plate especially for the solid timber technology with moulded fibre as the basic material. Recycled natural fibres are the basic material for the moulded fibre. They originate to almost 100% from the recycling cycle of paper and cardboard. Paper and cardboard are dissolved in their single fibres to produce a liquid fibre pulp. Without adding any binders or other chemicals and with the help of forms (templates) the fibre mouldings can be produced out of the fibre pulp. The moulded fibre should be used as a plaster base system for silt, lime and clay plastering. In addition to the static requirements of the base material the sound and fire protection are of utmost importance for an unproblematic usage. The complex appearing form of the plaster base plate arose from the requirements in the sound protection (cavity damping – apply plaster only on one side) and also from the additional use as a wall heating support system. Only preliminary examinations on the fire behaviour of the moulded fibre plates are published in this paper.

Materials

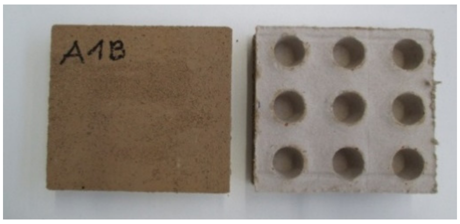
Four different test series are investigated, see Table 1. In test series A und B the clay is applied at one side, in test series C und D the clay is applied at both sides.

Series A und B can be distinguished by the way the spruce board is applied. In series A the board is applied with a PU-adhesive, in series B the board is applied with screws. Series C and D can be distinguished equally.

The specimens dimensions are 100 x 100 x 40 mm. Thereby the thickness of the moulded fibre board is 25 mm with a 15 mm thick Norway spruce board applied.

The test specimens are stored at 20°C and 60% relative humidity for at least three weeks to reach equilibrium moisture content (EMC).

Table 1. Test materials

Test nomenclature	Figure: Front- and Backside
<u>Test specimen: A and B:</u> (two different base plates) Structure: moulded fibre with clay applied at one side. Overall depth: approx. 25-26 mm	 *Figure 1. Test specimen A and B*
<u>Test specimen: C and D:</u> (two different base plates) Structure: moulded fibre with clay applied at two sides. Overall depth: approx. 20 mm	 *Figure 2. Test specimen C and D*

Methods

The fire tests are performed using a cone calorimeter (pre- and post-test procedure according to ISO 5660-1). Three replications are conducted of each of the four test series. This results in an overall test scope of 15 tests.

Before testing the specimen were wrapped into aluminium foil to approximate real scale moisture transport behaviour. After applying the thermocouples, the specimen is placed in a sample holder. The sample holder consists of a cover frame on the top, to protect the sides and edges of the specimen of combustion, and a bottom frame, which positions the sample holder on the balance. The bottom of the specimen is thermally insulated. The top of the specimen is located 25 mm under the bottom of the conical heater in the horizontal position.

The net heat flux exposure is set to 50 kW/m², during a test duration of 30 minutes.

Results

The presented results are the mass loss rate (*MLR*), the heat release rate (*HRR*), the maximum of heat release rate (HRR_{max}) and the total heat release (*THR*).

In Fig. 3 the *MLR* can be seen. The highest *MLR* can be observed for series D at the first 60 seconds of thermal exposure. In Fig. 4 the *MLR* is averaged over time intervals of 10, 20, 60, 90, 120 and 300 seconds for better illustration. A coincide of the test series after about 600 s can be recognized.

In Fig. 5 and Fig. 6 the *HRR* can be seen. Test series A exhibit the highest *HRR* over the entire test. Series C and D exhibit the lowest *HRR* with a very well coincidence too. The steady state *HRR* can be observed at about 30 kW/m² for test series A and at about 15 kW/m² for test series C and D.

The maximum of heat release rate HRR_{max} can be seen in Fig. 7. Test series A exhibit with 40 kW/m² more than twice energy release than series C and D.

The *THR* exhibit approximately a twice energy release for test series A in comparison to test series C and D, see Fig. 8.

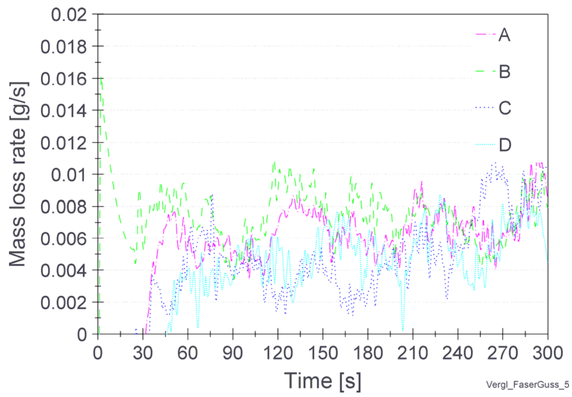


Figure 3. MLR for the first 300 seconds.

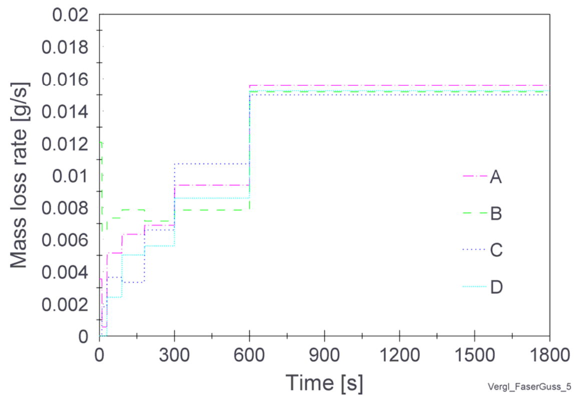


Figure 4. Averaged MLR over the entire test.

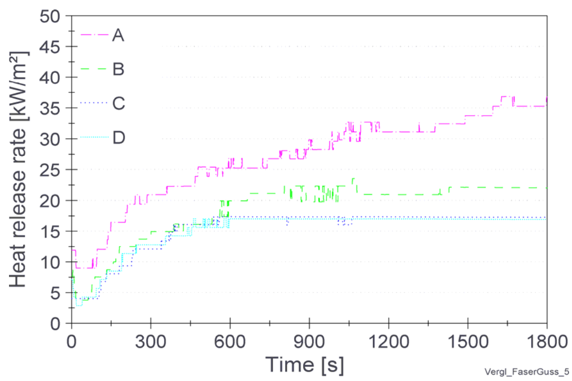


Figure 5. HRR over the entire test.

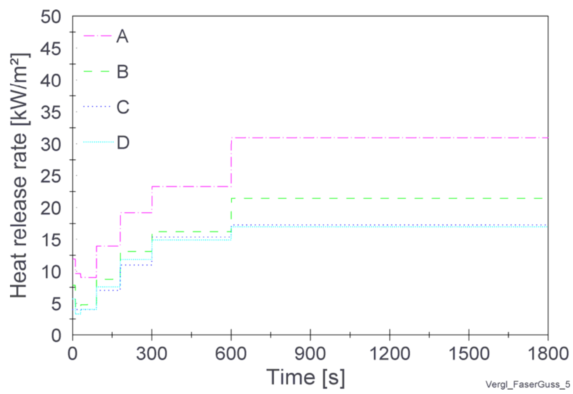


Figure 6. Averaged HRR over the entire test.

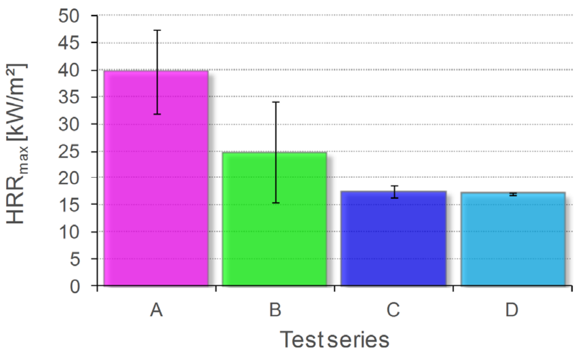


Figure 7. HRR_{max} over the entire test.

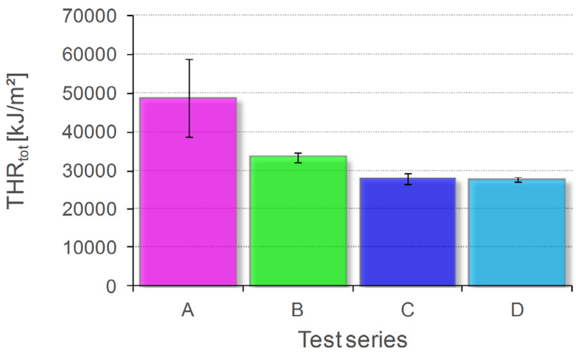


Figure 8. THR over the entire test.

Conclusions

After applying the thermal exposure different *MLRs* can be observed between the test series. Hence a different drying behaviour can be concluded. However after about 600 s the *MLR* coincide in the steady state level of approx. 0,015 g/s. A comparison with unprotected wood (spruce) – with a *MLR* of approx. 0,05 g/s - indicate a protective effect of the moulded fibre boards.

The *HRR*, the HRR_{max} and the *THR* differ about 50% between the test series. Generally the *HRR* and the *THR* (or fire load), are believed to have the greatest influence on the fire hazard. Furthermore Schartel [1] denoted HRR_{max} to be one of the most important fire hazards.

Taking this into account, the moulded fibre plates with clay applied at only one side (series A and B) exhibits inferior fire behaviour than test series C and D. This can be concluded by lower heat capacity (results from lower mass) and energy convection which can occur in the hollow spaces of test series A and B.

However a comparison with unprotected wood indicates a protective effect for both test series. The steady state levels of *HRR* of the moulded fibre plates deviates between 20 and 40 kW/m². Unprotected wood exhibit steady state levels of *HRR* at about 80 kW/m².

As mentioned in section Materials, the difference between series A and B or respectively series C and D are the screws that fix the moulded fibre plate on the subjacent wood. Even though a possible energy entrainment along the screw, no increased charring can be observed around the screws, see Fig. 10. On the contrary the screws prevent chipping or spalling of the clay from the moulded fibre.

Summarised series D - with clay applied at both sides and screws that fix the plaster base plate well on the subjacent wood - can be constituted as the most effective variant regarding to fire protection.

Figure 9. Test series A after test.

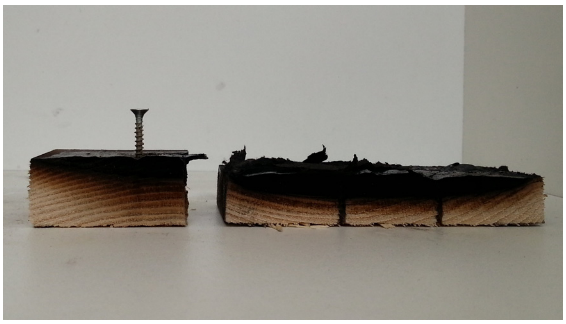


Figure 10. Cross-section through the screw-holes*.*

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Fire retardant wood polymer composites: preparation, flammability, mechanical Properties

De-Yi Wang*, Ehsan Naderi Kalali, Jeremy Croyal

IMDEA Materials Institute, C/Eric Kandel, 2, 28906 Getafe, Madrid, Spain

*Corresponding Author: De-Yi Wang; E-mail: deyi.wang@imdea.org

Keywords: Wood polymer composites; Fire Retardant; Flammability; Mechanical Properties

Wood polymer composites (WPCs) have received considerable interests in terms of their industrial applications due to environmental and economical concerns [1–3]. The advantages of natural fibers are high specific strength, light weight, low cost, absence of toxic byproducts and biodegradability. Among various polymer matrices, polypropylene (PP) has been widely used to produce WPCs because of its low density, high water resistance, low cost, ease of processing and chemical resistance. Maleic anhydride grafted polypropylene (MAPP) is used as an effective compatibilizer for wood powder/PP composites to enhance the interfacial adhesion between hydrophilic natural fiber and hydrophobic PP matrix [4]. However, one of the main drawbacks of WPCs is their high flammability that restricts their applications. Flammability of WPCs can be reduced by introducing flame retardant additives into WPCs. Ammonium polyphosphate (APP) is conventionally used as a phosphorous flame retardant additive, while layered double hydroxide (LDH) is a very efficient nano-additive in improving fire retardant performance of polymers [5].

In this work, conventional flame retardant additive in combination with nanotechnology was utilized to prepare flame retardant WPCs. LDH was modified by natural based phytic acid (Ph) to facilitate the dispersion in the WPC composite, and subsequently the combination of APP and Ph modified LDH was incorporated into WPC composite. The thermal properties, fire resistancy and mechanical properties of WPC nanocomposite were investigated by thermogravimetrical analysis (TGA), vertical burning test (UL94), limiting oxygen index (LOI), cone calorimeter, tensile and bending tests. In figure 1, it was clear to show that after using APP and functional LDH, the WPC composites reached UL94 V-0 rating

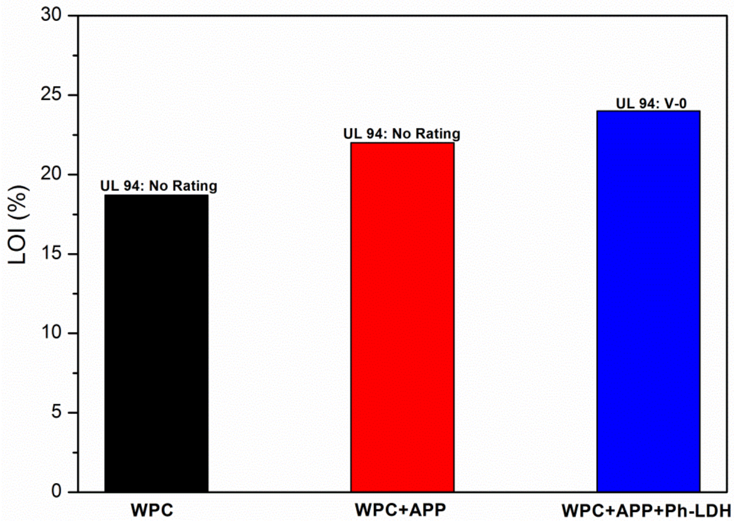

Figure 1: LOI and UL 94 results of WPC composites

In addition, the tensile test results shown in Figure 2 indicated that the addition of flame retardants improved the tensile strength as compared to the unmodified WPC.

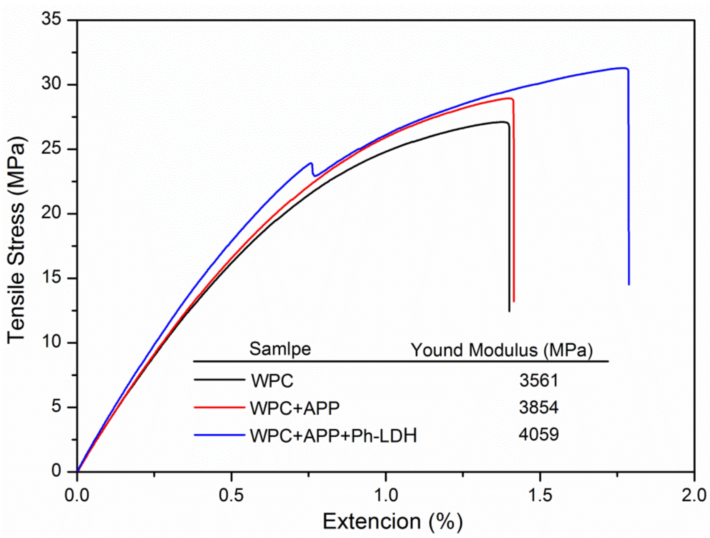

Figure 2: Tensile test results of WPC composites

In conclusion, based on this research fire retardant WPC nanocomposite exhibited a V-0 rating in UL-94vertical burning test, a high LOI value, low heat release rate, low smoke production, and high strength and stiffness. From the results, it can be concluded that intumescent char was formed by introducing the APP into the WPC composite and its synergism with Ph-LDH further consolidated the char layer that inhibited the heat and mass transfer and generated low amount of flammable organic degradation volatiles into gas phase. The methodology presented herein provides a promising approach to highly effective flame retardant WPCs for industrial application.

Acknowledgments

The authors wanted to acknowledge Ramón y Cajal grant (RYC-2012-10737).

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CFD Simulation Study on Fire Propagation in Wooden Façades and the Influence of Façade's Geometry

María P. Giraldo[1*], Ana M Lacasta.[2], Jaume Avellaneda[3]

[1] Ctra. St. Llorenç Km 2 Solsona, CTFC-Forest Sciences Centre of Catalonia INCAFUST Catalan Institute of Wood, Spain.

*Pilar.giraldo@incafust.org

[2] Av. Doctor Marañón 44 08028 Barcelona, Barcelona School of Building Construction, Universitat Politècnica de Catalunya, Spain.

[3] C/ Pere Serra 1-15 Sant cugat del Vallès. Barcelona, Spain, Architectural Buildings Department. Technical University of Catalonia (UPC).

Keywords: wooden façades, fire propagation on façades, configuration and design of façades, computational fire dynamics.

This research is part of a series of studies carried out to evaluate the influence of the façade configuration and design in fire propagation, in this case, in façades with combustible claddings.

Fire propagation through the façades is widely recognized as one of the fastest pathways of fire spreading in the buildings [1, 2]. The risk increases significantly in the case of façades with combustible claddings [3, 4] given that the heat flux intensity and speed of fire spreading may be higher. Furthermore, the fire spreads not only vertically as normally occurs, but also spreads horizontally due to the flammability of the cladding material. Thus, in terms of safety, the study of mechanisms controlling the spread of fire through the façade is an issue that needs to be addressed, especially when it involves combustible material claddings such as wood. In several European countries the building regulations restrict the use of combustible materials in façade claddings. In Spain there is no an important restriction related to the use of combustible claddings, these are allowed in buildings up to 18 m, except in public accessible areas where claddings with B-s3,d2 fire reaction class are required until 3,5 m high minimum. Nonetheless, in general, the use of wooden claddings is very low due to mistrust generated by its combustibility. The application of appropriate passive protection measures to control the spread of fire would help minimise such risks. Although wood is highly fire resistant when it is used in structural elements with large sections, it is a combustible and flammable material; therefore it has a weak fire performance when used in thin sections. Usually, the wooden façades are made up of thin boards or small elements arranged in strips, planks, tiles, etc. Therefore, the fire behaviour of a wooden cladding is mainly defined by its combustibility. The carbonization of the cladding pieces does not have a significant effect in limiting the spread of fire. Two options must be taken into account to limit the risk of fire spread through wooden façades:

- Flame retardant treatments to improve the reaction to fire performance of the cladding material, although with highly questionable durability in front of outdoor conditions.

- Construction elements capable to avoid the contact between the fire plume and combustible cladding and deflector elements with the ability to change the flames trajectory and prevent the heat flux and the incidence of the flames on the surface of façade, such as eaves or balconies. This study is focused on the second option.

In this research, computer-simulation techniques are used to study the behaviour of flames ejected through the windows on wooden façades. We study five wooden façade types which combine different configurations of windows, eaves and non-combustible elements which act as fire barriers. The results show the strong influence of geometrical configuration of the façade elements in controlling the spread of fire. They also show that is possible to use fire protective elements (non-combustible material) without altering the aesthetics of a wooden façade. The study has been performed using field models of computational fluid-dynamics. In particular, the Fire Dynamics Simulator (FDS) software has been used to numerically solve the mathematical integration models, PyroSim for the graphical interface, and Smokeview for viewing the results.

Objectives

This study aims to assess the influence of some geometric factors of the façade on the fire propagation through the façade. The main objective is to assess the level of protection provided by horizontal projection elements (eaves) and non-combustible bands. We also analyze the influence of the window size. The figure 1 and the table 1 shows the variables considered in this study.

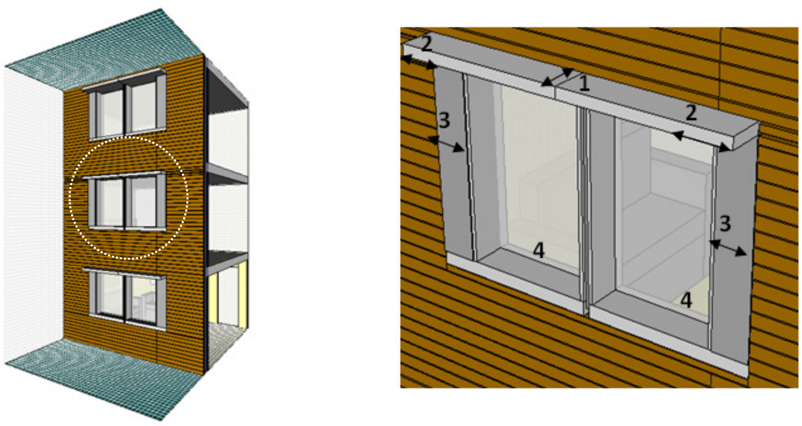

Figure 1. Geometric variables (according to table 1). Horizontal projection: (1) Depth (2) Length. Bands: (3) Width. Widows: (4) Small (1.50x1.00 m) and Large (1.50x2.10 m).

Table 1. Variables of the scenarios

Case	Horizontal projection		Bands	Windows
	Depth /Variable 1 (cm)	Length /Variable 2 (cm)	Width /Variable 3 (cm)	Size /Variable 4
1	15	-	15	Small
2	15	15	-	Small
3	30	-	-	Small
4	30	30	30	Small
5	60	-	-	Small
6	60	60	60	Small
7	30	-	-	Large
8	60	-	-	Large
9	80	-	-	Large

Nine cases are evaluated based on a common computational domain and a fire scenario. The main characteristics of the computational domain are as follows:

- The grid size is 6.50x 4.90x8.25 m.
- Each cell has a uniform size (0.10x 0.10x0.10 m). The total number of cells in each domain is 241,920.

Results

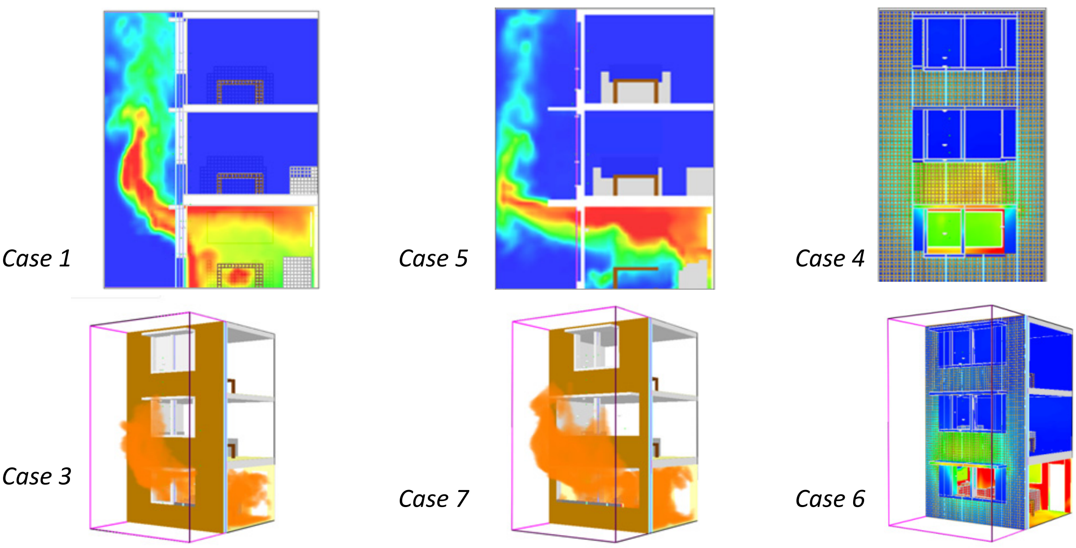

Figure 2. (top) Temperature distribution graphics (side view/front view).
(Bottom) fire plume spread diagrams and temperature distribution graphics.

The results show that the building façade geometry can greatly impact the behavior of fire and its propagation. Horizontal projections of more than 60 cm are required to deflect the trajectory and shape of the fire plume. However, projections greater than 80 cm are appropriate to reduce the heat flow on the façade surface when the risk is higher, for example, due to the size of the windows. Window size is an important issue in controlling the spread of fire through the façades. Small windows reduce the risk of propagation because the emitted heat flux is lower in comparison to large windows. Horizontal bands of 60 cm of non-combustible material located on either side of the window openings can significantly reduce the risk of horizontal fire spread, which is usually associated with combustible façade claddings.

Acknowledgments

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Factors affecting smouldering combustion of bio-based thermal insulation materials

A. M. Lacasta[1], M. Palumbo[1]*, P. Giraldo[2], L. Haurie[1]

[1] Av. Doctor Marañon 44 08028 Barcelona, Barcelona School of Building Construction, Universitat Politècnica de Catalunya, Spain.
*mariana.palumbo@upc.edu
[2] Ctra. de St. Llorenç Km 2 Solsona, INCAFUST – Catalan Institute of Wood, Spain.

Keywords: corn pith, alginate, thermal insulation, fire behaviour, smouldering combustion.

The present paper presents further results of an on-going research previously exposed in the first COST FP1404 meeting in April 2015. The research focuses on the analysis of the smouldering combustion of an innovative thermal insulation rigid board based on vegetal pith and a natural gum (corn pith and sodium alginate) which is completely compostable. This new composite was developed in previous work and presents promising hygrothermal and fire behaviour when compared to other organic foamy materials commonly used in building insulation such as polystyrene and polyurethane. However, this refers only to flaming combustion and a smouldering process is also observed, which slowly burns the specimens [1]. In the present investigation, the smouldering combustion process of this material is evaluated using an experimental set-up adapted from the one described by Hagen et al. [2] and designed to determine the velocity of propagation of the smouldering front. In these experiments, the heat source is a hot plate with controllable temperature, on top of which the specimen is placed. The behaviour of plain samples is compared to wood fibre insulation specimens and to samples incorporating different amounts of fire retardants such as boric acid (BA), aluminium hydroxide (AH) and ammonium polyphosphate (APP). The effect of the ignition source and temperature, of the density of the samples and of the different additives is analysed. The results are completed with thermogravimetric analysis (TGA) using both nitrogen and oxygen atmosphere. Previous outcomes point out that the velocity of combustion propagation greatly depends on the density of the samples, as for low density materials (corn pith and wood wool) it is higher than for high density ones (wood fibre and in rice husk). However, some materials such as rice husk show a much better behaviour: smouldering beginning at higher temperatures and propagation being 10 times slower than that of corn pith materials [3]. Such results are summarised in Fig. 1. Current results validate and complete the previous ones showing an important improvement in the smouldering behaviour of corn pith samples treated with ammonium polyphosphate (APP): the velocity of propagation is reduced by almost three times and the temperature at which smouldering begins increased in 20°C, as depicted in Table 1. Moreover, a positive coupled effect is observed in samples treated with a mixture of ammonium polyphosphate and boric acid (APPB), which combust from 30ºC higher than untreated samples, but 20ºC lower than the wood based samples used for comparison. The results are depicted in Table 1. BA stands for boric acid treated samples, AH for aluminium hydroxide and APP and APP-3 for ammonium polyphosphate. In addition to the experiments described, some specimens have been subjected to a flame instead of the action of the hot surface. In this case a quick flaming combustion is observed which, in the case of APP treated samples, allows the creation of a protective char which prevents the apparition of smouldering. The mass loss in this case is much lower than when smouldering occurs, indicating an incomplete combustion of the samples.

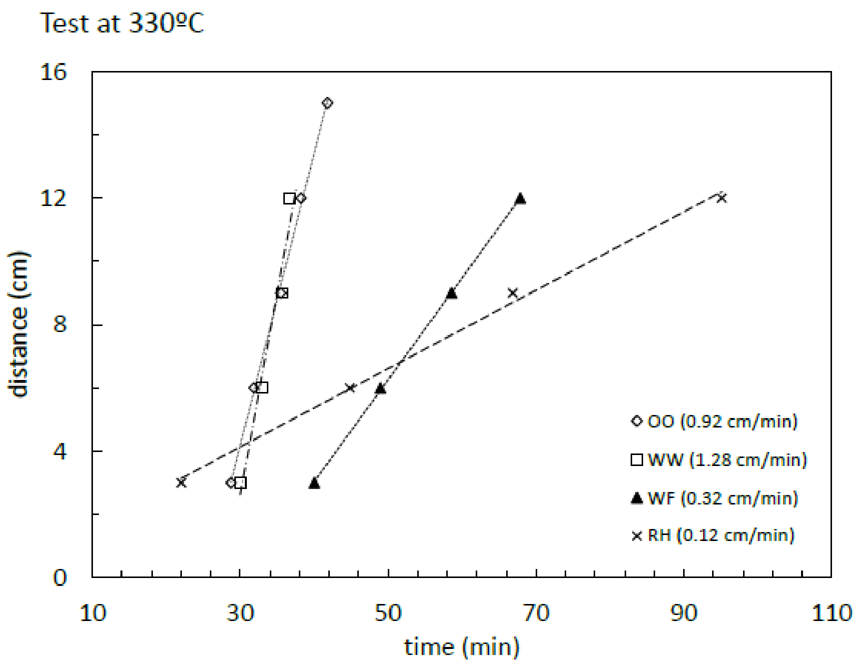

Figure 2. Thermocouple position versus time at which temperature reaches 250ºC for the various materials. OO stands for untreated corn pith samples, WW and WF for wood based samples and RH for rice husk.

Table 1. Effect of the treatments on the velocity of propagation and the temperature at which smouldering begins.

Specimen	T_{onset} [ºC]	Speed at T_{onset} [mm/min]	R^2
00	< 280	10.0	0.997
BA	< 280	6.6	0.999
AH	< 280	7.3	0.999
APP	300	3.6	0.983
APP-3	290	9.7	1.000
APPB	310	5.9	0.981
WW	330	10.7	0.998

Acknowledgments

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Cellulose insulation, fire and smouldering

Lucia C. Groß[1]

[1] ECIA (European Cellulose Insulation Association), Dreve du Pressoir 38, 1190 Forest, Brussels, BELGIUM, lucia.gross@ecia.eu.com

Keywords: cellulose, insulation, fire, smouldering

Introduction

Bio-based building products are generally burnable due to their high carbon content. This characteristic can become essential and lifesaving in case of a fire in a building. While burning, bio-based building products start to carbonise on the surface. As the microscopic structure of carbon is in layers, heat is spread on the surface and lower layers are protected from fire penetration.

With a generally high heat storage capacity, bio-based building products also store unwanted heat in case of an external heat source like a fire. This heat storage, in combination with material carbonisation, causes smouldering. The consumption (smouldering) of the bio-based material becomes a calculable, slow process. In case of a fire in a building, persons can be evacuated safely.

Earlier studies tried to avoid burning or smouldering of bio based insulation products. However, this paper is a summary of several experimental research studies. These research studies show the major advantage of burnable, smouldering insulation materials like cellulose insulation in comparison to other conventional insulation products.

Horizontal Cellulose Insulation, Attic, Fire

A radiant panel test is carried out on a 0.35 m cellulose insulation layer with a density of 30.8 kg/m³ (figure 1). The sample box is constructed of steel. After 30 min the intact layer of cellulose insulation has still a thickness of 0.22 m (figure 2).

Figure 1. Cellulose insulation sample before testing and thermal elements in the sample box

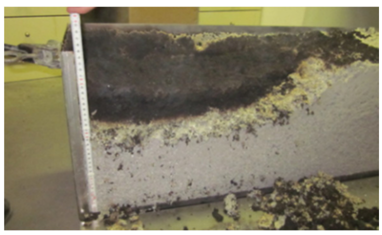

Figure 2. Cellulose insulation sample after testing.

The result shows that after 30 min of flame impingement there is no significant temperature increase at the lowest thermal element. [1] states: "*The conclusion based on this study can be that a* *standard height of 300 mm insulation ensures a protection of about 90 min of building elements below the cellulose insulation."* Converted in a real life fire situation in a roof, attic insulation with cellulose insulation can prevent the lower levels from burning. This fact has been proven in Strass, Zillertal, Austria. A hotel's attic was insulated with cellulose insulation. A few days later, the roof was ignited by plumbers. Only 0.02 m of the cellulose insulation layer was burned. The landlord claimed the cellulose insulation layer saved lives.

Vertical Cellulose Insulation, Wall, Fire

In a research project on the fundamentals of the evaluation of fire resistance of wooden wall constructions [2], 66 large scale fire tests are performed. The results are summarized in [3]. The tested cellulose insulation according to ETA-06/0076 with a density of $\rho \geq 50$ kg/m³ and a fire class of B-s2,d0 shows equal or better fire performance than glass wool according to ÖNORM EN 13162 at a density of $\rho = 11$ kg/m³. Wooden and steel-concrete constructions are well protected by cellulose insulation in case of fire. Essentially, the insulation material has to stay in place. Falling out is a fundamental issue of insulation materials, no matter if they are loose fill or mats, bio-based or not.

Vertical Cellulose Insulation, Wall, Smouldering

A research study is carried out about risks in case of fire when using burnable insulation materials [4]. A wall with six compartments including an insulation layer of 100 mm is constructed. The compartments are filled with loose-fill cellulose insulation, cellulose insulation mats, wood fibre, glass wool, rye and flax. Electric installations are placed in the compartments. After 54 min at the end of the fire test, 90 mm of the cellulose insulation remain intact (figure 3). The intact layer of glass wool is only 10 mm (figure 4) and a vast fusion near electric installations is visible.

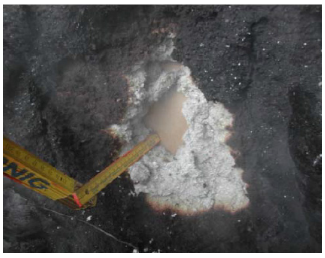

Figure 3. Cellulose insulation after 54 min fire test, [4]

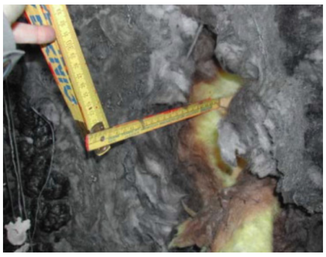

Figure 4. Glass wool after 54 min fire test, [4]

Horizontal Cellulose Insulation, Ceiling, Smouldering

A ceiling is constructed with an insulation layer of 200 mm [4]. Loose fill cellulose insulation, cellulose mats, soft wood board, glass wool, rye and flax are used as insulation materials. Thermal elements are installed in the insulation layer at the fire side, at the cold side and at the surface of the cold side. The temperatures after 30 min fire testing are visible in figure 5. Figure 5 shows no temperature increase in the cellulose insulation while the temperature in the glass wool department on the cold side is already $\vartheta = 54.3$°C [4].

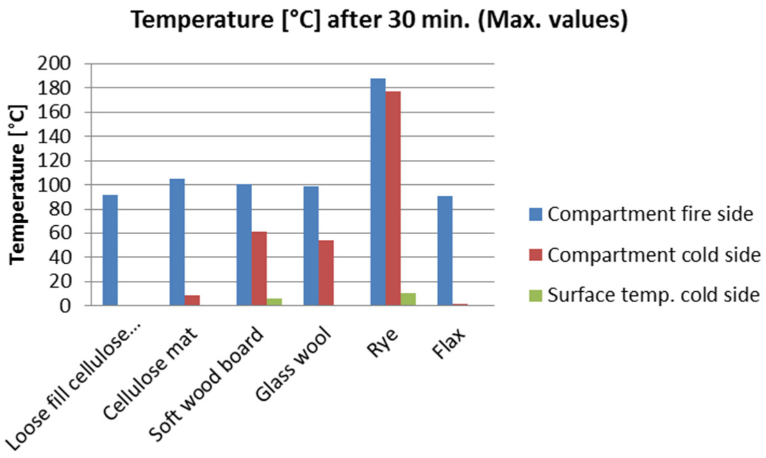

Figure 5. Ceiling 30 min under fire, 200 mm insulation. According to [4]

Conclusion

The fire class of a material has a minor significance on fire safety. More important for fire safety is a slow, steady process of consumption, instead of a suddenly changing characteristic like abrupt melting. Even though they have a lower fire classification, bio-based building products can provide a much longer time to evacuate people and save lives.

For fire safety, low temperatures on the far side are essential. Due to the generally high specific heat capacities combined with a high specific airflow resistance of bio based materials like cellulose insulation, these materials maintain low temperatures on the far side, and provide high fire safety. There seems to be a correlation between smouldering, the specific heat capacity and airflow resistance in combination of carbon. Low smoulder spread velocities are detected for bio-based insulation products like cellulose insulation.

Acknowledgements

For providing the large number of research reports and documents, I would like to express my gratitude to Isocell GmbH and CPH GmbH & Co KG. I am much obliged for Tim Fiechter's review on short notice.

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Working Group 2

Performance of CLT construction in real fire conditions

Christian Dagenais[1], Joseph Su[2], Gary Lougheed[2], Lindsay Osborne[3], Ineke Van Zeeland[4]

[1] FPInnovations, 319 Franquet St., Quebec City (Quebec) Canada, G1P 4R4, christian.dagenais@fpinnovations.ca

[2] National Research Council of Canada, 1200 Montreal Road, Building M-59, Ottawa (Ont.), Canada, K1A 0R6

[3] FPInnovations, 580 Booth St., 7-B4-1, Ottawa (Ont.) Canada, K1A 0E4

[4] Canadian Wood Council, 99 Bank St., Suite 400, Ottawa (Ont.) Canada, K1P 6B9

Keywords: CLT, real fire, mid-rise, fire performance.

Wood construction is experiencing a renaissance in that wood products for use in construction are undergoing a rebirth. Not only are traditional wood products being used in different ways, but a variety of innovative new engineered wood products and building systems, including structural composite lumber and mass timber frames and plates, are being introduced into the marketplace.

One of the most promising systems is cross-laminated timber (CLT). The advent of CLT, which can have impressive strength, durability and fire performance, are supporting initiatives to potentially allow taller and larger wood construction in Canada and in the United States. While CLT is very-well established in Europe, it has only been recently implemented as an approved building system in Type IV construction (i.e. *heavy timber construction*) in the 2015 International Building Code in the US [1]. Work is still ongoing in Canada with respect to its implementation in the National Building Code of Canada (NBCC) [2]. It is however expected that the 2016 supplement of CSA O86-14 Engineering Design in Wood [3] will provide CLT structural and fire-resistance design provisions.

Currently, the acceptable solutions provided in the 2010 NBCC Division B limit the use of combustible construction based on building height and area requirements. For buildings that exceed the height and area limits for combustible construction, the NBCC requires that noncombustible construction is used. The intent of the requirements for noncombustible construction is "*to limit the probability that combustible construction materials within a storey of a building will be involved in a fire, which could lead to the growth of fire, which could lead to the spread of fire within the storey during the time required to achieve occupant safety and for emergency responders to perform their duties, which could lead to harm to persons*".

As a result of code change requests from the Province of British Columbia and the Canadian Wood Council (CWC) asking to increase the current height limits for combustible construction (i.e. wood-frame construction), a collaborative research consortium involving private and public sector organizations was formed to develop technical data on the fire, acoustic and building envelope performance of wood-based structural products used in mid-rise buildings (5- and 6-storeys). The first objective of the research was to provide scientific and technical data as input to the code change proposals. A second and long-term objective is to develop solutions to determine whether the concept of combustible/noncombustible construction could be eliminated or replaced with performance-based fire requirements. A total of 28 reports documenting the research activities conducted under the mid-rise project have been published by the National Research Council of Canada (NRCC). Three (3) summary reports are also available [4, 5, 6].

Among other fire performance attributes, of which the outcome are detailed in the various NRCC reports, four (4) real-scale fire tests using 3-storey mock-up apartments, each being built using different types of construction, were conducted to assess their behaviour when exposed to real fire conditions. Two (2) wood-frame structures, one (1) CLT structure and one (1) cold-formed steel structure were built and instrumented throughout. The cold-formed steel construction was used as the benchmark to a code-compliant noncombustible construction.

This presentation focuses on the fire performance of the encapsulated CLT apartment fire test [7]. The concept of encapsulation (or protective cover for the wood materials) is used in order to delay their ignition and thus the effect of the structural element on fire severity for a determined time period, which would satisfy the NBCC objectives and functional requirements attributed to the requirements for noncombustible construction.

The test arrangement was 8.5 m long by 6.5 m wide, replicating a one-bedroom unit on the second floor of a 6-storey mid-rise building. CLT panels were designed for fire-resistance according to the revised fire chapter of the Canadian CLT Handbook [8] and were protected with 2 layers of 12.7 mm thick Type X gypsum board. The fuel load within the fire floor was comprised of typical furniture and contents found in residential occupancies. Figures 1 to 3 show the CLT apartment fire test at various stages of the construction and testing. The test setup was located beneath a large hood, which was used to collect the hot gases and smoke produced by the fire, and was instrumented to measure the heat release and smoke production rates. Thermocouples were also installed at several locations within the framing assemblies to measure heat transfer. Thermocouple trees were also placed inside the apartment floor to measure the fire growth.

Figure 1. CLT apartment during construction.

Figure 2. Fuel load.

Figure 3. CLT apartment in the early stage of the fire test.

This presentation provides further information with respect to the assembly configuration and instrumentation. It also provides the outcome of the fire testing with respect to fire growth and temperature profiles as well as encapsulation performance used to protect the CLT structural elements.

In summary, the test with the CLT apartment construction was terminated after 3 hours. Approximately 40 min into the test, the fuel load was entirely consumed. The results showed that properly encapsulated CLT structures can withstand complete burnout based on a residential fuel load. It also demonstrated the effectiveness of encapsulation in delaying the time to ignition of wood components and their potential contribution to fire growth. Compared to the noncombustible construction, the CLT structure provided equivalent or better performance in limiting involvement of the structural elements in fire.

Acknowledgments

The research consortium comprised of NRCC, CWC and FPInnovations would like to acknowledge the financial support from Natural Resources Canada, the governments of British Columbia, Quebec and Ontario, and the dedicated staff at NRCC, CWC and FPInnovations for efficiently conducting the research on mid-rise wood construction.

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Comparison of test results and the Reduced Cross-Section Method using a Zero-Strength Layer

Joachim Schmid[1,2], Michael Klippel[3] , Alar Just[1,4], Daniel Brandon[1]

[1] SP Wood Technology, Sweden, [2] ETH Zürich, Switzerland, [3] LTU, Sweden, [4] TUT, Estonia

Keywords: Zero-strength layer, fire resistance, timber, design model

The actual design method for the load-bearing resistance of timber members in fire (criterion R) in Eurocode 5 (EN 1995-1-2:2004) is the Reduced Cross-Section Method (RCSM) using an effective cross-section. This effective cross-section can be calculated using the charring depth (depending on the time of fire exposure) as well as a fictive further reduction to compensate strength and stiffness losses due to elevated temperature of the residual cross-section near the char layer. This additional depth is called zero-strength layer and was computed for glued-laminated timber beams in bending by Schaffer [1]. This constant value of slightly above 7 mm was determined by averaging strength (tension and compression) and stiffness (single function) based on available measurements on small wood samples. This averaging of strengths might be a reasonable approach for cross-sections with approximately constant stress distributions (e.g. tension members) at normal temperature but not for members (i) exposed to fire or (ii) in bending where the cross-section depth influences the inclination of the stress distribution. In [1], this zero-strength layer was in good agreement with simulations of one glulam beam, further agreement with fire resistance tests for glulam beams exposed to 30 min standard fire on three sides was *mentioned, an extension to four sided exposure* and 60 min standard fire was found reasonable but no comparison or verification was documented. The idea of the RCSM is to compensate all losses in strength and stiffness due to the heated zone of about 40 mm when wood is exposed to fire by an additional reduction of the cross-section. The depth of this compensation layer (zero-strength layer) cannot be measured but determined by simple backwards calculation using the appropriate mechanical model at normal temperature, e.g. bending model or buckling model, and comparing it to results of tests or advanced calculations [2]. Simulations [3] showed

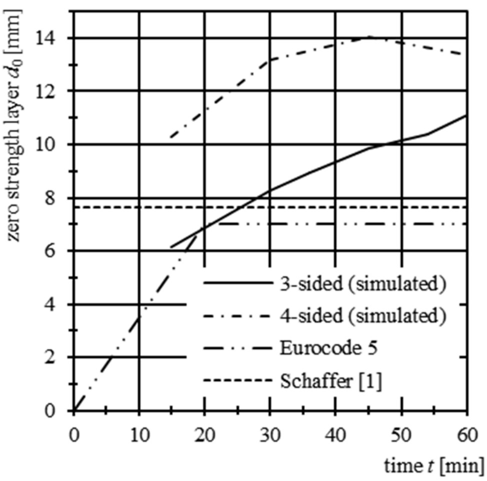

Figure 1. Zero-strength layers for an initially unprotected beam 134 mm x 420 mm [3].

reasonable agreement of Schaffer's result for three-sided fire exposure at 30 min, see Figure 1. Figure 1 shows further that the zero-strength layer is depending on the fire resistance time or load ratio of the beam (corresponding to the time of failure in a fire resistance test; the later the failure occurs, the lower the applied load) and the number of exposed sides. Schaffer recommended further investigations to verify the application of the proposed design method but this has not been followed up by the scientific community. Recently comprehensive review of available fire resistance test results of bending members [4] showed that the corresponding zero-strength layer deviates considerably from the value proposed by Schaffer, see Figure 2. The analysis of 117 full-scale fire tests in bending showed that most likely the poor prediction of the material properties is responsible for the large scatter and only a limited number of results agree with Schaffer's value. It is recommended to not use these tests to verify the general model of Schaffer.

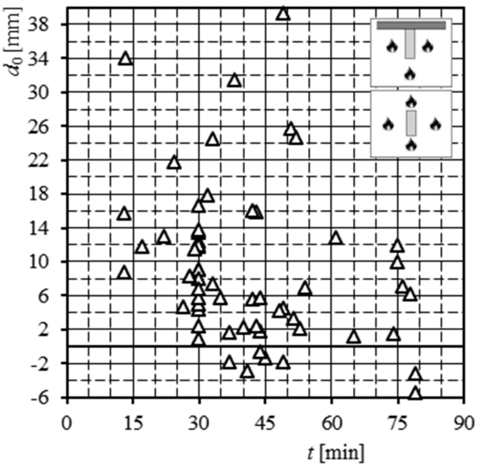

Figure 2. Zero-strength layer corresponding to full-scale fire resistance test results of timber beams. Results taken from [4].

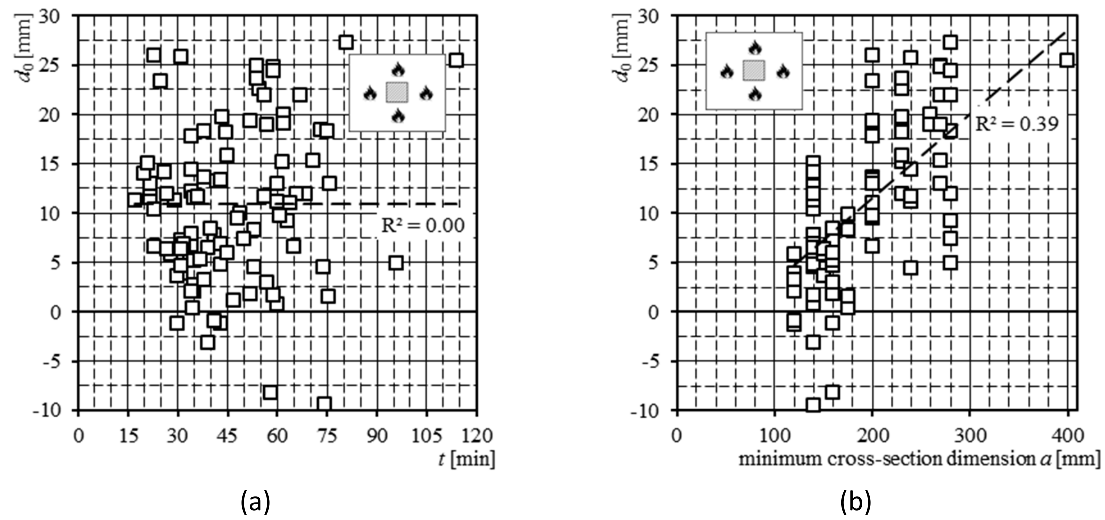

Figure 3. Comparison of the zero-strength layer corresponding to full-scale fire resistance tests of columns and (a) the regression using a fixed value in Eurocode 5 and (b) a linear function considering the depth a of the column.

A comprehensive analysis for buckling members [5] in general confirmed findings for members in bending even for members in buckling (problems with material and support characterisation, large scatter of results). A constant value ([5] calculates a mean zero-strength layer of 11 mm) does not reflect the mechanical model while a linear function depending on the cross-section of the column would improve the design, see Figure 3.

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Evaluation of the fire resistance of cross-laminated timber floor elements

Massimo Fragiacomo[1], Agnese Menis[2]

[1] L'Aquila - Via Giovanni Gronchi 18, University of L'Aquila, Dept. of Civil, Construction-Architectural & Environmental Engineering, Italy, fragiacomo@uniss.it

[2] Alghero - Piazza Duomo 6, University of Sassari, Dept. of Architecture, Design and Urban Planning, ,Italy

Keywords: Cross-laminated timber, Floor, Fire resistance, Modelling, Reduced cross-section method

Introduction

Cross-laminated timber (CLT) is a wood-based material made up from a variable number of layers composed by timber boards. The adjacent layers are arranged at a right angle and glued to each other. The good insulation properties and structural performances of this wood product have led to a large utilization of CLT panels as structural elements for buildings all over the world. At present, no specific indications for CLT structural elements are given by the European standard for design of timber structures at normal and fire conditions, respectively EN 1995-1-1 [1] and EN 1995-1-2 [2]. Experimental researches have proved the good performance of CLT panels exposed to fire, showing however a different behaviour with respect to other wood-based products such as glued laminated timber [3-7]. The fire resistance of timber elements can be estimated and verified by means of advanced numerical models implemented in finite element (FE) software packages, and/or simplified analytical methods, such as the reduced cross-section method (RCSM) proposed by EN 1995-1-2 [2].

This paper presents a numerical and analytical parametric investigation to analyse the variation of fire resistance of CLT floor elements due to different CLT panel build-ups. Two easy-to-use design methods for CLT floors exposed to fire on the bottom side are finally proposed.

Numerical predictions

A two-dimensional FE model representing a 50 mm long part of longitudinal section of an unprotected CLT panel at mid-span was implemented in Abaqus software package. Uncoupled heat transfer and mechanical analyses were carried out to simulate the behaviour of CLT floor elements subjected to one-dimensional standard fire exposure [8] on bottom side. The timber properties depending upon the temperature as proposed by EN 1995-1-2 [2] were adopted in the modelling. The numerical results in terms of temperature within the cross-section, residual cross-section, deflection and failure time were compared with experimental data collected during fire tests carried out at different research institutes, namely SP Technical Research Institute of Sweden and Trees and Timber Institute of the National Research Council of Italy [4,5]. The modelling outputs were also compared with results obtained by means of similar FE models already implemented for protected and unprotected CLT floors subjected to different load levels [5,9].

The validated model was used to predict the fire resistance of different CLT floor build-ups varying the number of layers (three, five or seven layers) and the layer thicknesses (30 or 40 mm) with panel depths ranging from 90 to 280 mm. The design values in fire conditions of strength and modulus of elasticity implemented in the modelling were calculated according to EN 1995-1-2 [2] by assuming a wood strength class C24 for the boards used in the CLT panels. The fire resistance of each examined CLT floor panel is shown in Fig. 1 in terms of load-bearing capacity ratio (design bending moment in fire due to the applied load divided by the design bending resistant moment in fire) versus time of fire exposure. The curves have the same trend characterized by nearly linear decreases of resistance when charring affects layers parallel to main floor direction, and plateaus when charring affects layers perpendicular to the main floor direction. The influence of layer number and layer thickness on the load-bearing capacity of CLT floor panels exposed to fire can be clearly noticed.

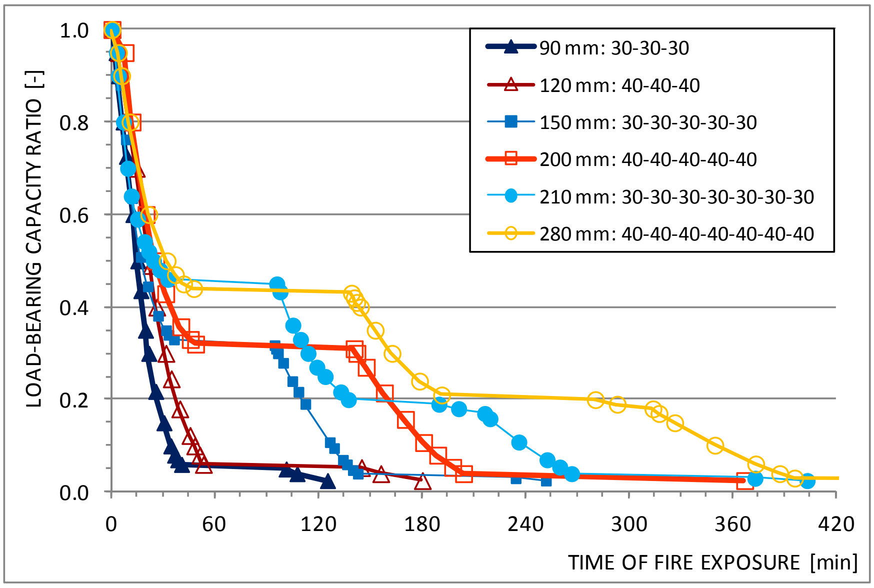

Figure 1. Numerical fire resistance of CLT floor panels with different build-ups.

Analytical estimations

The fire resistance of timber elements can be predicted analytically by means of RCSM proposed by EN 1995-1-2 [2] and a simplified design method purposely developed for CLT panels based on RCSM (‘RCSM for CLT’) [4]. The load-bearing capacity of CLT panels exposed to standard fire is estimated considering an effective cross-section corresponding to the actual residual cross-section reduced by a zero-strength layer d_0. This quantity is constant (d_0 = 7 mm) according to EN 1995-1-2 [2], whereas it depends upon the type of structural element (wall/floor), the panel depth, the layer number and the use or not of fire-resisting for CLT elements [10]. The resistance predictions with RCSM for CLT are slightly more conservative than using RCSM.

Fig. 2 shows the variations of fire resistance estimated by means of RCSM for CLT for panels composed by three, five or seven layers of 20, 30 or 40 mm thick manufactured by different European producers. In the calculation, the contribution of the layers perpendicular to main floor direction was neglected. The contribution of the layers parallel to the main floor direction was considered only for a residual layer of at least 3 mm thick. The curves are plotted as load-bearing capacity ratio versus a dimensionless fire exposure time determined as ratio between failure time under a certain applied moment and failure time of the unloaded element t_f calculated according to EN 1995-1-2 [2] using equation (1):

$$t_f = d_{char}/\beta_0 \tag{1}$$

where the char depth d_{char} and the charring rate β_0 are respectively the CLT panel depth and 0.65 mm/min as proposed by EN 1995-1-2. Conservative approximations (dashed lines) of the analytical curves are also displayed in Fig. 2 for CLT elements with three, five and seven layers.

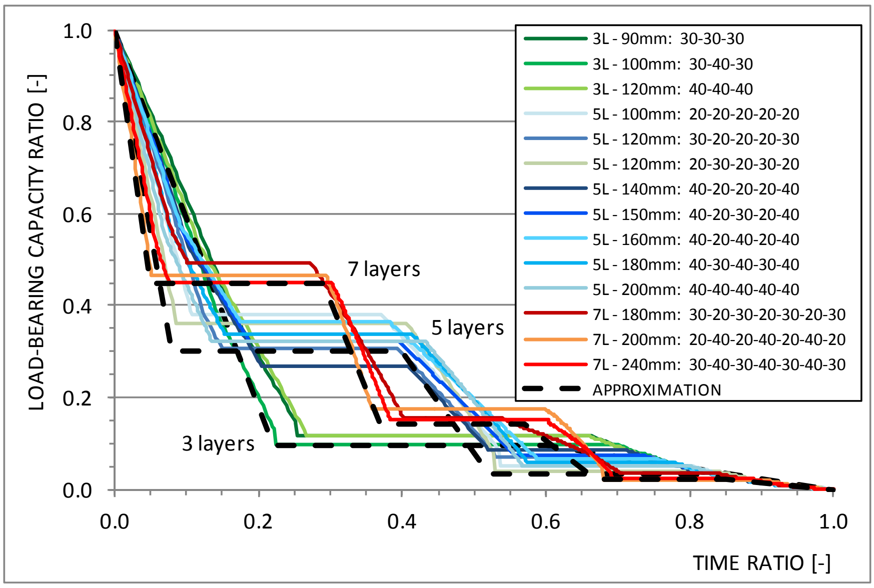

Figure 2. Analytical fire resistance of CLT floor panels with different build-ups.

Simplified calculation approaches

Two easy-to-use design methods based on the results of the numerical and analytical parametric studies can be proposed to determine the fire resistance of CLT floor elements. By knowing the demand of load-bearing capacity and the required fire resistance class, the designer could easily choose the suitable CLT floor elements by means of a graph such as Fig. 1. Similarly, the conservative approximating piecewise curves (dashed lines) proposed in Fig. 2 could be utilized for fire design as simplified analytical approach instead of calculation with the RCSM method for CLT. This second approach leads to more conservative results than estimations based on numerical curves. The material behaviour in fire conditions is described more realistically by means of the numerical modelling that considers the reduction of thermal and mechanical properties of timber with temperature. Whereas the simplified analytical calculations with RCSM take into account the decrease of strength by assuming a residual cross-section reduced with respect than the actual one.

Conclusions

A parametric investigation on resistance of various CLT floor panels exposed to fire on bottom side was performed by means of a two-dimensional numerical modelling and the simplified analytical method RCSM for CLT. Different CLT build-ups in terms of panel depth, number of layers (three, five or seven) and layer thicknesses (20, 30 and 40 mm) were analysed.

Easy-to-use design methods derived from the parametric study are proposed to verify the fire resistance of specific CLT floor panels, or to design the build-up of the CLT floor element known the applied load and the required fire resistance. The proposed simple design tools could be an alternative to numerical models or analytical calculations based on RCSM. The use of the numerical modelling leads to fire resistances higher than the use of analytical estimations since the fire behaviour of timber is described more realistically in the former methods.

Further analytical and numerical investigations should be performed on CLT products manufactured using boards of different strength classes. Furthermore, the fire resistance of CLT wall elements should be also analysed in order to propose simple design tools.

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Charring behaviour of cross laminated timber with respect to the fire protection, comparison of different methods

Mattia Tiso[1], Joachim Schmid[2], Massimo Fragiacomo[3]

[1] Ehitajate tee 5, 19086 Tallinn, Tallinn University of Technology, Estonia, mattia.tiso@sp.se

[2] Drottning Kristinas väg 67, SE-114 86 Stockholm, SP Technical Research Institute of Sweden, Sweden, joachim.schmid@sp.se

[3] Piazza Duomo 6, 07041 Alghero, University of Sassari, Italy, fragiacomo@uniss.it

Keywords: Cross-laminated timber, CLT, Fire resistance, Cone heater, Fire protections

Timber buildings made with Cross-laminated Timber (CLT) panels are becoming wide spread in Europe. The fire resistance of CLT panels depends upon several parameters, including the number of layers and their depth. At the present, EN 1995-1-2:2004 [1] does not provide specific information on the fire design of CLT panels. The large number of possible combination of CLT products makes the full scale tests a complicate and expensive tool for the verification of the fire resistance of different building configurations.

This work presents nine small-scale tests in cone heater on CLT and massive sawn timber specimens carried-out at SP Wood Building Technology (Technical Research Institute of Sweden). One CLT and one solid sawn timber (cross section 45 mm x 135 mm) specimen have been tested unprotected as reference tests, then two different types of fire protection (gypsum plasterboard type F 15 mm depth and plywood 9 mm depth) have been used. Stone wool insulation has been placed on the sides to obtain one-dimensional heat propagation along the specimen depth (Fig. 1).

To reproduce the ISO 834 [2] fire exposure typically followed during a standard fire resistance test, the cone heater was calibrated to provide initially a net heat flux to a surface at ambient temperature equal to 50 kW/m^2. After 23 minutes, the exposure was increased to 75 kW/m^2 (Fig.2). These two exposure levels were measured with a water cooled heat flux meter.

The purpose of this work is the development of a faster and cheaper tool for investigating the charring in timber specimens. The charring of wood stud unprotected and protected by gypsum plasterboard was studied by Tsantaridis and Östman [4] in the cone calorimeter with a net heat flux at ambient temperature (50 kW/m^2) and compared with data from full-scale furnace tests, obtaining results in full agreement for the first 30-40 min of testing.

The increased level of the net heat flux to the surface (75 kW/m^2) was considered to extend the investigation beyond the first 30-40 minutes, following the heat transfer expressed in terms of adiabatic surface temperature measured in furnace during a standard fire resistance test without any specimen (the “SP furnace” curve in Fig.2).

It is important to underline that the wording “net heat flux to a surface at ambient temperature”, often used in Fire Safety Engineering, could be ambiguous if the surface emissivity, the convective heat transfer coefficient, gas temperature and surface temperature are not given. The boundary condition is sufficiently well defined to calculate the heat transfer to a surface at a given temperature only when these parameters are known [3].

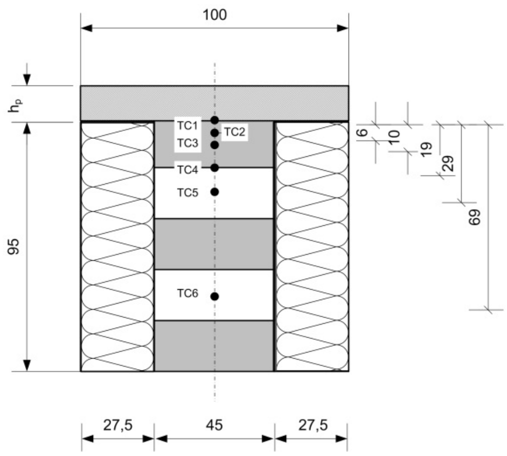

Figure 1. Cross-section of CLT test samples with the fire protection on the top and the thermocouples, dimensions in mm.

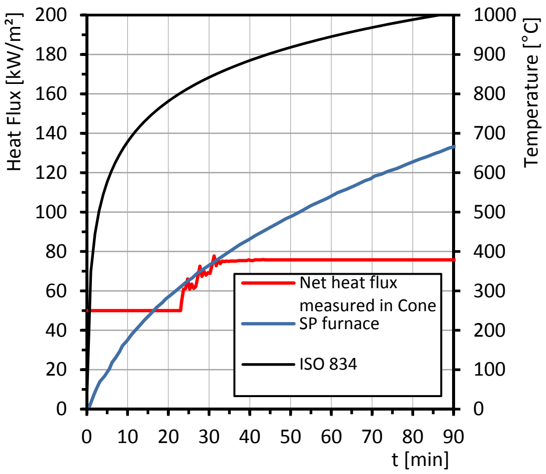

Figure 2 “SP furnace” time-heat flux curve and net heat flux to surface at ambient temperature measured during the calibration of the cone heater.

The results from the cone heater tests have been validated against the results of charring obtained in (i) the model scale fire tests on CLT in horizontal furnace performed at SP Technical Research Institute of Sweden [5] and (ii) in the large scale fire tests in vertical furnace performed at CNR-Ivalsa in Italy [6].

Thermal simulations with the same set-up of the cone heater tests have been implemented in the finite element software package Safir 2007, with the time-temperature curve given by ISO 834 as input. Properties such as thermal conductivity, specific heat capacity and loss in density used to define each material have been taken from the European guideline *Fire Safety in Timber Buildings* [7].

Numerical and experimental results have been compared with analytical models for the charring depth prescribed in Eurocode 5 part 1-2 for a timber deck, identified as an infinitely wide element (iwe) and a timber beam (using the charring rate suggested for glulam when evaluating the charring depth of the CLT specimen) with the sides protected by stone wool identified as a non-infinitely wide element (niwe). This last assumption has been made since the width of the specimen tested on cone heater could not be considered infinitely wide and the stone wool placed on the side might influence the heat transfer, i.e. charring, on the specimen (see Fig.1).

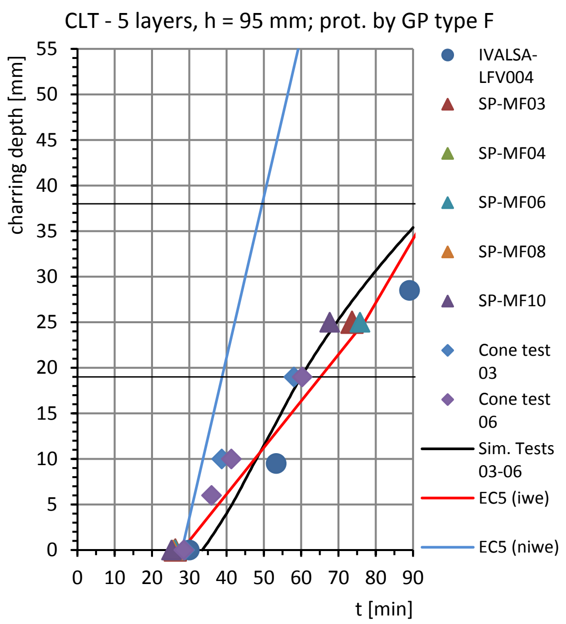

Figure 3. Comparison among furnace tests, cone heater tests, simulation and analytical results for CLT protected by gypsum plasterboard.

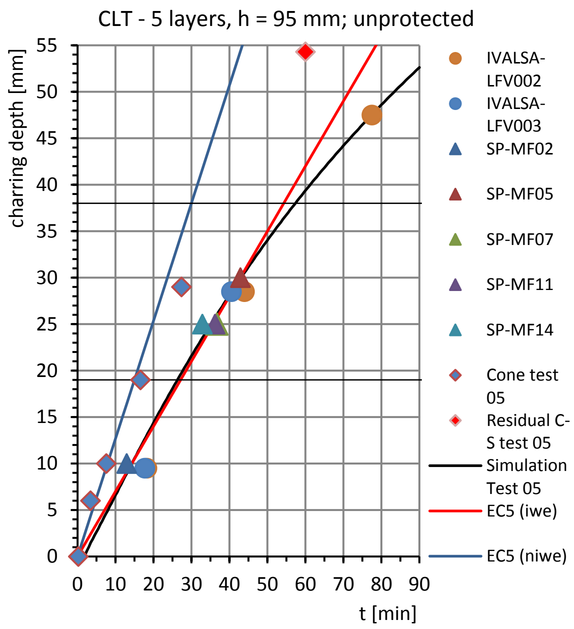

Figure 4 Comparison among furnace tests, cone heater test, simulation and analytical results for unprotected CLT.

In the first 40 minutes of test, the charring depth in the small specimens (cone heater tested) protected with gypsum plasterboard is slightly larger than in the furnace tested specimens, while agrees well at 60 minutes (Fig. 3). For the unprotected elements, the charring from cone heater tested and furnace tested elements could not be compared (Fig.4).

Conversely, by comparing the cone heater tests with the analytical models, the results suggest that the charring depths for an unprotected specimen tested in a cone heater agree well with the charring depths that can be calculated following the rules given by the Annex C of Eurocode 5 part 1-2, namely considering as a non-infinitely wide element. From the comparisons for the gypsum plasterboard protected specimens, it is evident that the charring depths are closer to the analytical charring depth given by Eurocode 5 for an infinitely wide element.

Similar comparisons can be done with the charring results obtained on the massive sawn timber specimens protected by gypsum plasterboard and unprotected.

Analysing the simulation results for the gypsum plasterboard protected tests, the start of charring time behind the protection is underestimated by the cone heater tests. For the unprotected specimens, the results agree well with an infinitely wide specimen, i.e. not with the cone heater test results.

For validating the results further investigations on cone heater are necessary. Based on the slight overestimation of the charring rate after the change of the heat flux for gypsum plasterboard protected tests, it could be interesting to test the specimens with an intermediate step between the

50 and 75 kW/m^2 heat flux. The simulation with the gypsum plasterboard as fire protection should be improved regarding the start time of charring.

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Design of separating function - state of the art

Alar Just[1], Mattia Tiso[2], Massimo Fragiacomo[3]

[1,2] Ehitajate tee 5, 19086 Tallinn, Tallinn University of Technology, Estonia, alar.just@ttu.ee

[3] Via Giovanni Gronchi 18, 67100 L'Aquila, University of L'Aquila, Italy

Keywords: separating function, fire design

Separating function means the limited integrity (E) and insulation (I) in standard fire. Criterion I (insulation) is satisfied where the average temperature rise over the whole of non-exposed surface is limited to 140 K, and the maximum temperature rise at any point on that surface does not exceed 180 K (for fire exposure of standard time-temperature curve). Criterion E (integrity) is satisfied when no sustained flaming or hot gasses penetrate to the unexposed side. The latter can appear due to the cracks or openings of the protective materials.

In Europe the fire resistance can be proved by full scale fire testing or by the design.

Insulation (Criterion I) can be analysed by design methods. Criterion I is clearly defined, and it is possible to verify it through heat transfer calculations. Integrity (criterion E) is mostly determined by testing. Calculations are impossible in most of the cases because there are too many variables (crack formation, dynamics of hot gases, etc.) and lack of data [2]. However, from extensive investigation via full-scale tests, it was possible to define some rules about detailing of wall and floor assemblies that have been included in Eurocode 5 part 1-2 [1]. Therefore Eurocode 5 assumes that Criterion E is satisfied when Criterion I has been satisfied and the cladding remains fixed to the timber structures on the side not exposed to fire. The Criterion E still needs improved regulations for design.

Design methods

Component additive methods can be used for the calculation of fire resistance with regards to the separating function of timber assemblies. These methods allow determining the fire resistance of a layered construction by considering the contribution of each layer.

Annex E of Eurocode 5 part 1-2 [1] presents a design method that is based on modification of the Swedish component additive method [5] by extending it to floors, including the effect of joints in claddings that are not backed by members, battens or panels. This design method is capable of considering claddings made of one or two layers of wood-based panels or/and gypsum plasterboards, and also voids or insulation-filled cavities; the insulation may be made of mineral wool. However this method covers only a limited range of timber structures. The method in

Eurocode 5 is the only one in the European design standards for the design of separating function in fire.

A research project on the separating function of timber assemblies [4] has been carried out in Switzerland. The outcome of this project was an improved design method for determining the separating function, based on extensive experimental results and finite-element thermal analysis. The advantage of this method is the capacity of considering timber assemblies with an unlimited number of layers made of gypsum plasterboards, wood panels or combinations thereof.

Following the basics of the component additive methods, this improved design method provides the total fire resistance as the sum of the contribution from the different layers considering different heat paths and according to their function and interaction:

$$t_{ins} = \sum_{i=1}^{i=n-1} t_{prot,i} + t_{ins,n} \tag{1}$$

The summation of the protection times $t_{prot,i}$ of all the layers (in the heat flux direction) except the last layer is summed to the insulation time of the last layer $t_{ins,n}$. Protection times are based on 250 K temperature rise as an average and on 270 K as a maximum. The insulation time is based on temperature rise limited with Criterion I (140 K / 180 K respectively). Protection and insulation times of the layers should be calculated according to general equations 0, taking into account the basic values of the layers, the coefficients for the position of the layers in the assemblies and the coefficients for the joint configurations.

The method was developed for a limited number of materials [4], however the coefficients of the design method (basic values, correction time and position coefficient) were obtained by extensive finite-element thermal simulations based on physical models for heat transfer through separating multi-layered construction [3], [4]. The material properties used for the finite element thermal simulations were calibrated and validated by fire tests performed on unloaded specimens using fire exposure of the standard temperature-time curve.

The described method is also included in the European technical guideline *Fire Safety in Timber Building*s [2] as an improved method for separating function of timber construction.

The method is presented as an open model, where the introduction of new materials is allowed through the previous verification by fire tests and FEM analysis. Therefore this method is recommended instead of the present method in Annex E of Eurocode 5 Part 1-2. The improved method will form a basis for the revision of the fire part of Eurocode 5.

For the improved component additive method there is a need to develop a system for including new materials including the bio-based boards and insulations.

Improvement needed for bio-based materials

At the moment no European standard is available to develop product specific equations to be used in the novel design models available today.

According to [4] to determine the protection time and the position coefficients for new materials the following material properties are needed:

- Thermal conductivity vs temperature
- Heat capacity vs temperature
- Density vs temperature

Sometimes not all properties, depending on the temperature are available; often values at normal temperatures are available only. In this case the additional fire testing has to be provided in certain conditions. Based on the data named above the simulations with different construction set-ups will be performed using thermal simulation software.

Density is not the value that needs to be declared by the producers according to the European rules. Therefore the average density range in practice proved by measurements should be used.

The common procedure is needed for determination of the parameters for fire design methods for wide range of materials.

The collection of the data for bio-based materials and the other new materials used as fire protection should be performed to open more possibilities for fire design of structures with bio-based materials. Data for bio-based insulations and claddings as well as claddings protecting the bio-based materials should be in focus. On request the data on the database shall be confidential.

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Structural fire design of timber connections – current design rules and recent developments

Pedro Palma[1], Andrea Frangi[2]

[1] Research Assistant, ETH Zurich, Institute of Structural Engineering, palma@ibk.baug.ethz.ch

[2] Professor, ETH Zurich, Institute of Structural Engineering, frangi@ibk.baug.ethz.ch

Keywords: timber connections, fire resistance, design, tests, review

Scope and objectives

The fire resistance of timber connections is one of the key aspects regarding the structural fire design of timber structures. The proposed presentation will review the current design rules of EN 1995-1-2:2004 and reference the relevant research background and its scope. Experimental research conducted since EN 1995-1-2:2004 was published will be reviewed and its impact in current design rules analysed. Recent analytical and numerical developments will also be presented and, finally, the ongoing review of EN 1995-1-2:2004 will be discussed, focusing what the authors perceive as key issues regarding the design of timber connections in fire.

Current design rules and recent developments

The design rules in EN 1995-1-2:2004 apply to symmetrical three-member connections with laterally loaded fasteners, under standard fire exposure, and for fire resistances below 60 minutes. These rules are mostly aimed at connections with side members of wood, but some guidance is also given regarding axially loaded screws.

Two approaches are laid out for the designer: a simplified method, where the required fire resistance is attained by either increasing the member sizes or by protecting the connection with the addition of wood-based panels or gypsum plasterboards; and the "reduced load method", where, based on the design effect of actions in the fire situation and the load-carrying capacity of the connection at normal temperature, either the connection's load-carrying capacity after a given fire exposure or its fire resistance, can be assessed.

The simplified rules for unprotected timber-to-timber connections assume that connections designed according to EN 1995-1-1:2004 satisfy a fire resistance of 15 minutes (nails, screws, bolts, and connectors) or 20 minutes (dowels) , given that a minimum side member thickness is used. Even though not explicitly stated in EN 1995-1-2:2004, this assumes a load ratio $E_{fi}/R_{20°C}$ of approximately 0.3 (as presented in Figure 1, for dowelled timber-to-timber connections).

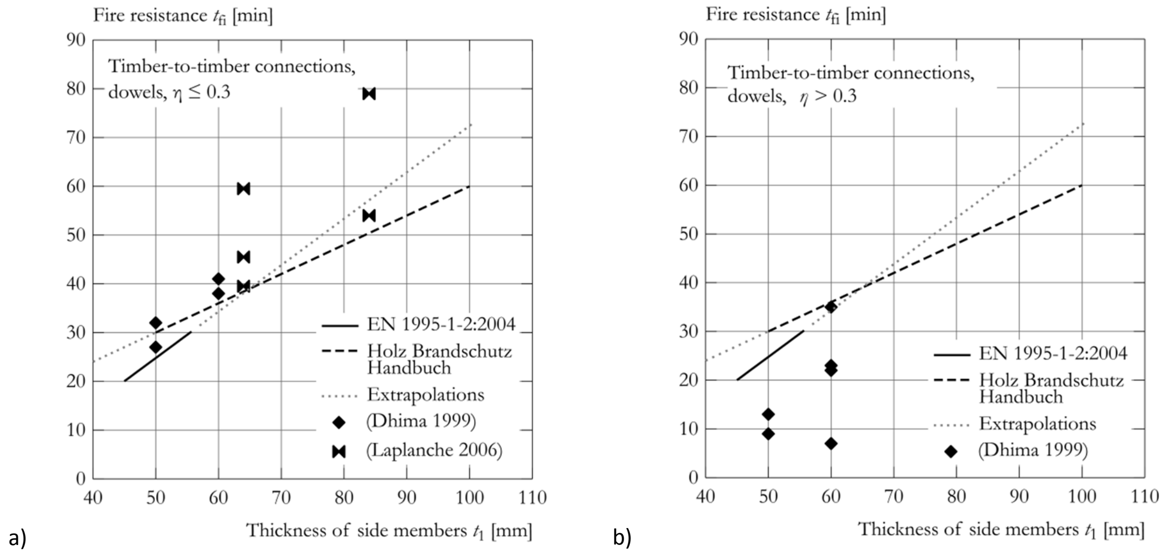

Figure 1. Simplified rules and experimental data for unprotected timber-to-timber dowelled connections: a) load ratio $\eta \le 0.3$; b) load ratio $\eta > 0.3$.

For connections with fasteners with non-projecting heads (nails, screws, and dowels), fire resistances greater than those assumed for connections with the minimum end and edge distances prescribed by the design at normal temperature (according to EN 1995-1-1:2004) can be achieved if the thickness of the side members t_1 and the end a_3 and edge a_4 distances are increased by a_{fi}. According to König and Fontana (2001), this rule is based on Norén's (1996) tests with nailed timber-to-timber connections. EN 1995-1-2:2004 does not prescribe a minimum thickness for the side members of nailed connections, but Norén's (1996) tests show that this should be at least t_1 = 28 mm for a fire resistance t_{fi} = 15 min (Figure 2a, for $a_{fi,t1}$ = 0 mm). However, assuming the minimum end and edge distances prescribed by EN 1995-1-2:2004 and comparing it to available tests results (Norén 1996; Lau 2006), the extra end distance ($a_{3,min} + a_{fi}$) does not seem to be so

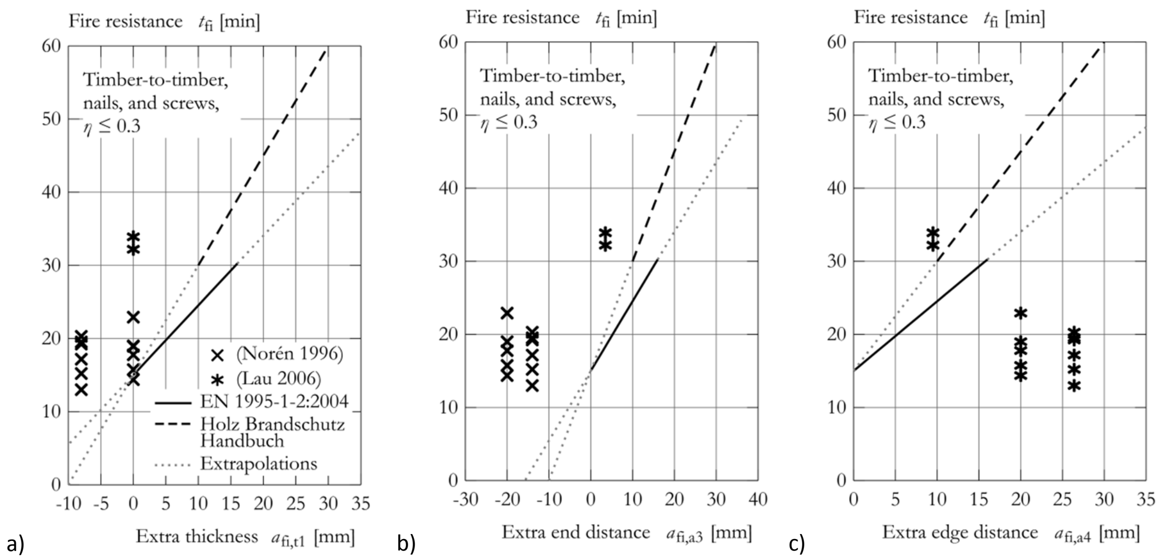

Figure 2. Fire resistance of unprotected connections: a) extra thickness; b) extra end distance; c) extra edge distance.

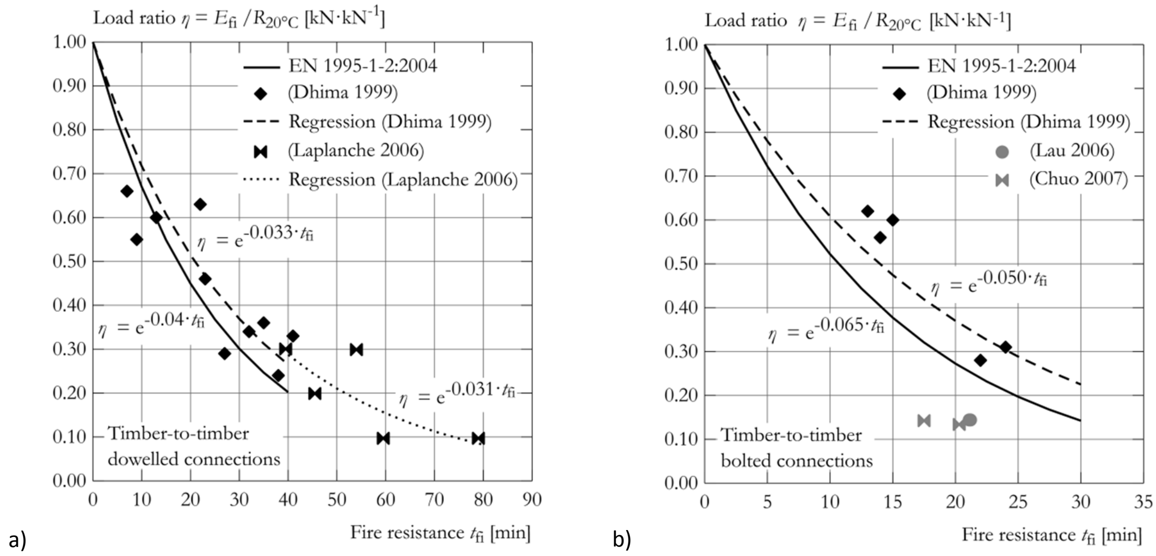

Figure 3. Reduced load method and experimental data: a) dowelled timber-to-timber connections; b) bolted timber-to-timber connections.

relevant (Figure 2b), as the required fire resistance is achieved with even smaller end distances (most likely because the end surface of the members is usually not directly exposed to fire). On the other hand, regarding the extra edge distance ($a_{4,\min} + a_{\mathrm{fi}}$), the opposite effect can be observed in Figure 2c, which suggests that extra thickness and extra edge distance might be more relevant for fire resistance than extra end distance (as the results by Erchinger et al. (2006) seem to show).

The reduced load method is based on limited test results (Norén 1996; Dhima 1999; Ayme 2003) and more recent data can be used to validate and extend current rules. As an example, tests on timber-to-timber dowelled connections reported by Laplanche (2006) make it possible to extend current rules for fire resistances longer than 40 min (Figure 3a). On the other hand, the results by (Lau 2006; Chuo 2007) show lower fire resistances than those predicted by EN 1995-1-2:2004 (Figure 3b). However, all these experimental results are not easily combined, as different authors determine the load ratio in different ways: some report it as the ratio between the load applied during the fire tests and the experimental load-carrying capacity at normal temperature; while others use the estimated load-carrying capacity. In addition, the rules to estimate the load-carrying capacity at normal temperature have changed significantly from ENV 1995-1-1:1993 to EN 1995-1-1:2004 and, therefore, some of the older tests results on which EN 1995-1-2:2004 is based must be reanalysed.

Ongoing review of EN 1995-1-2:2004

Besides the issues described above, the ongoing of EN 1995-1-2:2004 should address other key aspects such as the lack of design guidance for different connections typologies (e.g. secondary to main-beam connections and beam-to-colum connections loaded in shear (Palma et al. nd)) and to extend current rules so that unprotected connections can be designed for fire resistances of up to 60 min (Scheer and Peter 2009).

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Fire resistance of joist hanger connections for timber structures

Norman Werther[1], Martin Gräfe[2], Veronika Hofmann[3], Stefan Winter[4]

[1,2,3,4] Chair of timber structures and building construction,

Technische Universität München, Arcisstrasse 21, 80333 München, Germany,

m.graefe@tum.de ; n.werther@tum.de

Keywords: fire resistance, timber buildings, joist hangers, timber connections

Despite current political initiatives to support the use of timber and the several advantages of build with timber there are still large concerns and limitations by authorities and design codes related to fire safety. Furthermore engineers often facing the problem of limited knowledge about the fire behaviour or missing normative design rules for typical connections used in timber structures, like engineered joist to beam and joist to column connections. To overcome this gap of knowledge a German research project [2] was conducted which sought to investigate the thermal and structural performance of typical engineered connections for timber structures in the event of fire. Primary focus has been laid to investigate the fire behaviour of connections with joist hangers and screwed connections with fully threaded screws.

The following article comprises only the investigations and results for joist hangers. The experimental and numerical investigations for connection with fully threaded screws will be subject of additional articles by the authors and will be published in due course.

Figure 1. Unloaded test specimen after fire exposure.

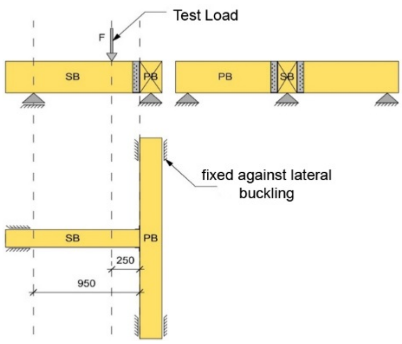

Figure 2. Principal setup in the loaded tests, ambient and fire.

Figure 3. Loaded fire test with joist hanger.

The investigations conducted in this research project were based on three steps, see Fig. 1 - 3:

(1) unloaded small scale fire tests to assess the influence of geometry and material interaction,

(2) mechanical testing of the connections at ambient conditions under consideration of the results gained in step (1),

(3) loaded full-scale fire tests of optimized connection systems, based on the results gained in the previous steps (1) and (2).

The test configuration for the unloaded fire test consisted of a U-shaped specimen made of 100 mm CLT panels, with 300 mm long glulam beams mounted on their inner sides, as illustrated in Fig. 1. Two sizes of 2 mm thick galvanized zinc coated joist hangers (W x H =100 mm x 240 mm and 200 mm x 300 mm) were investigated, each for internal and external wings. To fix the joist hangers to the beam sections and CLT wall elements, rink shank nails with a diameter of 4 mm and screws with a nominal diameter of 5 mm were used as fasteners. Both types were 50 mm and 70 mm in length respectively. The connections were equipped with type-K thermocouples to measure the temperature formation within the connectors, joints and fasteners.
In comparison the mechanical loaded tests (fire and ambient) showed a typical T- shape and were assembled each of a primary beam (PB) with a length of 2000 mm and a secondary beam (SB) with a length of 1200 mm, see Fig 2. The cross section of the beams varied in subject to the type of the connection, see Table 1. All specimen were supported on two points of the primary beam (pinned) and one point of the secondary beam (roller) and were fixed against lateral buckling. The T-shaped specimens were placed in a diesel fired furnace and exposed to standard fire over 30 minutes in accordance with EN 1363-1. A comparable setup, considering the requirements of EN 26891 and ETAG 0015 also was used to determine the load displacement behaviour and failure load at ambient conditions for each connection type as basis for the loaded fire tests.
In the fire tests a constant load of 40 % of the estimated capacity after fire exposure was applied during the time of fire exposure by a force controlled hydraulic jack. At the end of the designated exposure time (30 minutes) the load was increased until the connection reached failure.

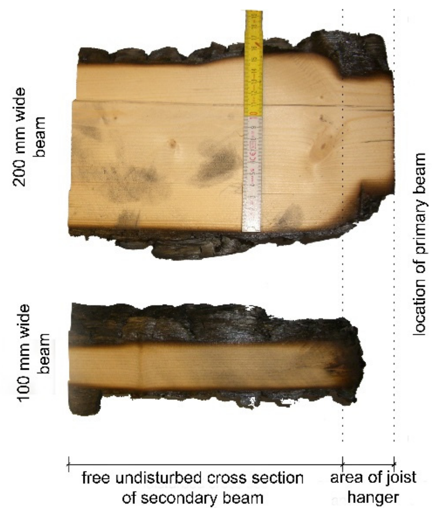

Figure 4. Horizontal section through fire exposed secondary beams.

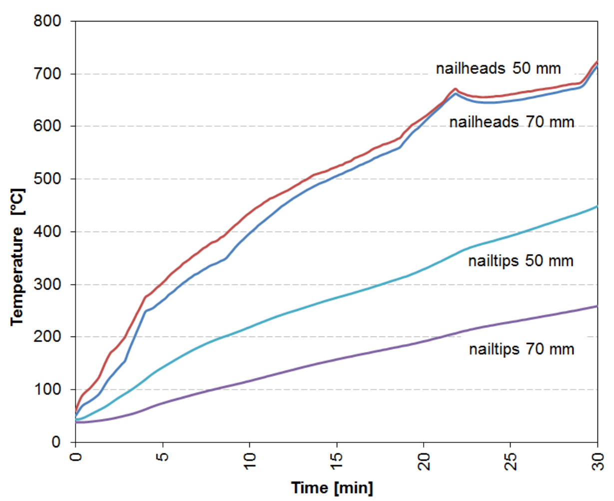

Figure 5. Temperature formation in rink shank nails 4x50 and 4x70 (mean values).

The conducted series of fire tests with joist hangers showed, that the type of fastener mainly influences the charring of wood, which is in contact with the metal fasteners. The unprotected fasteners conducted the heat from the surface into the interior of the timber members, resulting in a larger charring depth compared to free undisturbed areas of the beams not adjacent to the fasteners (see Fig. 4).
The examined screws with a nominal diameter of 5 mm (3.3 mm core diameter) performed better than the 4 mm nails with same length, resulting in more slowly heating curves within the temperature measurements of the screw tips.
A comparison of the temperatures at the fastener tips showed that the 50 mm long fasteners heated up more quickly than the 70 mm long fasteners, if the same fastener type and diameter was used, see Fig. 5.

All conducted loaded full-scale fire tests showed a similar behaviour to each other, which can be described as follows:
After a few minutes, the connections start to deform. After approximately 15 minutes, the rate of deformation started to increase significantly. All specimens showed relative displacements between primary and secondary beam of about 30 mm towards the end of the fire exposure, collapse occurred at about 40 mm displacement. The fasteners had been considerably deformed and the connections failed after pulling out of the fasteners. The sheet metal itself failed in no case.

Connections using the number of fasteners required according to ETA [1] reached a lower load bearing capacity than connections with the maximum number of fasteners possible by the number of punched holes. The obtained maximum load bearing capacities are summarised in Table 1.

Table 1. Overview of investigated connection setups and obtained results after 30 minutes fire exposure.

Speci-men	**secondary beam [mm]**	**Fastener/ nailing pattern**	**Failure load R_{fi} [kN]** [a]	**$R_{k,20}$ [kN]** [b]	**μ $R_{fi}/R_{k,20°C}$**
B1	120 x 160	rink shank nails 4x60 mm/ according to ETA	0	39.9	0
B2	120 x 240	screws 5x60 mm according to ETA	7.7	94.6	0.08
B3	140 x 200	screws 5x70 mm according to ETA	17.8	85.4	0.21
B3 a	140 x 200	screws 5x70 mm all holes used	26.2	79.0	0.33
B4	140 x 200	rink shank nails 4x75 mm all holes used	14.9	76.6	0.19

[a] *characteristical load bearing resistance according to ETA [1] at ambient conditions,*

[b] *R_{fi} represents the measured value at the connection in the moment of failure,*

Based on the results the connection of joist hanger to the secondary beam appears as the critical area under fire exposure and will govern the failure. The results show that unprotected 50 mm long fasteners are not long enough to embed in the residual timber cross section after 30 minutes. The position of the wings has no essential influence, although internal wings are positively affecting the strength of the connection at the main beam. In the interest of a maximum in strength during fire exposure, the gap between the timber beams should be as small as possible.

Connections with joist hangers exposed to fire on four sides over 30 minutes are able to bear loads of $0{,}33 \cdot R_{k,20}$, when designed according to the following recommendations:

- joist hangers Type 04 according to ETA 08/0264 [1], or equivalent
- minimum cross section of joist of 140 mm x 200 mm
- screws 5 x 70 mm in all holes, in two rows over the entire height of the joist hanger
- maximal gap between primary and secondary beam 4 mm
- both inside and outside position of the wings possible
- a/h >0,7 (according to EN 1995-1-1)

Identical connections, but made up with ring shank nails 4 x 70 mm instead of screws are able to bear loads up to $0{,}19 \cdot R_{k,20}$. The lower load bearing capacity can mainly be explained by the lower pull-out resistance of the nails.

It is assumed, that bigger cross sections of joists lead to a better load bearing ratio, as side influences from the upper and lower edge declines and the calculated load bearing capacity increases linearly with the height of the joist. Furthermore, an increase of the sheet metal thickness will not negatively influence the fire resistance of a connection, due to the increased heat storage capacity and reduced heating up.

Acknowledgments

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Review of timber-concrete composite beams in fire conditions

Tomaž Hozjan[1], Staffan Svensson[2]

[1] UL FGG – University of Ljubljana, Faculty of Civil and Geodetic Engineering, Jamova 2, SI-1000 Ljubljana, Slovenia (tomaz.hozjan@fgg.uni-lj.si)

[2] University of Borås, Allégatan 1, Borås, Sweeden, (staffan.svensson@hb.se)

Keywords: fire resistance, timber concrete beam, composite, slip, advanced analysis

Composite structures present very optimized and popular structural bearing system. They can be found in construction of new buildings and bridges as well as in the rehabilitation or strengthening of existing ones, where the unsound material, damaged due to various reasons is replaced by new one or, for any reason, strengthened to increase initial bearing capacity and/or ductility. Usually composite structures are composed of two different materials in such way that each off the material can be fully exploited, for instance timber-concrete composite systems combine the high compressive load capacity of the concrete and tension capacity, low weight and also lower environmental impact of timber (Fig 1). Timber-concrete-composite systems (TCC systems) became popular for restoration of historical buildings. Main reason is in increased floor capacity, shallower floor depth and reduction in floor weight, and improved acoustic performance.

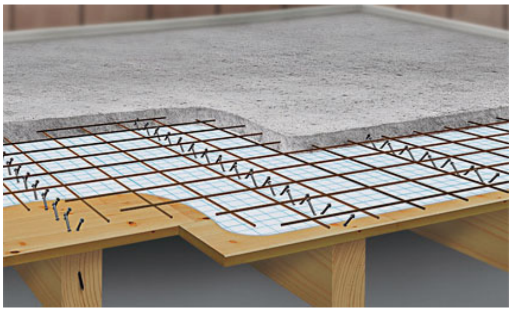

Figure 1. Conventional timber-concrete composite system (source: http://www.spillner-ssb.de/sfs/sfs-advantages.php)

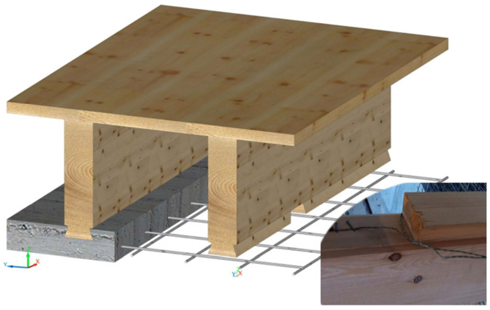

Figure 2. Timber-concrete floor system [2].

Additional advantages compared to a concrete slab are found in the relatively rapid erection of the system due to the use of the timber element as formwork, and reduced carbon dioxide emissions [1]. Recently somewhat unnatural TCC systems emerged, where timber beam is positioned above the concrete slab (Fig 2). In comparison with concrete floor is lighter and has better acoustical properties than a lightweight timber floor. As stated in [2] the system also significantly improves the possibilities to integrate mechanical installations, the connection to timber structural systems, and has higher fire resistance. It's worth mentioning that this system is not totally unknown since fire tests on these systems were carried out in the 90's of the previous century [3], yet up to now its usage has been limited. The most vital parts of the composite systems are undoubtedly the connectors/fasteners. The connection between the two materials must be stiff enough to ensure composite action and the materials must be strong enough to resist tensile/compression stresses due to the loading. In engineering the rigid connection is most often desirable, although in many applications, like in timber-concrete composite beams, fully rigid connections are not possible to achieve due to the deformability of the connectors. In case of fire this is even more evident since connection rigidity can be lost rapidly due to the increased temperature. Therefore, understanding the behaviour of connectors in fire situation is crucial for more realistic description of composite beam exposed to fire and for performance based approach almost necessary.

Review of the research in field of timber-concrete composite systems

Experimental work of the TCC systems exposed to fire is not extensive as in case of the room temperature. Preview of the research on many aspects and components of TCC systems at ambient conditions can be found in [4]. Here, short review of the research work of the TCC systems in fire conditions carried out in recent years is presented.

Frangi and Fontana [5] investigated two TCC systems exposed to standard ISO 834 fire. First system was a solid timber decking composed of nailed planks or glue laminated beams with concrete layer cast on top. The second system was a sawn timber beam system consisting of inclined self-drilling screws for the connection system implanted into a concrete slab cast on plywood sheathing. Two full scale furnace tests were conducted and both systems exceeded 60 minutes of ISO fire exposure without structural collapse. It was found out that the form of connection is important, as the integrity of the connection during the fire is governed by the behaviour of its weakest element, which can sometimes be difficult to predict. Interesting observation was also that the performance of their screw connectors was a linear function of the temperature of the surrounding timber. As presented in [6] simplified design method for timber-concrete composite floors based on the effective cross section method from Eurocode 5 [7] gave good results when compared with full scale fire tests.

O'Neill [8] investigated the failure behaviour of timber-concrete composite floors exposed to standard ISO 834 design fire. Beams were made from Laminated Veneer Lumber (LVL). Two different types of connections between concrete slab and LVL beam were used in each test specimen. First type of connection was notched connection with steel screws and second type was a plate solution connection (i.e. toothed steel plate). Overall two tests with different beam heights (300 mm and 400 mm) were carried out. Main conclusions from the tests were: (i) the LVL beams with the steel plate connection system exhibited stiffer performance and lower deflections when compared with the notched connection beams, (ii) failure of the TCC systems was governed by the charring rate of the timber, (iii) the charring rate on the sides of the LVL beams was found to be 0.58 mm/min on average which is lower than reported values of 0.72 mm/min for plain LVL beams (iv) separation of the double LVL members during the latter stages of burning was noticed, which increased the charring of the LVL beam, (v) the charring rate on the underside of the beams was on average four times as large as the charring rate from either side of the beams, (vi) concrete spalling in the slab was noticed for the lower quality concrete mix. Beside full scale test also series of small scale test to investigate the failure strength and behaviour of the LVL at different temperatures were carried out.

As reported, connections are key component of the TCC systems. It is important to know behaviour of the shear connections in fire conditions, especially how their stiffness and strength varies with temperature. Series of tensile and shear tests of the shear connections with screws at ±45° inclination was presented in [9]. Tests were performed on smaller timber beams with different heights and length of 1 m. Main results of the test are tensile and shear resistance of the connections as a function of the mean temperature around the screw. This data is important for advanced calculation methods of the TCC systems. Noticeable loss of strength and stiffness of the screwed connection was observed. For the fire resistance of TCC slabs simplified design method was developed on the basis of the known as γ-method and is based on reduced cross-section method given in [7]. Method was verified with full-scale TCC tests [5].

Most recently, reports on fire testing of new TCC floor systems can be found [2, 10]. Research of unconventional TCC floor system with timber beams on top and concrete slab on bottom is reported in [2]. The shear connection between timber and concrete is achieved by mechanical interlocking through grooves. Full scale tests were performed with main objective of proving 60-min of standard fire resistance (REI 60). Beside reinforcement multilayer pipe system for surface heating was cast in to the concrete slab. The effective fire resistance rating of the TCC system was proven to be 60 min which can be achieved with minimum concrete cover of 25 mm for the reinforcement. During the test thermal cracks appeared on the upper side of the concrete slab and water from the pipes leaked trough these cracks. Test showed that trapped water within the concrete slab presents no risk since water will eventually evaporate through thermal cracks in concrete. To achieve 60 min fire resistance and not to lose beam-slab connection during the fire a concrete cover of 50 mm is sufficient for the timber beam grooves. Beside tests a numerical model was developed and validated to analyze the temperature profiles for different setups and extensive temperature data from experiment is presented.

Research on fire behaviour of timber-concrete composite slabs made of a thin beech laminated veneer lumber and a concrete layer on top can be found in [10]. Two full-scale tests were performed, first with 80 mm thick LVL plate and 120 mm of concrete layer on top and in second test TCC system was made from 40 mm thick LVL plate with 160 mm covering layer of concrete. TCC slabs were exposed to standard ISO fire. Connection between LVL plate and concrete deck is achieved with notched connection with depth of 15 mm into the LVL plate. To achieve higher fire resistance concrete slab is reinforced with upper and lower reinforcement mesh with covering layer of 20 mm. First TCC system, with thinner LVL plate showed a 90 min fire resistance and integrity while for second system 60 min fire resistance was proven. During the test also an explosive spalling of concrete slab was noticed after the beech veneer plywood either burned away or fall off due to loss of the connection with concrete slab. The complete burn away and fall off of the LVL plate was noticed around 60 min and delamination on contact surface was noticed around 50 min for both tests.

Summary and Concluding Thoughts

Given the review research in field of timber-concrete composite systems, it may be concluded that research data on the fire resistance of TCC systems is still in its early stage of development. All of here presented tests were performed in standard fire conditions. Considering the natural fire and many possible variations of TCC systems more research data, especially on the behaviour of connections in the fire conditions, is needed for full development of advanced calculation tools that are essential for performance based design. As presented in the review, up to now some simplified methods for calculation of fire resistance of TCC systems were developed, yet they were validated in standard fire test conditions and therefore their usage in natural fire conditions is limited. Advanced calculation models for steel-concrete in fire conditions are already well established in performance based design [11], on the other hand advanced models for TCC systems are rare and not fully validated especially in natural fire conditions [12]. Hopefully, future research in this field will lead to full development of advanced TCC models that will be suitable for performance based design and consequently enable wider use of the TCC systems in high-rise buildings.

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Enhanced fire behaviour of wood-based buildings by resource-efficient material wood lightweight concrete

Alireza Fadai[1], Wolfgang Winter[2]

[1] Vienna University of Technology, Department of Structural Design and Timber Engineering, Karlsplatz 13/259-2, A-1040 Vienna, Austria, fadai@iti.tuwien.ac.at

[2] Vienna University of Technology, Department of Structural Design and Timber Engineering, Karlsplatz 13/259-2, A-1040 Vienna, Austria, winter@iti.tuwien.ac.at

Keywords: Wood-based construction, wood lightweight concrete, fire protection, fire resistance

The European countries have to face increased changes in the demands on buildings. A set of new requirements concerning environmental aspects and sustainability is obliged to be translated into the built reality. To reduce dependency on the non-renewable resources, it needs new alternatives especially in the construction sector. The demand can be relieved by recycling and substitution. Wood as a sustainable and an ecological material has an excellent chance to be an alternative construction material in urban areas. The renewable raw material wood is available in a sustainable way; the basic technologies are well known and good examples of wood-based building already exist - in the past few years, an increasing number of wood-based buildings have been constructed in Central and Western Europe e.g. single-family houses, multi-storey condominiums, schools, hospitals and office buildings [1].

Within several research projects and with the aim to optimize structural performance, energy efficiency and ecological characteristics of structural building components the Department of Structural Design and Timber Engineering (ITI) at the Vienna University of Technology (VUT) developed several wood-based composite systems, which combine timber products with other conventional building materials and components. Thus, the timber's fire behaviour can be improved when it combines with other materials [2-6]. As a representative example for these developments, the application of wood lightweight concrete composites illustrates the extent of interrelationships in the development of complex system solutions when focusing on the increase of resource efficiency [7]. The proposed technology combines concrete construction tradition with organic renewable resources as an alternative to conventional concrete or masonry, also opening opportunities to reduce carbon emissions through the increased use of wood for construction. This opens new application fields for a smarter wood-based construction, with an increased volume and use of locally available wood from renewable resources, allowing for substitution of more traditional construction materials by a more ecological, economic and sustainable building technology. Experimental research, design and assessment of structural wood-based wood lightweight concrete (WLC) composites are illustrated in this paper.

Structural building material WLC

WLC is a mixture of cement, wood chips or saw dust, which can be applied for building interior and outer construction. Wood-particles as they are used in WLC are a by-product of the timber production (waste product). The primary advantage of waste wood aggregate (around 90 % of the volume content) is the low weight and high thermal insulation value of the material. WLC is a well-established building material for use in non-structural components. Many products are on the market – cement-bonded wood, wood wool or wood-fibres boards – typically used for insolation and surface finishing. Developments that are more recent deal with WLC bricks and complete monolithic walls elements [8-9]. These developments show new ways in the use of WLC and broke the ground for new fields of application. The newly developed timber-WLC composite elements by the ITI show a new direction to future generations of polyvalent multi-material and highly competitive ecological building components (Fig. 1 and Fig. 2). Due to the used aggregates and additives, WLC compositions can provide differing material characteristics.

Figure 1. Timber-WLC composite floor system.

Figure 2. Timber-WLC composite wall.

Fire safety design and building requirements

The fire regulations in Austria allow building construction in timber up to six floors; higher buildings could be realized with timber-based products in combination with other construction materials providing fire safety. The multi-layer composite elements should also provide a certain fire resistance, beneficial effects with regard to building physics and thermal energy. For timber buildings with over six storeys the building code provides for a permissible special case authorization if a full sprinkler system is installed or if load-bearing timber components and space-enclosing timber components are coated with mineral-based material thus fulfilling the requirements of the permitted “Euro class” A2 (non-combustible) with a fire resistance class REI 90. Since timber components also constitute a fire load that prolongs the fire’s duration the requirement of building material class A2 aims at excluding a longer fire duration and thus preventing the components of buildings with over six storeys from collapsing [5]. However, in multi-storey residential buildings, which are realized as cross-wall construction type, such an application is possible, i.e. physical separation or encapsulation of combustible materials, such that a fire cannot cause the failure.

The Austrian Guidelines are organised according to the basic requirements for construction works of the EU Construction Products Directive. It is issued by the Austrian Institute for Construction Engineering (OIB) upon decision in the General Assembly and are thus available to the federal states. The OIB Guideline 2 [10] provides the framework regarding fire protection in building construction and serves to harmonize the construction engineering regulations. The federal states may declare OIB Guidelines as binding in their building codes, which is already the case in the majority of federal states. However, the OIB Guideline may be deviated from in accordance with the provisions of the relevant regulations of the federal states, if it is demonstrated that an equivalent level of protection in compliance with the OIB guideline is achieved. This is intended to ensure the necessary flexibility for innovative architectural and technical solutions.

Results of current research

The objective of the research projects is to develop innovative wood-based composites as structural building components with distinctly improved fire performance characteristics (Fig. 1 and Fig. 2). The overall goal of the research projects is to improve substantially the fire performance of the timber structure itself, to reduce effectively the need for further safety-ensuring measures. Hereby the aim is to investigate and exploit beneficial thermal effects, which arise when timber is combined with other conventional building materials and components under the extreme conditions of a fire load, while keeping or, ideally, improving the structural efficiency of the building components under regularly assumed mechanical loads.

Tests on fire resistance

The fire safety characteristics of the WLC were identified by explorative tests (Fig. 3). The aim of the test was to contribute to the optimisation of timber-WLC composite constructions in terms of flammability. The specimens were tested and evaluated in fire safety tests (Fig. 4).

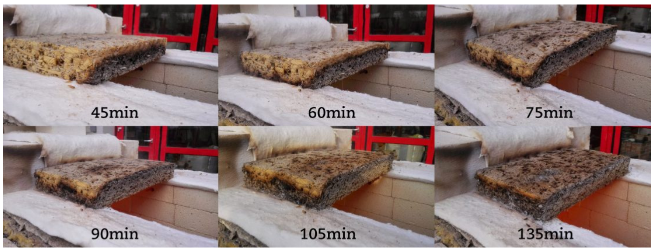

Figure 3. Fire performance of 50 mm prefabricated WLC noise protection chipboard.

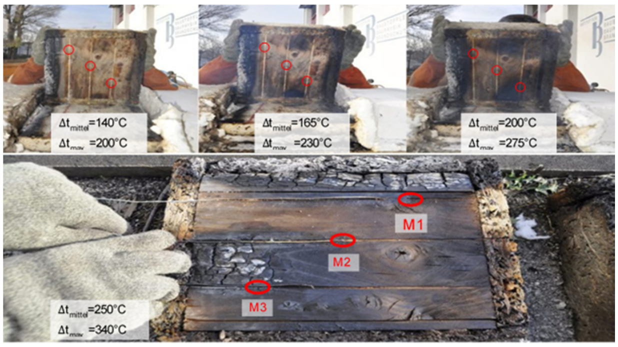

Figure 4. Fire performance of timber-WLC composite wall.

The fire safety characteristics of the most promising conceptual designs for floor and wall elements were developed and analysed.

Conclusions

The test results are compared to traditional configurations in timber/timber-concrete composite. These show that timber-WLC composite constructions considerably contribute to fire resistance without additionally encapsulation of timber. Based on these, buildings containing timber-WLC composite constructions can achieve the same levels of safety as buildings made of non-combustible materials. This shall form the basis for new fire protection strategies, which shall ultimately be drawn up in design guidelines to facilitate implementation in structural design practice.

Acknowledgments

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Practical challenges regarding the improved design method for separating function of timber construction

Kathinka Leikanger Friquin[1], Jorun-Marie Hisdal[2]

[1] SINTEF Building and Infrastructure, PhD, Norway, kathinka.friquin@sintef.no

[2] SINTEF Building and Infrastructure, MSc, Norway, jorun-marie.hisdal@sintef.no

Keywords: fire separating function, external wall, insulating property

In our work at SINTEF Building and Infrastructure we use the improved design method for separating function of timber constructions as given in [1] and [2] frequently in order to determine the separating function of walls and floors. During this work some questions have aroused as to how the method should be applied for certain structures. As EN 1995-1-2 is under a revision we believe it is of importance to look into how the encountered challenges should be dealt with. In this abstract we point focus on the following area: Calculation of the separating function for an exterior wall with ventilated wood cladding when the wind barrier is a thin membrane. This is a very common construction in Nordic countries. The result is strongly dependent on how the layers are defined. The main question is whether the mineral wool or the cladding is the final layer when calculating the separating time, t_{ins}. In the following, different ways the layers can be defined are described, and evaluated.

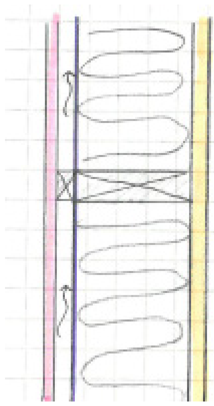

Figure 1. Exterior wall with a thin wind barrier membrane and ventilated cladding

A common exterior wall construction is shown in Fig. 1. From inside to outside; 13 mm standard plasterboard Type A, 48x198 mm solid wood studs, 200 mm mineral wool insulation (glass wool or stone wool), thin wind barrier membrane (typically 0.4 mm), and finally, ventilated timber cladding ventilation void which is approx. 20 mm.

In Fig. 2 three different definitions of the layers are given. In case A, a temperature rise up to 250 °C is allowed on the unexposed side of the mineral wool, i.e. the basic protection time is calculated as $t_{prot.2}$. In case B, it is assumed that the mineral wool is the last layer, i.e. the basic protection time for the insulation is calculated as $t_{ins.2}$. This means that average temperature increase on the unexposed face of the insulation can reach 140 K. And finally, in case C, the wooden cladding is considered to be the last layer, with $t_{ins.3}$. Since the ventilation gap is less than 45 mm, it is not taken into consideration.

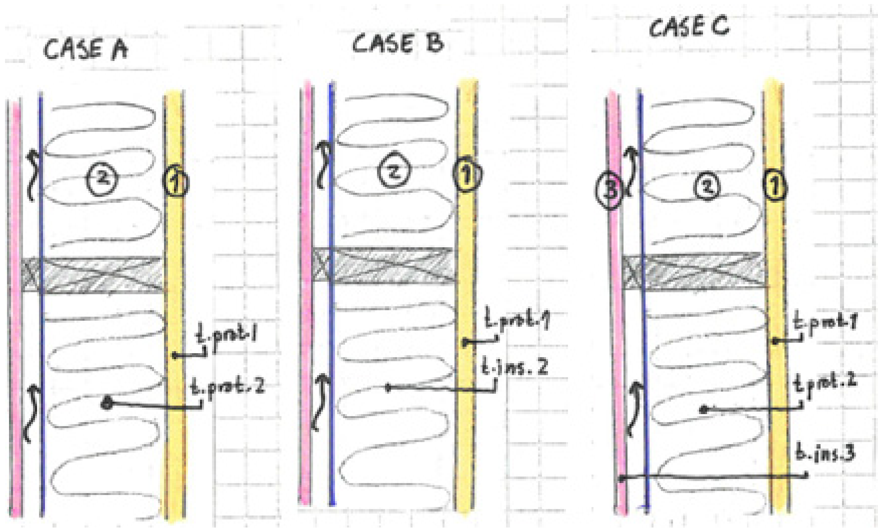

Figure 2. Three different definitions of the layers for the construction in Fig. 1.

Since the wind barrier is a thin membrane, this product will not provide any protection. Therefore, the temperature rise on the unexposed surface of the wind barrier would be equal to the unexposed surface of the mineral wool. It is assumed that the cavity must be closed (no ventilation) in order to have the described effect on the separating function, even though this is not defined in [1] or [2]. The wall in Fig. 1 has however a ventilated air gap and this could both have advantages and disadvantages for the separating function. An advantage would be that the ventilation would transfer some of the heat away by convection possibly leading to a somewhat belated temperature rise on the exposed side of the cladding. On the other hand, the same ventilation could spread warm gasses and smoke, and in worst case, flames in the cavity. This could increase the risk for fire spread. Calculating the separating time it is of interest to determine how long the construction can withhold its integrity (not let hot gasses and smoke through) and insulating ability (not let the temperature on the unexposed side get over a certain temperature). It may not be critical that the temperature rises to 270 °C on the unexposed side of the mineral wool as long as no flames are present. Self ignition of the wood cladding would require a higher temperature than 270 °C.

Therefore, when the wall is filled with stone wool, defining the cladding as the final layer could be a possible approach (case C). However, if the wall is filled with glass wool the situation is different. The glass wool collapses when exposed to fire, and therefore the integrity will fail earlier than for stone wool. When calculating the char depth, d_{char}, for the reduced cross section method, Eq. 1 states the time t_{ins} until the glass wool does not have any ability to protect the studs, where h [mm] is the thickness of the insulation (which equals the height of the stud) and t_f [min] is the failure time of the cladding. The glass wool insulation degrades at a rate of 30 mm/min, which means that an insulation with thickness 200 mm will be completely degraded and have lost its ability to protect the studs after only 6.7 minutes.

$$t_{ins} = t_f + \frac{h}{30\, {mm}/{min}} \qquad (1)$$

However the time until the glass wool lets flames through is probably much shorter. Due to this it might be more correct to consider the glass wool as the final layer for walls filled with glass wool. According to the reasoning above it is probably not critical that the temperature rises to 270 °C (case A), so therefore the protection time could be calculated as $t_{prot.2}$ and not $t_{ins.2}$ (case B) for the glass wool insulation.

An important factor that must be determined is the joint coefficient, k_j. Usually mineral wool is available with thickness that fits the height of the studs, and which fits perfectly between the studs. However, when the mineral wool is installed there will be some minor horizontal gaps. In [1, Tabl. 4.6] joint coefficients are given for wood based panels and gypsum boards, but not for mineral wool as the final layer. This is because it was considered rather rare to have mineral wool as the final layer in a construction. It seems reasonable that the joint coefficient for a layer with a void cavity behind would be the same as for a final layer, and this is also the case in [1, Tabl. 4.6]. Based on this, an estimated guess would be that k_j for t_{ins} for mineral wool could be set equal to 0.8. Further, in [4, Tabl. E6] joint coefficients are given for wood based panels which are not backed by mineral wool. Joint type a) corresponds to the horizontal joint between the mineral wool layers, and k_j then equals 0.2.

The separating time for the wall in Fig. 1 is calculated for the three cases shown in Fig. 2, both for k_j =0.2 and k_j =0.8, for insulation as the final layer, and for external cladding as the final layer, and insulated with glass wool and stone wool. The results are shown in Table 1 and Table 2. The cladding is assumed to be a wooden based panel with thickness 11 mm.

Table 1. Calculation results of separating time for the wall in Fig.1 filled with glass wool

CASE A	**$k_{j.2a}$**		**CASE B**	**$k_{j.2b}$**		**CASE C**	**$k_{j.2c}$**
t_{ins}	**0.2**	**0.8**	**t_{prot}**	**0.2**	**0.8**	**t_{prot}**	**1.0**
$t_{prot.1}$	18.6 min	18.6 min	$t_{prot.1}$	18.6 min	18.6 min	$t_{prot.1}$	18,6 min
$t_{prot.2}$	1.7 min	6.9 min	$t_{ins.2}$	1.2 min	4.9 min	$t_{prot.2}$	8,7 min
						$t_{ins.3}$	0,8 min
t_{ins}	20.3 min	25.5 min	t_{ins}	19.8 min	23.5 min	t_{ins}	28.1 min

Table 2. Calculation results of separating time for the wall in Fig.1 filled with stone wool

CASE A	**$k_{j.2a}$**		**CASE B**	**$k_{j.2b}$**		**CASE C**	**$k_{j.2c}$**
	0.2	**0.8**		**0.2**	**0.8**		**1.0**
$t_{prot.1}$	18.6 min	18.6 min	$t_{prot.1}$	18.6 min	18.6 min	$t_{prot.1}$	18.6 min
$t_{prot.2}$	9.3 min	37.0 min	$t_{ins.2}$	2.5 min	10.0 min	$t_{prot.2}$	46.3 min
						$t_{ins.3}$	0.5 min
t_{ins}	27.9 min	55.6 min	t_{ins}	21.1 min	28.6 min	t_{ins}	65.4 min

Calculations of the separating function according to the improved method [1] give very different results for the wall, based on which value is chosen for $k_{j.i}$ for the insulation layer, and whether or not the external cladding is included. The separating function for the wall with glass wool insulation varies from 19.8 min to 25.5 minutes, when the cladding is not included, i.e. almost 6 minutes. And including the cladding the result is 28.1 minutes. For the wall with stone wool the difference is even larger, ranging from 21.1 minutes to 55.6 minutes, more than 34 minutes without the cladding. Including the cladding, the result is 65.4 minutes.

Based on these results, it is obvious that there is a pressing need to determine how to calculate the separating function in situations where the wind barrier is a thin membrane and the external cladding is ventilated. This is a very common construction in Nordic countries.

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Behaviour of Wall and Floor Assemblies with OSB Firestop Boards

P. Kuklík[1], M. Charvátová[1], J. Pošta[1], P. Ptáček[1], R. Jára[1]

[1] Třinecká 1024, 273 43 Buštěhrad, University Centre for Energy Efficient Buildings CTU in Prague, Czech Republic, kuklik@fsv.cvut.cz

Keywords: OSB FIRESTOP, fire test, fire resistance

This paper is focused on testing of the new product OSB Firestop boards made by Kronospan OSB, spol. s r.o. in Jihlava. The most important result is the behaviour of the new fire board protection. Six fire tests were performed in the laboratory PAVUS, a.s. in Veselí nad Lužnicí and another fire tests are still in progress. Four walls were tested according to the standard EN 1365-1 and a roof panel and a floor panel were performed according to the standard EN 1365-2. The new product OSB Firestop was used in a different assemblies, on the fire exposed side. The first two fire tests performed in 2014 were presented in Barcelona [1].

This new product OSB Firestop differs from the standard wood-based board in a new layer with surface treatment. This layer contributes to fire resistance. The testing plan is prepared for analysis of new board built in different assemblies because there are a lot of requirements for timber structures in terms of fire safety in the Czech Republic.

In the Table 1 all test samples are described. The maximum load or typical load of public buildings is used for walls, floors and roofs in the fire tests. The test of the wall with empty cavity was also performed for analysis of contribution of the new board OSB Firestop to fire resistance. The fire tests of a load-bearing walls were performed on samples with dimensions 3.0 x 3.0 m (One layer cladding with empty cavity, Fig. 1). OSB board with a fire protection cladding (17 mm) was used on the fire exposed side, while an OSB board without any surface finish (15 mm) was used on the fire unexposed side. There were 21 pieces of thermocouples used inside the specimen for measuring temperature. The coating is composed of a cement-based mixture of magnesium oxide reinforced by fibreglass with a thickness of 1.7 (± 0.3) mm. The calculation of fire paints and coatings is not possible according to EN 1995-1-2.

The test of the roof panel was performed with the slope 30°, because the results can be used for roofs form slope from 15° to 45°. Another test is planned for flat roof and results can be applied to the roof up to slope 15°. The clear span of the roof sample was 4,85 m. The value of the load was calculated for the IV. snow zone in Czech Republic where the characteristic value is 2kN/m^2. The OSB Firestop boards were placed above the visible rafters during the fire test of roof. The advantage of this solution is the final surface of the OSB Firestop with fire resistances.

Table 1. Results of test

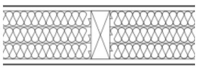
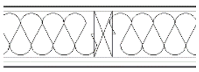
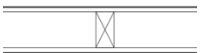
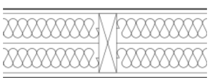
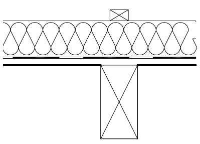
	Diagram	Structure description	Sample description
1	 Wall -REI 45	- OSB Superfinish ECO, 15 mm - Mineral insulation ROCKWOOL - Timber studs 60/120 mm - OSB Pyrotite ECO, 17 mm	Dimensions: 3 x 3 m Loading: 32,04 kN/m One layer cladding with insulation. Distance between centres of the studs is 625 mm.
2	 Wall -REI 60	- OSB Superfinish ECO, 15 mm - Mineral insulation Isover WOODSIL 160 + timber studs 60/160 mm - OSB Pyrotite ECO, 17 mm - OSB Pyrotite ECO, 17 mm	Dimensions: 3 x 3 m Loading: 73,14 kN/m Two layers cladding with insulation. Distance between centres of the studs is 625 mm.
3	 Wall -REI 20	- OSB Superfinish ECO, 15 mm - Mineral insulation ROCKWOOL + Timber studs 60/120 mm - OSB Fire stop ECO, 16 mm	Dimensions: 3 x 3 m Loadng: 32,04 kN/m One layer cladding with empty cavity. Distance between centres of the studs is 625 mm.
4	 Floor -REI 30	- OSB 3 Superfinish P+D, 15 mm - Mineral insulation Isover DOMO + Timber studs 80/200 mm - OSB Pyrotite ECO, 16 mm	Dimensions: 3 x 4,4 m Loding: 2,1 kN/m2 Two layer cladding with insulation. Distance between centres of the joists is 625 mm.
5	 Wall – REI 60	- Fiberboard DFP,16 mm, Tongue groove - Mineral insulation +Timber studs 60/140 mm - OSB Pyrotite ECO, 16 mm	Dimensions: 3 x 4,4 m Loading: 32 kN/m One layer cladding with insulation. Distance between centres of the studs is 625 mm.
6	 Roof REI 30	- Roof battens 30x50 mm - TOPDEK 022 PIR tl. 100 mm - TOPDEK AL BARRIER - OSB Firestop tl. 18 mm - Rafter 100x200 mm	Dimensions: 3 x 5,15 m Loading: 2,0 kN/m2 One layer cladding with insulation. Distance between centres of the rafters is 833 mm and span is 4,85 m.

Figure 1. One layer cladding with empty cavity.

Figure 2. Roof panel with one layer of OSB Firestop.

Results and Conclusion

All planned fire tests have not been finished yet. Only the partial results are available. The fire resistance of the walls with mineral or glass fibres insulation were calculated according to standard Eurocode 5 (part 1-2) in accordance with Annex C. Another fire tests will focused on used materials as blown cellulose or insulation panel (PIR), because the calculation of the fire resistance of these materials in not possible according to standard Eurocode 5 (part 1-2).

Acknowledgments

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[2] EN 1365-1 Fire resistance tests for loadbearing elements - Part 1: Walls

[3] EN 1365-2 Fire resistance tests for loadbearing elements - Part 2: Floors and roofs

[4] EN 1995-1-2 Eurocode 5: Design of timber structures - Part 1-2: General - Structural fire design

Evaluation of differences between the determination of the charring rate following the DIN and EN standard using comparable experimental setups.

Kai Pandtle

Winzererstraße 45, 80797 München, Holzforschung München (Technical University Munich), Germany, kai.pandtle@mytum.de

Keywords: charring rate, wood, test setups, standardisation, fire resistance

The aim of the paper is to provide an insight for the scientific work to develop a foundation for a possible standardized test regime for fire testing on a small scale furnace.

In a first step research about the commonly used test methods was done. Therefore a literature review was done to identify the existing test methods. The literature review contained scientific works that have been published in the past and were analysed regarding the applied test setups and scientific goals. Also the different methods used for measuring the charring rate were part of the research. Another topic in the research was the test procedure. On the other hand, the existing regulations through German and European standardization were analysed with respect to the conducted experiments. In addition to that an overview about the history of the evaluation of the charring rate at the Holzforschung München (HFM) was done. The reviewed standards were compared to each other, especially the DIN 4102-8 (10/2003) and the DIN EN 1363-1 (10/2012). These were chosen because they mainly describe the regulations for standard fire testing.

Using the results of the so concluded state of knowledge regarding the charring rate of wood and wooden products, a series of experiments was performed. The materials used were test specimen made of spruce and a clamping plate because a large amount for data is available for these materials. In addition to these experiments spruce specimen treated with a fire retardant were tested. The experiments were performed on a vertical small scale furnace at the HFM. One aim of the experiments was to show the differences between the national and European standard.

Another goal was to show possible weaknesses and missing regulations in the already existing standards. Using different test setups and test procedures as well as measuring methods a comparison between the influencing factors was concluded. To show the differences between the 2 standards mentioned above first a series of experiments following the DIN 4102-8 (10/2003) was performed. Afterwards using the same materials another set of experiments was done in accordance to the regulations provided by DIN EN 1363-1 (10/2012). Therefore the already existing small scale furnace was modified to fulfil the requirements given by the European code.

In regards of providing a foundation to formulate a European standardized test regime for small scale furnace fire tests in the future another point of interest was to get information were the human factor plays a large role regarding the test setups. This is because the DIN EN 1363-1 (10/2012) mentions the human factor as a source for possible mistakes in the determination of the charring rate [1]. Also other factors that are able to influence the charring rate were analysed. In common standards not all factors are regulated, for example the extinction of the sample isn't formulated yet. Therefore a small amount of experiments was done comparing different methods that can be used to extinguish the test specimen after the experiment. The results then were compared and strengths and weaknesses have been analysed to find the best method available to be taken into concern for standardization.

Because of the various different furnaces used for testing as well as the different test setups and test methods, it wasn't possible to do experiments for every type of test. Nonetheless the commonly used methods on a small scale furnace could all be conducted. The methods used to determine the charring rate were the measurement after the experiment, the method using cone shaped exchangeable specimens, the method using thermocouples and the method where the charring rate can be calculated by determining the moment where the specimen is completely burnt through.

Regarding the measurement after test also a 3D laser scanner was used to determine the char depth. It was also an approach to be able to combine the measurement of the charring rate with the possibility to visualize details on the test sample like if there is a different char depth in certain areas of the specimen. These areas can for example be knots, certain grain areas or the edges where the test specimens are glued together. In addition to that the 3D laser scanning is compared to the normally applied method to evaluate the charring rate in regards of the quality of the achieved results. Another aspect of the Application of this measurement system was to research the possibilities provided for a reduction of the already mentioned human factor, when measuring the char depth after the end of the experiment.

References

[1] DIN EN 1363 1 (10/2012); DIN EN 1363 Fire resistance tests Part 1: General Requirements; German version 1363-1:2012; October 2012

Numerical simulation of the charring of timber structures under non-uniform fires

Franz Richter[1],Guillermo Rein[2]

[1,2] London SW7 2AZ, Department of Mechanical Engineering, Imperial College London, UK, g.rein@imperial.ac.uk

Keywords: Charring, Timber, Travelling Fires, Non-Uniform Fires, Redwood

The increased strive for greener and more sustainable buildings makes timber an increasingly popular material. However, its use is limited by current building codes. A deeper understanding of timber's fire behaviour is required to demonstrate the safety of timber structures. The controlling mechanism of timber's fire resistance (charring) is well documented for standard fire exposures. However, there has been little research into non-standardised fire exposures, such as travelling fires, which are a more realistic representation for large, open plan floors. This report investigates into the charring of timber under such non-standardised fire exposures.

In the first half of the project, three kinetic schemes from the literature were incorporated into Gpyro and extended into one-dimensional models. Their respective performance was evaluated against experimentally determined in-depth temperatures and mass loss rates at several heat fluxes (Fig. 1 and Fig. 2). One model was selected for further calibration, after which good agreement with the experimental data was achieved. A parameter sensitivity test was then carried out, which found that the predicted char depth is most sensitive to the kinetics.

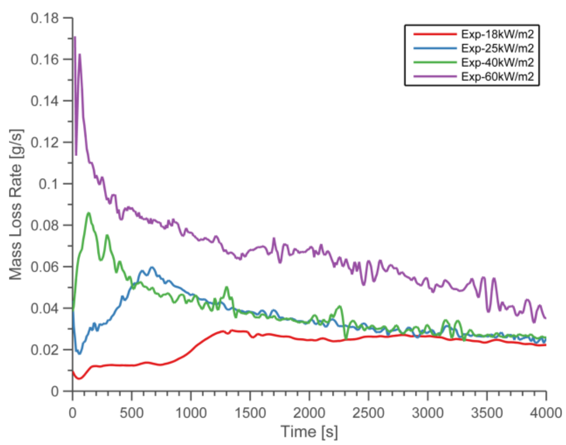

Figure 1. Experimental results of the mass loss rates from [1] at different heat fluxes (18, 25, 40 and 60 kW/m2)

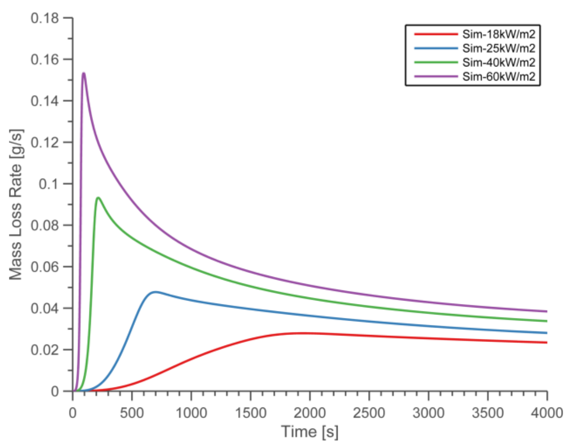

Figure 2. Simulated results of the mass loss rates at different heat fluxes (18, 25, 40 and 60 kW/m2)

In the second half of the project, the model was used to simulate the charring behaviour of redwood (Pinus sylvestris) under different fire scenarios (three standardised and seven travelling fires). It was found that redwood chars to a similar depth for uniform and non-uniform (travelling) fires, with smaller travelling fires leading to increased char formation. The simulations were validated by showing good agreement with values and models from the literature.

Based on the simulations a semi-logarithmic correlation (Eqn 1) between the char depth (c in m) and area under the temperature-time curve (A in °C-s) is proposed.

$$c = 0.04825 \log_{10} A - 0.2856 \quad (1)$$

The correlation achieves excellent agreement with the simulations (Fig. 3). The resultant expression provides an easy design tool for redwood, but further research is required to validate the relation for other moisture contents and wood species.

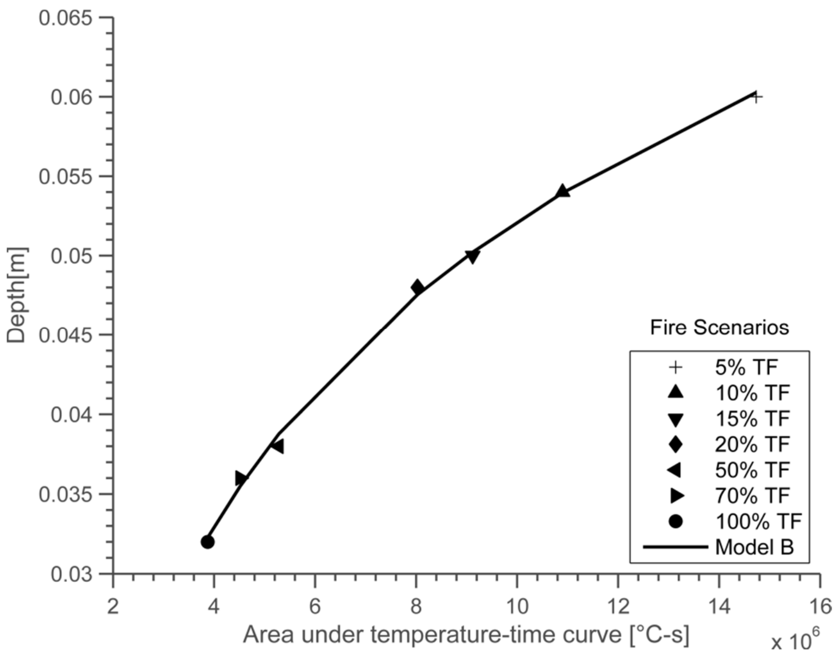

Figure 3. Simulated char depths and predictions by the proposed correlation. TF-Travelling fires, SF-Standard Fire, PFS-Parametric Fire Short, PFL-Parametric Fire Long

References

[1] Reszka, P. 2008 *In-Depth Temperature Profiles in Pyrolyzing Wood*. PhD. University of Edinburgh.

Mini-furnace testing of timber elements exposed to parametric fires

Sofia Månsson[1], David Ronstad[2], David Lange[3] , Lars Boström[3]

[1] Lund University, Lund, Sweden, [2] Luleå Technical University, Luleå, Sweden, [3] SP Technical Research Institute of Sweden, Borås, Sweden; corresponding author: david.lange@sp.se

Keywords: testing, parametric fires, timber.

A series of tests conducted at SP on glulam timber elements in 2013 collected information about the variation in a number of parameters required for determining the fire performance of timber exposed to standard and parametric fires [1]. These tests were conducted on a horizontal furnace. The analysis of these tests included a review of the zero strength layer and the 1-dimensional and notional charring rates of glulam timber when exposed to standard and parametric fires.

Limitations of these tests included: that the calculation of notional charring rate was based on the residual section after the end of the test once the last timber specimen had broken; and that more research was needed to determine the notional charring rates over, e.g. the heating phase only, as well as the charring rates for different fire curves.

To supplement these results, the authors have carried out additional tests using a miniature-furnace with a horizontal opening of 50 cm X 60 cm, using the same timber, from the same beams, as the tests carried out on the fire-resistance furnace. The tests had two different configurations, one to estimate the 1-dimensional charring through a massive timber section exposed to fire from underneath and one to allow us to determine the notional charring rate in a beam subject to 1-sided exposure. Thermocouples were placed in the specimens at distances of interval 10mm from the heated surface. In the 1-side exposed specimens these were inserted from both sides of each of 4 specimens, and in the 3-sided specimens these were inserted from the top of the beam and were positioned along the centreline, Figure 1.

Three different fires were studied, as per the original study. One standard fire, one short hot parametric fire and one long-cool parametric fire. Both configurations were tested twice using each fire and the tests were stopped at different times. One pretest was carried out, with the specimens in place and with the furnace controlled using a plate thermometer and with a shielded thermocouple also placed in the furnace. In subsequent tests the plate thermometer was omitted and the furnace was controlled using the shielded thermocouple following the measured temperatures from the pretests.

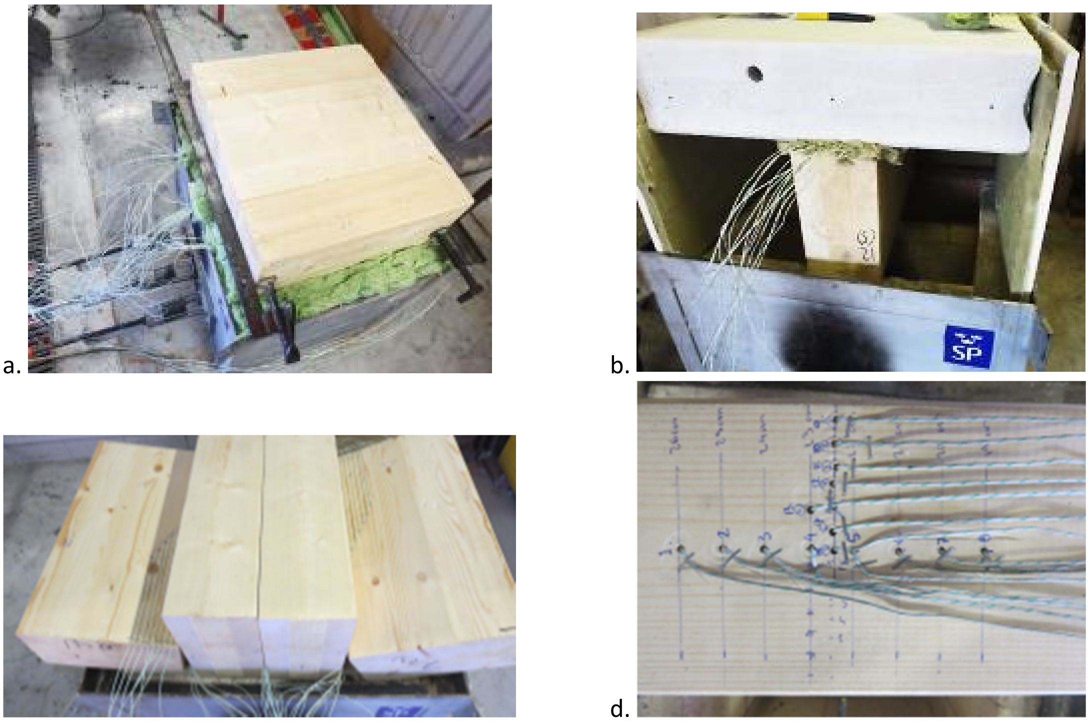

Figure 1. 1-sided (a) and 3-sided (b) exposed specimens, showing thermocouple placement (c and d)

As well as charring rates based on the measured temperatures which will be presented in conjunction with this abstract, we also evaluated the notional charring rates based on a visual inspection of the sections after the tests, a summary of these are given in Table 1.

Table 1. Summary of notional charring rates based on sectional analysis after the tests

Notional charring rate (mm/min)	fire curve	Phases	total exposure duration
1.0	Standard fire		60 minutes
0.8	Standard fire		90 minutes
0.9	Short hot	including cooling phase	60 minutes
2.0	Short hot	Heating phase only	25 minutes
0.6	Long-cool	including cooling phase	120 minutes
0.9	Long-cool	Heating phase only	60 minutes

References

[1] David Lange, Lars Boström, Joachim Schmid and Joakim Albrektsson; The influence of parametric fire scenarios on structural timber performance and reliability; SP Report 2014: 35; ISBN 978-91-87461-78-1

Experimental study of upward and lateral flame spread on MDF boards in corner configurations

Davood Zeinali, Tarek Beji, Georgios Maragkos, Joris Degroote and Bart Merci

Department of Flow, Heat and Combustion Mechanics, Ghent University, Belgium
Davood.zeinali@ugent.be

Keywords: flame spread, corner fire, single burning item test

The focus of this study is the nature of flame spread in corner configurations on Medium Density Fiber (MDF) boards. A set of experiments have been conducted [1] in the form of standard Single Burning Item (SBI) tests [2]. The work constitutes part of a more extensive experimental campaign designed to study this type of fires. The repeatability of the tests has been evaluated in terms of flame spread development, panel temperatures and global heat release rate, as well as heat fluxes at several characteristic points. The backside boundary condition of the corner fire and the level of symmetry of the thermal attack on the boards have been examined using the distribution and evolution of temperatures through the thickness and at the backside of the boards. The development of flame spread has been recorded via video cameras from two different angles which helps tracking the flame fronts and examining the symmetry of the flame spread on the two boards. Heat fluxes are measured using Schmidt-Boelter heat flux gauges, and the evolution of the total Heat Release Rate (HRR) and Smoke Production Rate (SPR) is determined based on the oxygen depletion technique by extracting the combustion gases.

The conducted tests comprise of three SBI tests, each with a duration of 20 minutes. For the most part of the test, the total HRR and SPR indicate reasonable repeatability as shown in diagram ‘a’ in Fig. 1. Nevertheless, divergences manifest toward the final minutes as fire starts to penetrates through the MDF corner. Most visibly, SPR in one of the tests starts diverging considerably from the other tests as early as 10 minutes into the experiments. As shown in the contour plots in Fig. 1, the symmetry of the backside temperatures on the two panels is similarly affected in the final minutes. Accordingly, the boundary condition at the backside of the burning panels proves repeatable amongst the tests up to about 15 minutes into the tests. The total heat flux measurements is less affected in the final minutes of the tests when compared to the other quantities measured (see diagrams ‘b’ to ‘d’ in Fig. 1). Through-thickness temperature measurements could help assessing the global evolution of temperatures within the panels and quantifying the level of symmetry of the thermal attack on the two panels which was found reasonable during most part of the tests. The fire growth is additionally characterized by tracking the flame heights and the propagation of the laterally spreading flames via software analysis.

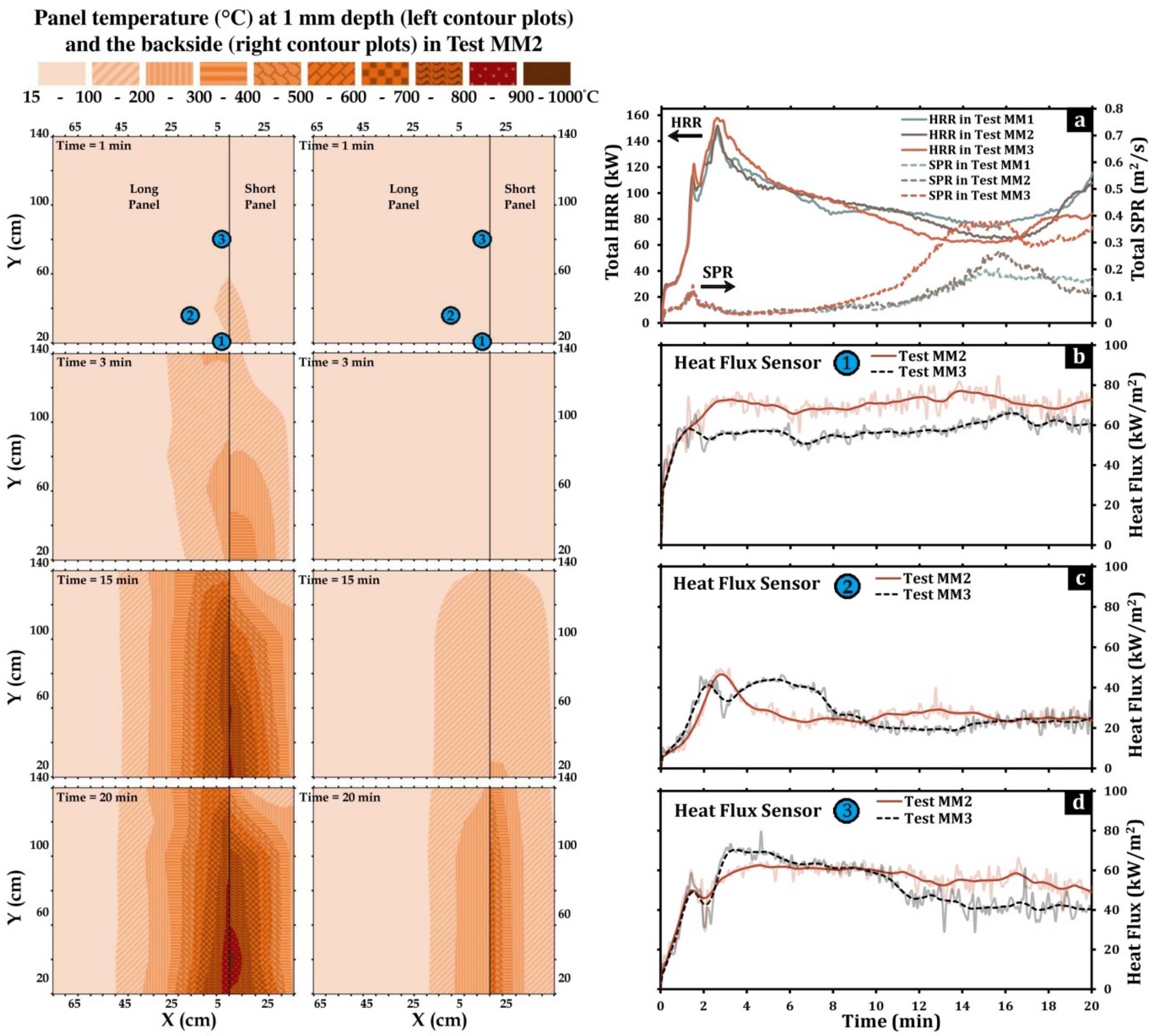

Figure 1. The evolution of the measured panel temperatures in Test MM2 (contour plots to the left), HRR and SPR (diagram 'a' to the right), and heat fluxes (diagrams 'b' to 'c'): X and Y on the contour plots denote the distance from the corner and the height from the bottom of the panels, respectively.

Acknowledgments

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[2] EN 13823, Reaction to Fire Tests for Building Products (2002) Building Products Excluding Floorings Exposed to the Thermal Attack By a Single Burning Item, European Standard, 2002.

Working Group 3

Fire Safety Engineering – Opportunities and Challenges for Timber Buildings

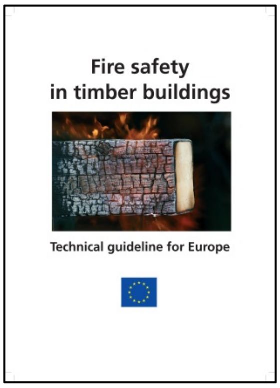
Birgit Östman[1]

[1] SP Technical Research Institute of Sweden, Wood Building Technology,
Box 5609, SE-114 86 Stockholm, Sweden, Birgit.Ostman@sp.se

Keywords: fire safety engineering, life safety, property loss prevention, performance based codes

The combustibility of timber is one of the main reasons that many building regulations strictly limit the use of timber as a building material. As fire safety is an important criterion for the choice of building materials, the main precondition for an increased use of timber as a building material is adequate fire safety.

World-wide, several research projects on the fire behaviour of timber structures have been conducted over the past decades, aimed at providing basic data and information on the safe use of timber. Novel fire design concepts and models have been developed, based on extensive testing. The current improved knowledge in the area of fire design of timber structures, combined with technical measures, particularly sprinkler and smoke detection systems, and well-equipped fire services, allow the safe use of timber in a wide field of application. As a result, many countries have started to revise their fire regulations, thus permitting greater use of timber. A European guideline for the fire safety design of timber buildings has been published [1].



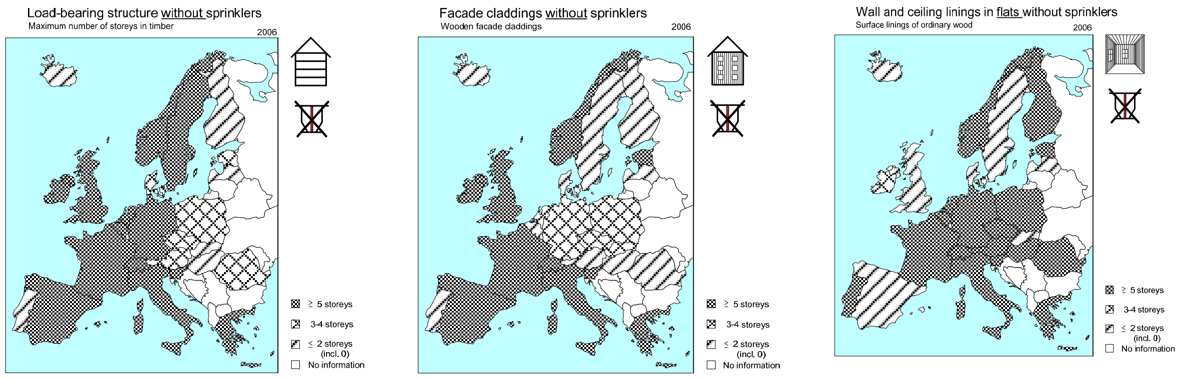
The very first Europe-wide technical guideline on the fire-safe use of wood in buildings has been published [1].

The technical guideline contains all essential information on the fire-safe use of timber structures and timber products which fulfil the European fire requirements. It also provides instructions for the design of timber structures in accordance with Eurocode 5 and practical guidelines for fire safety with clear examples. The content is intended for those working with timber and fire safety, e.g. architects, engineers, educators, authorities and the construction industry. www.sp.se/FSITB

National differences

Fire test and classification methods have been harmonised in Europe, but regulatory requirements applicable to building types and end users remain on national bases. Although these European standards exist on the *technical level*, fire safety is governed by national legislation, and is thus on the *political level*. National fire regulations therefore remain, but new principles for Fire Safety Engineering create opportunities and challenges for harmonised views on timber buildings.

Major differences between European countries have been identified, both in terms of the number of storeys permitted in timber structures, and of the types and/or amounts of visible wood surfaces in interior and exterior applications. Several countries have no specific regulations, or do not limit the number of storeys in timber buildings. However, a maximum of eight storeys is often used as a practical and economic limit for the use of timber structures. This limit may be higher for facades, linings and floorings, since these applications may also be used in, for example, concrete structures.



Restrictions of the use of timber structures and wood products in higher buildings, set by national prescriptive regulations, are different for different types of applications [1, 2].

Fire Safety Engineering - FSE

Fire Safety Engineering and performance based design create opportunities and challenges for harmonised views on timber buildings. A performance-based approach to fire safety design relies on the use of fire engineering principles, calculations and/or appropriate modelling tools to satisfy building regulations. Instead of prescribing exactly which protective measures are required, it is the required performance of the overall system that is presented against a specified set of design objectives. Fire and evacuation analysis is used together with experimental evidence to assess the effectiveness of the protective measures proposed in the fire safety design of a building.

The main principle in applying performance-based requirements is that the building should be designed and executed on the basis of design fire scenarios, which must cover the conditions which are likely to occur in the building. The following objectives must be shown to be fulfilled:

- Load-bearing capacity of structures must not be adversely affected when exposed to fire for a minimum specific period of time
- The generation and spread of fire and smoke must be limited
- Spread of fire to neighbouring areas or buildings must be limited
- Occupants must be able to leave the building or be rescued

- The safety of rescue teams must be taken into consideration.

This leads to the need for defining criteria to satisfy life safety objectives (safety of occupants and rescue teams) and criteria for loss prevention.

National building regulations may define performance criteria to be applied in structural fire safety engineering design, such as:

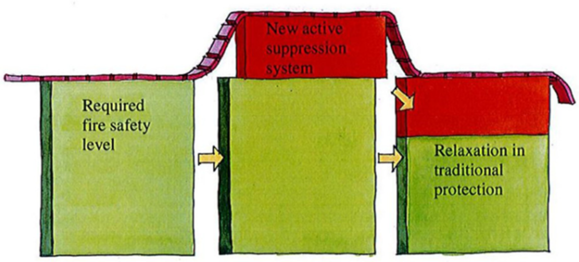
- A building of more than two storeys must not collapse during the fire or cooling phase, *or*
- A building of not more than two storeys must not collapse during the period of time required for securing evacuation, rescue operations and controlling the fire.

Performance-based regulations and standards have long been proven an effective way to facilitate innovation. A Nordic system was developed already in the 90-ties [3] and international standards are available [4]. However, several necessary elements are needed to ensure a creative yet robust environment. Unlike prescriptive regulation, performance based regulations do not specify how to achieve fire safety, thus allowing a variety of different possible solutions. New verification methods exist and new research provides a common basis for the implementation of innovative methods. In order to develop a more practical approach for FSE, Nordic standards are being developed [5] to facilitate innovation, freedom of trade but also consistency.

Active fire protection

The main reason for using active fire protection is to gain time for safe evacuation. The use of active fire protection measures is also the only way of controlling or suppressing a fire in order to minimise fire damage to contents and buildings. It is often advantageous to include expert fire safety input in the design of a building at a very early stage in order to ensure that the building will be acceptably safe in the event of fire, and also be cost-effective to design, build, operate and maintain. In contrast to passive fire protection, active fire protection systems become operational only when a fire occurs. Sprinklers are the most important type of active fire protection suitable for timber buildings.

Sprinklers save lives. In addition to saving lives, sprinklers may allow for an alternative design of buildings. Requirements on passive fire protection to provide means of safe egress may be at least partly reduced. This will facilitate a more flexible use of alternative building products. Wooden facades may, for example, be used in sprinkled buildings, which is logical since the risk of flames out of a window from a fully developed fire is eliminated.



Principle for fire safety design by sprinklers:

Increased fire safety by installation of sprinklers may lead to relaxations in the passive fire protection features, and still fulfil the same or higher safety level [6].

The implementation of alternative fire safety design with sprinklers may vary between countries. In Sweden four alternatives have been verified, if sprinklers are installed [6]:

- Combustible façade cladding up to eight storeys
- Decreased requirements on surface linings in apartments in multi-storey buildings, down to class D-s1,d0
- Decreased requirements on fire spread through windows in the same building
- Increased walking distance in escape routes.

Property loss prevention

National building regulations usually have the main focus on saving lives, but there is also an increasing interest in property loss prevention, especially from the insurance companies. Many of those have limited experience of large and high timber buildings and limited technical expertise. They therefore fear both larger property losses and water damages in timber buildings.

Opportunities

Fire safety engineering and performance based design offer a lot of benefits and opportunities for increased timber building, e. g. a more harmonised view on how to fulfil national fire requirements and insurance requirements. This will remove or reduce the still existing obstacles to trade within Europe and also facilitate for a more globalised market.

Challenges

There are a lot of challenges to overcome before reaching possibilities to utilising FSE for timber buildings. The most important are to ensure

- Quality of construction workmanship and inspection and Fire safety during construction, since proper detailing is the main challenge to reach fire safety
- Control of the main strategies to reach property loss prevention in relation to other types of buildings
- Control of the main strategies to avoid collapse of the building in case a fire is not extinguished by an automatic active system or by the fire services.

Acknowledgments

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Fire behaviour of cross-laminated timber (CLT)

Michael Klippel[1], Andrea Frangi[2]

[1] Institute of Structural Engineering, ETH Zurich, Switzerland
klippel@ibk.baug.ethz.ch

[2] Institute of Structural Engineering, ETH Zurich, Switzerland

Keywords: Cross-laminated timber; fire behavior; fire tests; charring rate; fire design

Introduction

Cross-Laminated Timber (CLT) is currently used in modern timber for load-bearing wall, floor or roof elements as a high quality, innovative and cost-effective structural element. Careful planning and implementation ensures the safe use of CLT in buildings with increased fire protection requirements and in accordance with the requirements of building-design standards (e.g. EN 1995-1-1 and EN 1995-1-2) [1,2]. At the Institute of Structural Engineering (IBK) at ETH Zurich, research projects on the fire behaviour of CLT have been carried out to investigate the influence of different cross-sectional build-ups and various adhesives on the fire resistance of CLT floor and wall elements. This paper summarizes the main results of extensive experimental studies at the ETH and at other institutes worldwide. Further, the paper gives fire design recommendations for CLT and further shows future research needs.

Overview on fire tests

Table 1 gives an overview on conducted and documented fire tests on CLT elements using accredited furnaces. It should be noted that the fire behaviour of CLT was also studied in full-scale compartment tests or on small sized elements using a radiant heat panel. However, in the present perspective, only furnace tests are considered. The most important conclusions drawn from these extensive experimental investigations can be summarized as follows:

- More than 30 fire tests on CLT wall and 70 fire tests on CLT floor elements can be found in the literature. This list does not include commercial fire tests for approval of the products that are usually performed by each company.
- All results should be critically examined because preparation and execution of fire tests have a major impact on the quality and therefore the validity of the results.
- The charring depth increases non-linearly with increasing fire duration, mainly due to fall-off of charred layers. The charring rate should be evaluated for each layer separately, if possible. Therefore, correct installation of the thermocouples in the adhesive joint between the individual layers is elementary. It is recommended to install the thermocouples already in the production of the CLT element. A subsequent installation by means of drilling holes can be problematic and distort the results.

- Test results indicated that the behaviour of thinner layers in case of fire is worse than the behaviour of thicker layers.
- The fire tests showed a different fire behaviour for CLT wall and floor elements.
- For floor elements, a local falling off of charred layers was observed. This resulted in an increased charring rate in these areas. In contrast, a local falling off of charred layers was not observed or only slightly pronounced in CLT wall fire tests.
- For a fire resistance of 30 minutes, there will be nearly no influence of falling off of charred layers, as only the first layer will be charred, but for a fire rating of 60 and more minutes a clear difference in the residual cross-section is expected.
- It has to be noted that the fire resistance of a CLT element is not linearly related to the charring rate, as the charring of a perpendicular layer with low stiffness and strength properties, has nearly no effect on the overall load-carrying capacity.

Table 1. Overview documented fire tests on CLT elements

Ref.	Author	No. of tests	Investigated parameters
[3]	Frangi et al. (2008)	10	Layer thickness, number of plies, wall and floor elements
[4]	Frangi et al. (2009)	11	Layer thickness, number of plies, adhesive
[5]	Teibinger und Matzinger (2010)	12	Layer thickness, number of plies, adhesive, wall and floor elements, with and without encapsulation, encapsulation
[6]	Wilinder (2010)	27	Layer thickness, adhesive, with and without encapsulation
[7]	Craft et al. (2011)	6	Adhesive, with and without encapsulation, encapsulation
[8]	Friquin et al. (2011)	6	Layer thickness, number of plies, fire curves
[9]	Gustaffson (2011)	2	Encapsulation
[10]	Osborne et al. (2012)	8	Layer thickness, number of plies, wall and floor elements, with and without encapsulation, encapsulation
[11]	Menis (2012)	7	With and without encapsulation
[12]	Aguanno (2013)	8	Number of plies, with and without encapsulation, encapsulation
[13,14]	Schmid et al. (2013, 2015)	16	Layer thickness, number of plies, with and without encapsulation, encapsulation
[15]	Klippel et al. (2014)	10	Layer thickness, number of plies, support conditions

Fire design of CLT

Based on the mentioned experimental investigations, the following conclusions can be drawn for the fire design of CLT elements:

- As the basis of the fire design of CLT elements, the reduced cross-section method according to EN 1995-1-2 [2] should be used. To determine the residual cross-section of floor elements, the following two boundary situations should be considered:
  (1) If the individual charred layers of the CLT panel do not fall off, the forming charcoal layer protects the remaining CLT cross-section against heat. In this case, the CLT panel has a similar fire behaviour as solid wood and the one-dimensional charring rate of β_0 = 0.65 mm/min can be assumed.
  (2) If local falling off of the charred layers occurs, the fire protective function of the charcoal is lost. After the charred layers have fallen off, an increased charring is expected due to the increased fire temperature. This phenomenon is similar to the increased charring observed for protected timber surfaces after failure of the fire protective cladding. This phenomena can be considered using a double charring rate for the second layer (and the subsequent layers) for the first 25 mm of depth when falling off of the first layer occurs, thus β_0 = 1.30 mm/min for these layers.
- For wall elements, the effect of falling off of charred layers was not significant in the performed experiments. However, load-bearing and unprotected wall elements should be carried out with at least 5-ply CLT elements to prevent buckling as a result of eccentric loading due to fire and thus charring from one side. With regard to the fire resistance, a thicker outer layer (30-40 mm) is generally beneficial so that a possible local falling off of charred layers occurs after about 45-60 minutes exposure to fire.
- Examples for fire design of commercial CLT floor elements in [15] showed that falling off of charred layers for common cross-laminated timber panels and typical fire design situations has no influence on the design of the panel configuration. As a consequence, the fire design should not govern the design of a CLT element and thus no change of the layered structure is expected (regardless of the adhesive). The thickness and number of layers is rather given by the design at normal temperature (SLS), such as vibration, deflection, etc.

Conclusion and Research needs

The residual cross-section of CLT elements can reliably be determined. In order to use the reduced cross-section method according to EN 1995-1-2 [2], in addition to the charring rate a second parameter is of importance, namely the so-called “zero-strength layer d_0”. This d_0 value considers the losses in strength and stiffness of the residual cross-section close to the char layer due to the elevated temperatures in this area. Nowadays, a general zero-strength layer thickness of d_0 = 7 mm is being used in Europe for the fire design of CLT. However, it has been also shown that d_0 is not a constant value and the thickness of d_0 depends on different parameters, such as the CLT layup, the applied load and the fire resistance [16].

In future research projects on the fire behaviour of CLT, the thickness of the zero-strength layer should be determined. Thereby, it is very important that this determination should ensure a safe fire design of CLT and equally provide an economically and ecologically worthwhile use of the product.

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Protection by gypsum plasterboards - state of the art

Alar Just[1,2], Kairit Kraudok[1], Joachim Schmid[2], Birgit Östman[2]

[1] Ehitajate tee 5, 19086 Tallinn, Tallinn University of Technology, Estonia, alar.just@ttu.ee

[2] SP Wood Building Technology, Sweden

Keywords: fire protection, fire design, gypsum plasterboards

Introduction

A design model for the determination of the residual cross section of the timber member with claddings (linings) of gypsum boards or gypsum boards backed with wood-based panels and cavity insulation of rock or glass fibre exposed to ISO 834 standard fire exposure was developed by König and Walleij [1]. Based on the research, the failure time of the gypsum cladding (loss of stickability) is dependent on two parameters, (i) the mechanical degradation of the material and (ii) the length of the fasteners where charring occurs behind the lining. The method is a basis for the design procedure by EN 1995-1-2 [2].

The charring of wood studs protected by gypsum plasterboards has been studied at SP Trätek by Östman and Tsantaridis [9]. As a result, a simple small scale technique was developed to measure the temperature behind the gypsum boards and the charring depth of wooden studs. Based on the results, the use of gypsum plasterboard, irrespective of type, increases the time to reach the start of charring temperature in wood stud.

Sultan [3][4] has investigated the effects of the set-up of the assembly on its fire resistance, by conducting a large number of full scale tests for timber lightweight wall and floor assemblies with gypsum boards. He has found that the temperature of gypsum board when the first piece falls off is not an appropriate criterion for gypsum board failure, as it varies too extensively with no identifiable correlation to assembly parameters.

In Switzerland, a comprehensive research project on the behaviour of protective claddings made of gypsum boards and wood-based panels was carried out in ETH Zurich and as a part of it, the fire behaviour of gypsum boards was investigated with a large number of model-scale fire tests by Schleifer et.al. [7]. As a result, a component additive method was developed for the verification of the insulation and integrity criteria of timber frame wall and floor assemblies with gypsum boards, which was also published in “Fire safety in timber buildings. Technical guideline for Europe” [5].

Analysis of the database

A database with data from full-scale fire test reports with assemblies including claddings made of gypsum plasterboards in accordance with EN 520 and gypsum fibre boards in accordance with EN 15283-2 was collected at SP Technical Research Institute of Sweden. The database consists of results of 388 full-scale tests from different institutes all over the world, although mainly from Europe.

The first analysis of the results of the full-scale fire tests was carried out by Just et al. [6] and the results of the analysis were published in the „Fire Safety in Timber Buildings. Technical guideline for Europe“ [5]. The analysis is based on minimum values of the protection times. The present analysis is performed by determining 5% fractile values and is based on an increased number of test data. Thicknesses (depths) of claddings that deviate from the most common thickness by ±2 mm, are grouped together and analysed. Those deviating by more than 30 minutes, were removed from the further analysis of the database. And in case there are less than 6 values for a certain thickness group, the 5% fractile for this group was not analysed.

Results and discussions

Based on the analysis the following conclusions can be made:

The scatter of the protection times is considerable. Design equations in EN 1995-1-2 do not satisfy most of the cases of start time of charring measured from full-scale fire tests. However, protection times calculated according to improved component additive method [7] and the 5% fractile analysis [8] of the database show very good correlation. See *Figure 3* and *Figure 4*. Thus, the improved component additive method is recommended to be used for determining start time of charring behind gypsum plasterboards.

Design values for the failure times of gypsum claddings, Type F (fire rated), based on 5% fractile analysis are proposed in *Figure* 5 to *Figure* 8. The variability of test results is large. Determining of product specific parameters or an improved classification system is recommended.

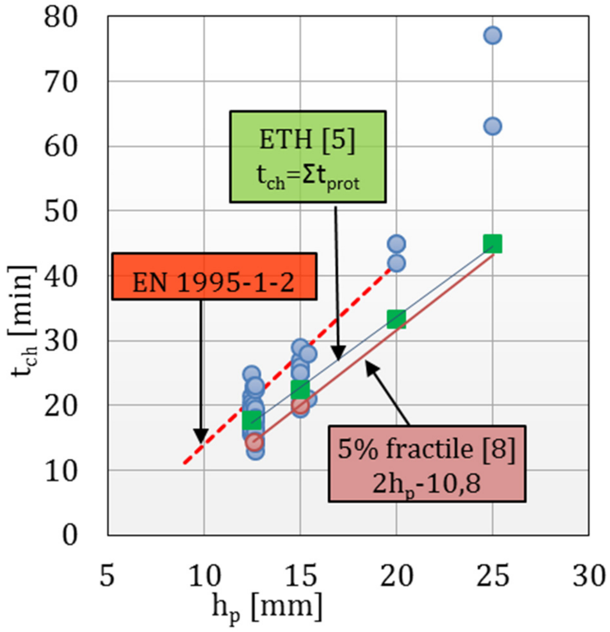

Figure 3. Full scale tests with recorded start time of charring behind one layer cladding of gypsum plasterboards. 5% fractile values compared to EN 1995-1-2 method and component additive method [5].

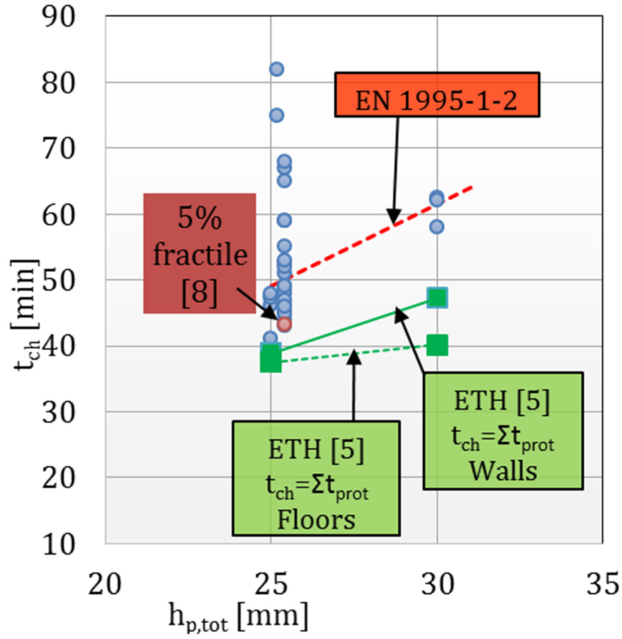

Figure 4. Full scale tests with recorded start time of charring behind two layers cladding of gypsum plasterboards, Type F. 5% fractile values compared to EN 1995-1-2 method and component additive method [5].

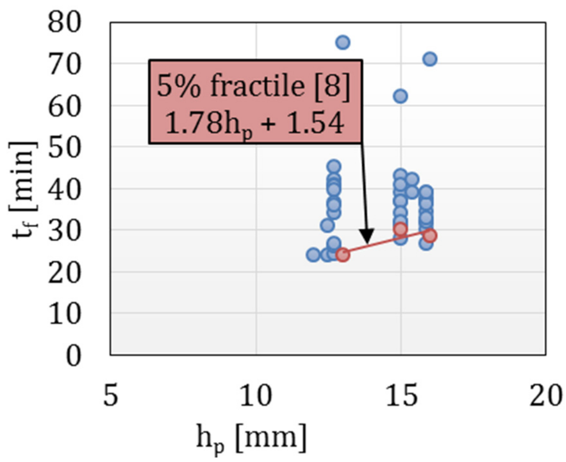

Figure 5. Failure times of floor claddings of single layer of type F gypsum boards

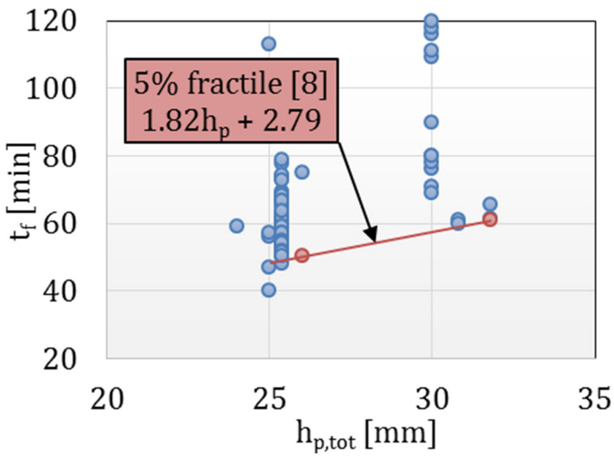

Figure 6. Failure times of floor claddings of 2 layers of type F gypsum boards

The analysis should be carried on. There is a need to add new data to the database, see Figure 9. Institutes and industry partners are asked to provide anonymized data sets. The results of this analysis can be a basis for the improvement of design methods in revision of EN 1995-1-2.

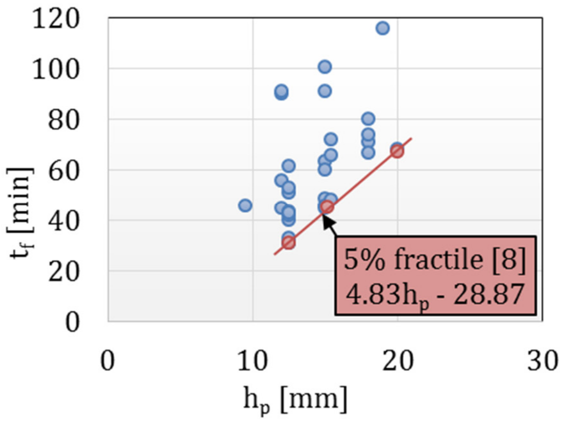

Figure 7. Failure times of wall claddings of single layer of gypsum boards type F.

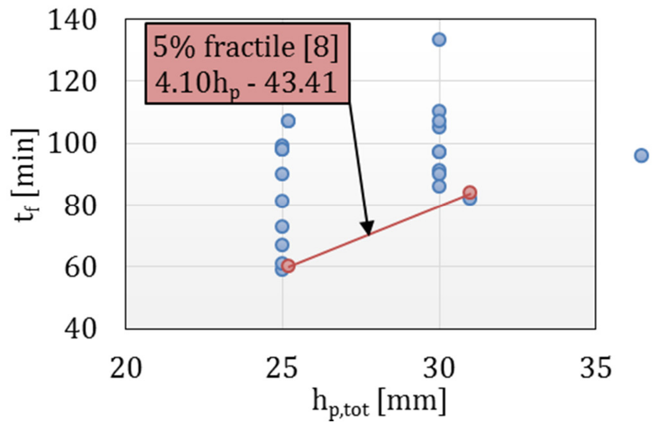

Figure 8. Failure times of wall claddings of 2 layers of gypsum boards type F.

Figure 9. Test results needed to complete the 5% analysis.

Gypsum board	Assembly	Number of layers	
Type A	Wall	1	15 mm
		2	30 mm
		3	
	Floor	1	
		2	
		3	
Type F	Wall	1	
		2	
		3	
	Floor	1	
		2	
		3	

- the number of test results of this type is sufficient (more than 6)

- more test results of this type are needed for all thicknesses of gypsum boards

15 mm - more test results of this type are needed for this certain thickness of gypsum board

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Fire Safety in Towns with Wooden Buildings. Experience from Investigation of Large Fires.

Anne Steen-Hansen[1], Karolina Storesund[1], Ragni Fjellgaard Mikalsen[1], Jan P. Stensaas[1], Andreas Gagnat Bøe[1] and Kristian Hox[1]

[1] SP Fire Research AS, Norway, anne.steen.hansen@spfr.no

Keywords: wildland urban interface fire, wooden buildings, fire preventive measures

Introduction

Wood has been used as a building material in Norway and in several of the other Nordic and North European countries for centuries, and is still a very popular construction material, both for private homes and for other types of buildings. One problem is that wood represents a fire risk that is higher than for non-combustible materials like concrete and bricks, and this fire risk has to be dealt with to obtain an acceptable level of fire safety in areas with a large number of wooden buildings. There has been many fires in wooden towns during the history. Lessons about how to improve the fire safety have been learnt, new preventive measures have been implemented, leading to more fire safe use of wood in both new and existing buildings.

180 areas with densely built wooden houses with value as cultural heritage have been identified in Norway. The authorities in many of these settlements have been focusing on fire safety for many years; fire safety preparedness plans are developed, fire preventive measures are installed and fire excercises have been performed. However, the fire safety in many areas with densely built wooden houses is still insufficient. In the past 10-15 years Norway has experienced several large fires in wooden buildings and through investigation of some of these fires valuable knowledge about fire spread in such buildings has been gathered and represents a good base for improving fire safety in both older and modern buildings constructed from wood.

Experience from the large fire in the municipality Lærdal in Januar 2014 has improved our knowledge about conflagration fires in towns [1,2]. Another source of knowledge is the fire preventive work in the Norwegian historical mining town Røros, which is listed on UNESCO´s list of the world´s cultural heritage [3,4]. The work in Røros led to development of official guidelines on how to enhance the fire safety in historic towns with densely built wooden houses. These guidelines will also be applicable to fire safety work in wooden towns in general, not only in towns with historic values.

The large Fire in Lærdal, January 2014

In the evening of the 18th of January 2014 a fire started in a private home in the small municipality Lærdal in the western part of Norway. There were strong winds, there had been very little precipitation during the last month, the ground was dry and without any snow. The fire spread quickly, heavy showers of glowing sparks and pieces of burning material spread the fire from house to house and to the vegetation in the hillsides around the community. The building where the fire started and in the area nearby were all built in the 1950's, and can be described as regular Norwegian residential single family houses. There was a considerable risk that the fire would spread to a large area comprising of listed cultural heritage wooden buildings from the 18th and 19th centuries. The telecom building was damaged by the fire at an early stage, which disrupted the telecommunication and severely complicated the organization of forces during the fire. Several fire brigades, the Civil Defence, Red Cross and many private volunteers put in a tremendous effort to control the fire and succeeded in protecting many residential homes and most of the listed buildings. Despite their efforts 40 buildings burnt down, including 17 residential homes and 3 listed buildings. 681 people were evacuated during the fire. Fortunately, no persons were seriously injured during the blaze.

SP Fire Research investigated the Lærdal fire, and the main goal of our project was to describe how the fire spread from the first house to the nearby buildings and further on. We also aimed to identify factors that helped restricting the fire spread, and factors that contributed to preventing buildings in critical positions from being ignited. Such factors may be connected to either fire preventive measures or to firefighting efforts.

The purpose of this work was to obtain new knowledge, both regarding fire spread mechanisms, and regarding measures that may prevent or restrict damage in large fires like this. Another objective was to identify areas where more knowledge is needed, knowledge that may become helpful in preventing and restricting future fires. The risk of large fires, both wildfires and fires in built environment, is regarded to be relatively high in periods with dry and windy weather, and can be considered as a consequence of a changing climate.

Several methods were used to obtain information about the fire in Lærdal and the surroundings and to collect updated knowledge about spread of large fires:

- Literature study
- Inspection of the fire scene
- Interviews with witnesses
- Study of photo and video material

By applying the different methods we were able to put together pieces of the complete picture that describes the fire. Our study does not include assessment of the firefighting efforts from fire brigades or other organisations or volunteers. Cost effectiveness of the different fire preventive and mitigating measures has not been assessed.

Large fires can spread in vegetation and built environment by a number of mechanisms, that can occur separately or in different combinations:

- Firebrands
- Thermal radiation
- Direct flame exposure
    - flame contact from building on fire
    - flame contact via vegetation

Wind is one of the most important factors for fire spread in wildfires and will affect both the combustion rate and the speed of fire spread [5]. Wind increases the oxygen supply, influences the direction of fire spread, dries the unburnt fuels, carries sparks and firebrands ahead of the main fire and preheats fuels ahead of the fire.

A large fire will also affect the air draughts in the surroundings. Hot smoke and air flow upwards and air from areas outside the fire will then flow along the ground into the flames. This can be thought of as the bonfire effect [6]. Wind may bend fire plumes and in this way increase the heat exposure downstream the fire. Strong wind will also effectively mix fresh air into the fire plume. In very large fires there may be a deprivation of oxygen in the centre of the fire, which leads to lower temperatures and a less intense fire in the central zone. Strong wind may prevent this oxygen deprivation to develop and more complete combustion with high temperatures is the result. The flame zone will be more concentrated and have higher temperatures when exposed to strong wind than without wind exposure.

Moisture content in building materials of wood may have been an important factor leading to the rapid fire spread. The weather in Lærdal had been very dry the month before the fire, and the relative air humidity (RH) the last days before the fire was steady abut 31-33%. It was of interest to study how this could have affected the moisture content of vegetation and construction materials. Wood with low moisture content will ignite more easily than wood with higher moisture content [7], and will burn fast with a high intensity. For a RH of 30% and a temperature in the range 0-25 °C, the equilibrium moisture content in wood materials can be estimated to 6-7% [8].

So what did we learn from the Lærdal fire?

- The first lesson learned was that large fires can happen also in Norway, even in winter time. This was one of three large fires during the winter 2014. May we expect more large fires with future climate changes?
- The second lesson learned was the high speed of fire spread between Norwegian houses by ignition from glows and firebrands, and how chaotic a fire like this may be. The combination of strong wind, fire brands and radiated heat from burning houses was critical.
- The third experience was that it is possible to stop such a fire from spreading by applying efficient details in the building structure, implementation of effective fire mitigating measures and by strategic fire extinguishing activities.

Based on the analysis of the fire spread several fire restricting measures can be recommended. The efforts from the fire brigades were crucial together with the effort form all the other organizations, volunteers and private persons who took part in the firefighting. The different methods for extinguishing fire were all useful parts in the large picture. It is not possible to point out one single measure that had larger effect than the others; they were all important parts in limiting the fire spread. This corresponds well with the conclusions from the earlier project on fire protection of Røros – fire safety is achieved by a number of different targeted measures of technical and organizational character.

Owners of private homes can increase the resistance against ignition by glows and sparks through simple preventive measures, and when building new houses or renovating existing ones cladding and roof construction can be upgraded.

The use of fire preventive and restricting measures have to be thoroughly planned, and includes measures to prevent a fire to spread out of a house to neighbouring buildings, and to prevent an external fire to spread into a building.

During our work we have seen clearly the need for more research on many topics connected to both large fires in built environment and wildfires. We need a better understanding of the fire phenomena involved, and investigation of the efficiency of existing technical and organizational fire protective measures should be undertaken. There should also be aimed at developing new fire safety measures built on today's knowledge and modern technology.

Some topics that should be investigated are:

- Is the risk of large fires like the Lærdal fire increased in Norway because of climate changes – e.g. more wind and dry weather?
- Has the fire risk changed because of changes in society with regards to human behavior, interior furnishing, building methods and construction materials?
- Development of cost-effective extinguishing systems and fire safety measures should be encouraged.
- The effect of different fire safety measures should be investigated:
    - simple measures for new and existing buildings o fixed firefighting systems for exterior use
    - different extinguishing media and techniques

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Bio-based products and national fire safety requirements

Esko Mikkola[1], Maria Pilar Giraldo[2]

[1] KK-Fireconsult Ltd, Espoo, Finland, esko.mikkola@kk-palokonsultti.com

[2] Incafust Catalan Institute of Wood - CTFC Forest Sciences Centre of Catalonia, Solsona, Spain

Keywords: fire safety, regulations, fire safety engineering, bio-based materials

One of the tasks of *COST ACTION FP1404 WG3, Regulations and standards for fire safety of bio-based building materials*, is to compare regulatory approaches in different countries for identifying unsolved topics/obstacles for use of bio-based materials in buildings. As a starting point for this activity FP1404 members were asked to provide state of the art information for the meeting in Barcelona (April 2015). After that a questionnaire was sent to all members asking additional data on national requirements and the use of fire safety engineering in design of buildings.

Based on the answers received and earlier comparisons of requirements [1,2,3] the main results are compiled in Table 1. It should be noted that in many cases there may be specific conditions in the national requirements, which are not taken into account in the summarizing table. Table 1 is trying to give a simplified overall picture on the situation.

Concerning the load-bearing structures, bio-based products (fulfilling at least D level reaction to fire performance, such as wood) can be used as follows:

Prescribed regulations:

- Up to 2 - 6 storeys or 30 m height without specific protection needs or
  - In some countries, the requirements are based on fire separation (EI)
  - In a few countries, coverings ($K_2$10/$K_2$30/$K_2$60 of A2 materials) or B-s1, d0 class protective layers are required
- When sprinklers are used, increased number of storeys in some countries

Performance based regulations:

  - No limit for number of storeys (theoretically)
  - In many countries PB approach is allowed, but it is not frequently applied

External claddings of D class products can be used as follows:

- With no sprinklers:
  - Between 2 and 8 storeys (or 30 m)
- With sprinklers:
  - Increased number of storeys in some counties.

As internal wall and ceiling linings D class products can be used in most countries (even without sprinklers) in buildings with at least 3 storeys, except in escape routes where only in some countries

D class wall and ceiling linings are allowed in case of additional protective measures (e.g. sprinklers or fire detection).

D_{FL} class floorings are accepted in apartments in all countries and in escape routes in majority of the countries listed in Table 1.

Table 1. Regulatory limitations and possibilities for D and D_{FL} reaction to fire class products based on present questionnaire and earlier data [1,2,3].

Country	Allowed number of storeys (or height of building in meters) for D class products					D/D_{FL} class products allowed in buildings with at least 3 storeys					
	Load-bearing structures			External cladding		Internal walls/ceilings				Floorings	
						Escape routes Sprinklers		Within apartments Sprinklers			
	Prescribed rules	Performance based (PB)	*Protection required*	No sprinklers	With sprinklers	No	Yes	No	Yes	Escape routes	Within apartments
Austria	6	No limit	*No*	6	6	-	-	+	+	-	+
Belgium	See PB	No limit	*No*	3 (10 m)	3 (10 m)	-	+[a]	+	+	-	+
Czech Republic	3-4 (12 m)			3-4 (12 m)	3-4 (12 m)	-	-	+	+	-	+
Denmark	3-4	No limit		3-4	3-4	-	-	-	-	+	+
Estonia	4	No limit	*No*	8	8	-	+	-	+	+	+
Finland	2 / 8[b]	No limit	*$K_2$10/$K_2$30*	2/4	8	-	-	+	+	+	+
France	No limit	No limit	*No*	4 or 50 m[c]		-	-	+	+	+	+
Germany	4-5	> 5	*$K_2$60*	3 (7 m)	3 (7 m)	-	-	+	+	+	+
Greece	No limit	No limit	*No*	No limit	No limit	-	-	+	+	+	+
Ireland	3 (10m)	No limit		≥ 5	≥ 5	-	-	+	+	+	+
Italy	See PB	No limit	*No*	(12 m)	(12 m)	-	-	-	-	+	+
Latvia	4	Not used	*B-s1,d0*	4	4	-	-	+	+		
Macedonia	2			2							
Netherlands	13 m	No limit		3-4	≥ 5	-	-	+	+	+	+
Norway	4	No limit	*EI30/EI60,$K_2$10*	4	4	-	-	+	+	+	+
Poland	3-4 (12 m)		*B-s1, d0*	(25 m)	(25 m)	-	-	+	+	-	+
Portugal	(9 m/single family)			(28 m)	(28 m)	-		+		-	+
Slovakia	2-4	Not permitted	*EI*	(12 m)	(12 m)	-	-	+	+	+	+
Slovenia	3 / 5[b]	No limit	*EI30/EI60*	3 (10 m)	3 (10 m)	-	-	-	+	+	+
Spain	See PB	No limit	*EI30-EI120*	6 (18 m)	6 (18 m)	-	-	+	+	-	+
Sweden	See PB	No limit	*No*	2	≥ 5	-	-	-	+	+	+
Switzerland	(30 m)	No limit	*No*	(30 m)	(30 m)	-	+	+	+	+	+
Turkey	3	No limit	*F30B2/F60AB*	3	3	-	-	-	-		
United Kingdom	See PB	No limit		≥ 5	≥ 5	-	-	-	+	-	+

[a] Fire detection is the required active means
[b] With sprinklers
[c] Applicable for dwellings; more than 4 storeys requires compliance with French façade test

The questionnaire answers showed that the use of fire safety engineering (FSE) methods is not very common when using bio-based building products in buildings. And if FSE methods are used, general methods are applied because no specific national methods concerning bio-based products seem to exist. Austria, Finland, Germany, Italy, Norway, Slovakia, Slovenia, Sweden and Switzerland have some guidance available to facilitate implementation of FSE option.

In general, some aspects of regulations are difficult to compare. Despite of the existence of the Construction Products Regulation of the European Union and the development of Eurocodes, there is a broad variety of criteria and requirements for buildings in the various European countries because fire safety in buildings is on political level governed by national legislation.

As a conclusion of the comparisons of regulatory requirements it is clearly seen that, if the national regulations allow only prescribed solutions, there are major limitations in using bio-based building products. These and other possible limitations arise mainly on categorising materials and products as non-combustible/at least A2 reaction to fire class (which is a common requirement) and combustible (which are not allowed at defined applications). Performance based regulations (or performance based options in regulations) are more flexible (being material independent).

Design flexibility in buildings regarding fire safety is possible through the provision of sprinklers. Nevertheless, at present, in Europe the use of sprinklers does not play a decisive role in fire safety in this kind of buildings. In most countries there are no benefits for bio-based product when using sprinklers.

Finally, to be able to influence future national regulations there is a need to disseminate commonly accepted scientific proof on acceptable fire performance levels of bio-based building products as well as on related assessment principles, calculation methods and acceptance criteria.

Acknowledgments

FP 1404 partners are thanked on their contribution to collecting data on regulatory requirements relevant for bio-based building products. Raido Jalas is specially thanked on collecting data from the presentations given in the Barcelona meeting of FP1404 and Danny Hopkin on supplying compiled data from various countries.

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Nordic Standardisation of Fire Safety Engineering Methods for Innovative Building Solutions

Daniel Brandon[1], David Winberg[2], Birgit Östman[3]

[1] Box 5609, SE-114 86 Stockholm, SP Technical Research Institute of Sweden, Wood Building Technology, Sweden, daniel.brandon@sp.se

[2] Scheelev. 27, SE-223 70 Lund, SP Technical Research Institute of Sweden, Sweden, Fire Research, Sweden

[3] Box 5609, SE-114 86 Stockholm, SP Technical Research Institute of Sweden, Wood Building Technology, Sweden

Keywords: Fire Safety Engineering, Standardisation, Performance Based Design

Introduction

Prescriptive building codes regarding fire safety are easy to use and potentially cost-effective for conventional buildings. No assessment of risks are required if the prescribed rules are followed. However, as not all fire safety solutions are prescribed, the number of applicable solutions is limited. Prescriptive building codes have been based on previous experience and the use of these building codes for the increased number of unconventional structures has been questioned [1]. It has been stated that the use of previous experience alone is rarely adequate to deal with fire hazards of unconventional buildings [2]. Therefore, performance based approaches, which rely on fire safety engineering principles and calculation models have been increasingly used in the past two decades. Using performance based fire safety design, can increase the justified use of unconventional structures, stimulate innovation and reduce costs as well.

The project described in this abstract has the ultimate aim to stimulate the use of innovative design and technology in the build environment. The approach taken to achieve this is through standardising verification methods and the process for review and control for Fire Safety Engineering. The resulting standard will facilitate the implementation of performance based regulations.

A previous step in line with the current project was the publication of the Nordic INSTA TS 950 [3] technical specification, which provides guidance for a comparative approach for fire safety engineering. The deliverable of the current project is a standard which is complementary to the INSTA TS 950.

Work packages

The project is divided into five work packages (WPs):

WP1 Identification and analysis of the barriers to innovation and trade;

WP2 Specification of technical verification methods;

WP3 Specification of the review and control process;

WP4 Confirmation of the results of work package 2 and 3 using existing buildings;

WP5 Finalisation and recommendations.

The project scope is limited to the Nordic countries and is seen as a first step to internationalise fire safety standards. In this abstract emphasis is put on WP 1 and 2.

WP1 Identification and analysis of the barriers to innovation and trade

In the current state, work package 1 is completed and work package 2 and 3 are running. The result of WP 1 is a report summarising the governance, fire safety procedures, control systems and fire safety requirements in all participating countries. Questionnaires sent to 40 experts in 15 EU countries and a comparative study of Nordic countries' building codes and procedures led to the identification of barriers for innovative building solutions. Some of main barriers found are listed below together with the corresponding work package of the current project dealing with these:

- There is a lack of verification methods for qualitative assessment and quantitative assessment with probabilistic analysis. (WP2)
- There are a lack of performance requirements within some areas of fire safety such as the development and spread of fire and smoke within the building and the safety of rescue personnel. (WP2)
- There are limitations in the use of scientific/engineering methods due to lack of design fire scenarios and input data. There is a need for applicable generic cases of common building types and uses and better statistically founded input data. (WP2)
- The link between the control of the design process and the control and onsite inspection differs among the Nordic countries and is not clearly defined in every country. (WP3)
- Expertise about fire safety of local authorities is not always sufficient. Guidance for third body inspection is needed. (WP3)

As indicated, WP2 and WP 3 focus on providing guidance and data that should reduce the barriers found.

WP2 Specification of technical verification methods

In WP 2, guidance on verification methods will be provided to ensure a more reliable and predictable verification. Furthermore, work package 2 will give suggestions for acceptance criteria where possible and will provide relevant fire statistics and reliability data.

Acceptance criteria and acceptable confidence intervals will be given for risk assessments such as occupant evacuation analyses and life safety. Although acceptance criteria regarding life safety can be highly disputed, they will be given in the form of FN-curves which will specify an acceptable relationship between frequency (F) and the number of fatalities (N). An acceptance criteria, as low as reasonably practicable (ALARP), is considered to be used as a basis for the FN-curves provided. Furthermore, pre-accepted solutions (e.g. solutions defined by the national building authorities that are currently accepted without any required analysis) are used as benchmarks for the level of fire safety required.

Guidance will be given for the defining design fires and selecting design fire scenarios. Furthermore, guidance for a number of methods for analyses will be given. For example the use of graphical methods such as Logic Tree Analysis and Bayesian Networks, in which probabilities are determined and visualised using a graphical representation of the risks, will be described.

Fire statistics and reliability data change in time and many commonly used sources of data are outdated. For this reason effort is made to summarise up-to-date fire statistics and reliability data where possible. The following will be included in the statistical data set.

- Frequency and distribution of area of damage
- Room of origin
- Fire load
- Ignition frequency per occupancy

Data regarding fire loss will be given as frequency and distribution of area damage so that it is independent of currency and the place- and time-dependent value of buildings. A strong relationship was found between the floor area of buildings and certain fire statistics such as fire load and ignition frequency [4]. Therefore, it is chosen to provide these guiding fire statistics as a function of floor area. Furthermore, reliability data will be provided regarding sprinklers and alarm systems and can be used for risk analyses.

Project status

The draft standard of WP2 is due on the 15th of September 2015 and is planned to be revised and submitted by the 31st of March 2016. WP3 has been initiated, aiming to describe the inclusion of fire safety engineering in the building review and control processes. WP4 will be initiated in 2016 and will test the results of WP2 and 3 against recent innovative building projects, in order to justify the level of safety and the acceptance criteria provided by the documents of WP2 and 3. The project will finish in 2017.

Acknowledgments

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Analysis of fires in buildings in Estonia

Raido Jalas[1], Alar Just[2]

[1] Estonian Rescue Board, raido.jalas@rescue.ee

[2] Tallinn University of Technology, Estonia

Keywords: fires, timber buildings, statistics

Timber buildings are often regarded as a big risk for fire. Current research gives appropriate picture of timber buildings in fire taking into account several practical and economical aspects. Main aim of the research was to find out the specialities of fires related to building materials, specifically timber. Buildings that are built with the main building materials as stone, steel and timber are compared looking at different aspects. Such as costs of fire damages, damaged area after the fire, injuries and deaths in fire.

Data and information is provided by Estonian Rescue Board. Period for investigations was April 1st to December 31th 2014. During this period the new system for database JÄIS was in use. There were 1419 fires on the investigated period. For buildings the Estonian official database EHR [3] data was used. There were 607928 buildings in Estonia in the database dated by September 2014.

The classification “other buildings” according to EHR and JÄIS is left outside of investigations as unknown. Only stone-, steel-, timber- and mixed buildings are taken into account. Only the buildings that are officially in use have been considered. These principles are needed for certainty and clearness of the conclusions made.

Taking into account the above mentioned principle, data of 831 fires are analysed and data of 562 448 buildings are taken into account.

Almost 45% of the fires took place in stone buildings and 33 % of the fires took place in wooden buildings (Figure 1). At the same time 62 % of buildings are made of wood and 35% of buildings are stone buildings (Figure 2).

Average costs to repair the fire damages are low in timber buildings and high in steel buildings. At the same time the frequency of fires to occur is highest in timber buildings (Figure 3).

Fires itself occurred most frequently in buildings with mixed structures, the next frequent were timber buildings (Figure 4). Probability of fire occurance in timber buildings is 60% less than in stone buildings. Fires with deaths and injuries occur 45% less in timber buildings compared to stone buildings. On the other hand fire spread in timber building is more extensive. Half of the building will burn down as an average. Probability of deaths when the fire occurs is 40% bigger in timber building compared to stone building.

In terms of where the buildings are located, it should be noted that fire accidents of timber buildings are distributed relatively evenly between high-density and low-density areas (56% and 44% respectively). See Figure 5.

As to other construction materials, it is evident that most fire accidents occurred in high-density areas, i.e. about two-thirds of fire accidents happened in densely populated areas.

As to the age of buildings, metal buildings might be pointed out since fire accidents occurred in about 20-year-old metal buildings, which stands in sharp contrast to the general average. When it comes to timber and mixed-construction buildings, then fire accidents happened in older buildings on average, i.e. mostly in 56-year-old buildings.

The result of the analysis provided in this research is intended to be a basis to indicate different aspects when making fire safety rules and concepts for timber buildings.

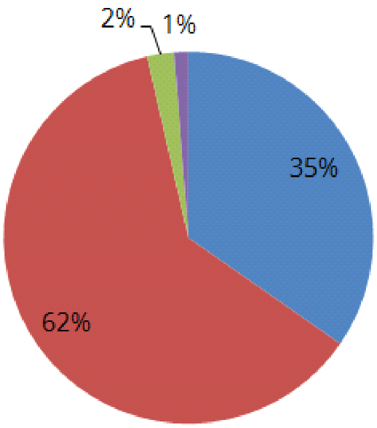

Figure 1. Buildings in Estonia divided according to the main building materials.

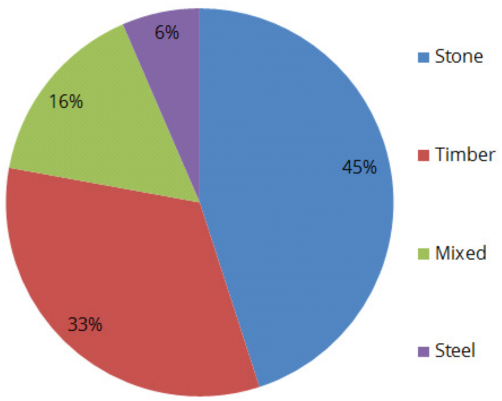

Figure 2. Fires in buildings divided according to the main structural material.

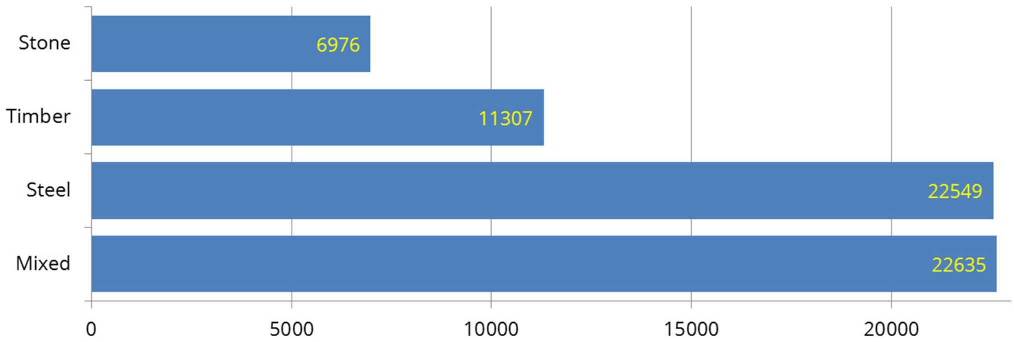

Figure 3. Average costs of fires according to the main structural material.

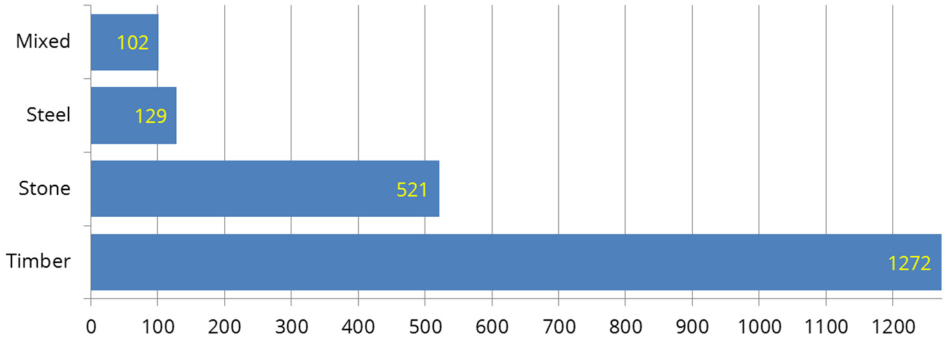

Figure 4. Frequency of the fires according to the main structural material.

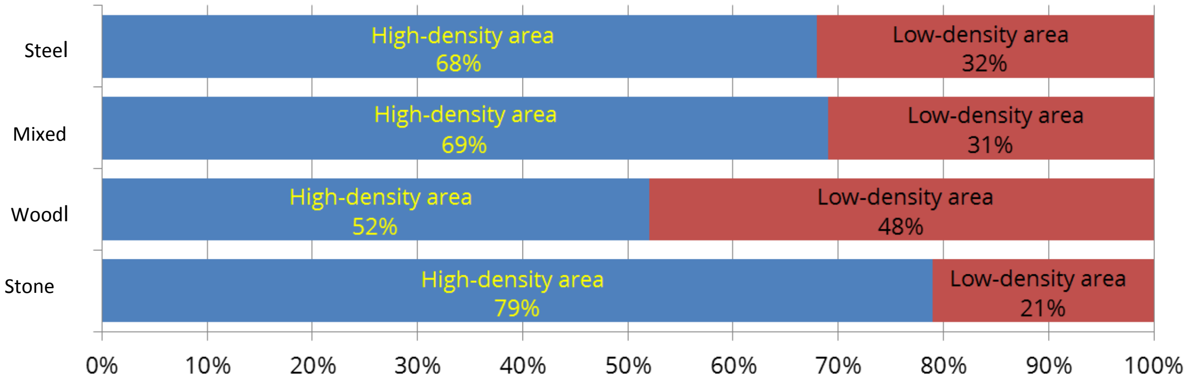

Figure 5. Location of buildings (blue-high density area; red-low density area)

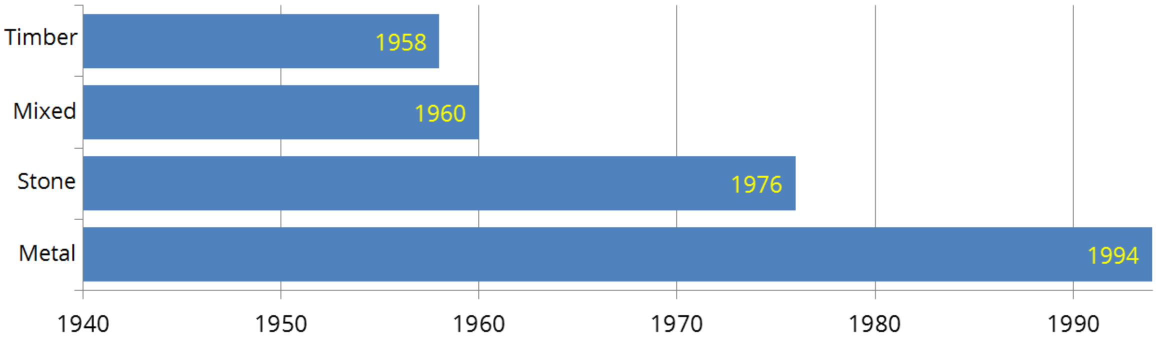

Figure 6. Fire accidents of buildings by their years of construction.

Acknowledgments

Authors would like to acknowledge Estonian Rescue Board.

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Investigations on fire safe use of bio based building products by iBMB

Judith Küppers[1], Jochen Zehfuß[2], Björn Kampmeier[3]

[1,2] Institut für Baustoffe, Massivbau und Brandschutz (iBMB), TU Braunschweig, Germany, J.Kueppers@ibmb.tu-bs.de

[3] Lehrstuhl für Brandschutz und Baukonstruktion, Hochschule Magdeburg-Stendal, Germany

Keywords: fire protection, risk-based, fire protection claddings, timber, wood fibreboards, insulation

The Institute of Building Materials, Concrete Construction and Fire Protection (iBMB) is part of the Technische Universität Braunschweig in Germany and originated from a building materials laboratory, funded in 1922. Since the mid-1990s, the iBMB is working intensively on the fire safe use of modern, bio based building materials. In times of limited fossil resources the relevance of sustainable materials increases, especially the application for multi-storey building is a current topic in Germany. These materials are combustible, so experimental investigations and risk analyses are needed for a fire safe use.

The results of a three-stage research project [1], in collaboration with the 'Versuchsanstalt für Holz und Trockenbau, Heusenstamm' and industrial partners, formed the basis for the "model guideline for fire protective requirements on multi-storey buildings made of timber (M-HFHHolzR)". In the past, timber constructions were limited to low buildings with a maximum height of 7 m in Germany. Aim of the research work was to enable higher timber buildings, while respecting the existing safety level. This led to a fire protection cladding consisting of noncombustible materials, e. g. gypsum plasterboards, resulting in a protection time of 60 minutes and a complete construction classified as REI 60 $K_2$60 according to EN 13501-2. Due to this, the fire safety level is the same compared to other constructions, e. g. concrete or masonry, during the required period of 60 minutes for multi-storey buildings (of building-class 4 according to the German model building code). The model-guideline, established in 2004 in Germany, is adopted in most of the federal states by now. Further experimental and theoretical studies have been carried out at iBMB and other institutions to develop solutions for the restriction of the model-guideline.

Sustainable, combustible insulation materials for example are not included in the model-guideline. They and possible fire protection measures were investigated in a collaborative research project, completed in 2007 [2].

In addition, solid plane timber elements (Fig. 1) like cross-laminated timber elements were examined in a research project, completed in 2008. The Experimental results show, that it is possible to generate smoke-proof joints between the elements and that extinguishing is possible due to standard extinguishing measures by a fire brigade [3].

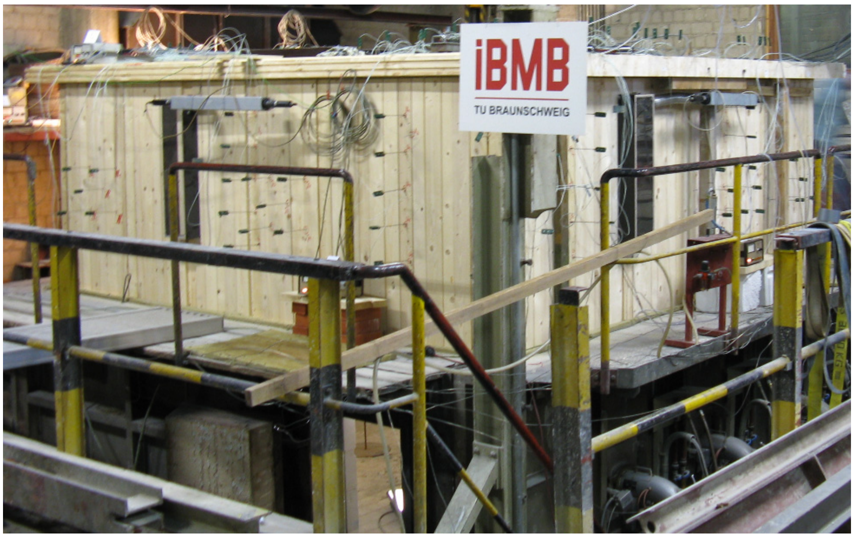

Figure 1. Exterior view of the room consisting of solid wood for the large scale fire test

Other collaborative research work focused on the optimisation of the fire protection cladding. The heat transport of the fixing screws causes decomposition and discoloration of the timber. A criterion defining uncritical decompositions was determined. Furthermore, adhesion measures and application of console-loads were investigated [4].

Based on these results a risk method was developed to assess different constructions with sustainable, combustible building materials using different compensation measures and a draft of new a model-guideline was formulated [5]. Another draft version is given from TU München in [6].

In addition to the described research on protection claddings, high performance fire protection coatings were developed and investigated at the iBMB, the Fraunhofer WKI and the Fraunhofer ICT in a collaborative research project, completed in 2009. Aim of the research work was to develop an intumescing coating as fire protection for timber elements like claddings and not only an improvement of fire behaviour. Based on this work an engineering model was developed for assessing the performance of these coatings [7].

Another collaborative project, completed in 2013, focused on clay and lime as protective cladding for multi-storey straw bale buildings. For this construction, consisting of load-bearing timber elements and straw bales as insulation material, the fire protection requirements are more strictly than for timber buildings with noncombustible insulation (Fig. 2). Furthermore, any weak spots like electrical installations within the construction must be avoided in general. Solutions for this and other details were developed in the research project [8].

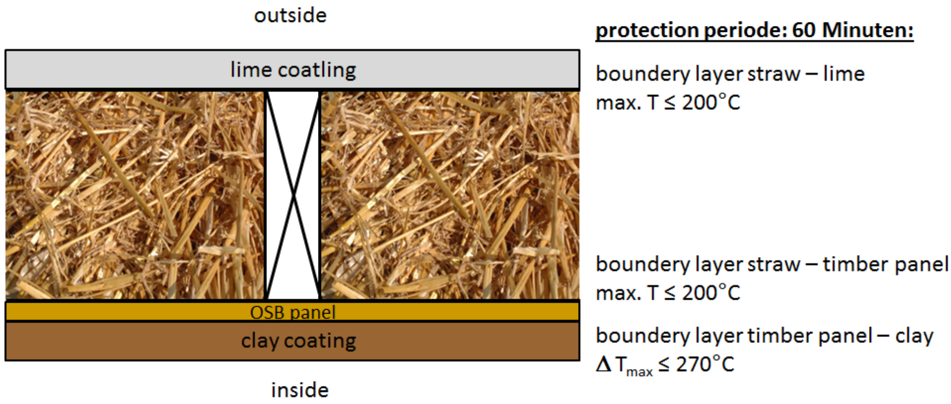

Figure 32 Coating-requirements [8, 10]

To assess the performance of various claddings with different additives and thickness, comparative experiments were performed in the cone calorimeter according to ISO 5660 [9]. The results of the cone calorimeter tests are not directly transferable to tests under standard fire conditions, but they served as orientation and comparison of samples for a reasonable selection assessed in more expensive standard fire tests. Due to this, a 6 cm light weight lime plaster was chosen and examined under standard fire conditions and complied with the increased requirements. The combination of a 45 mm thick clay board with a 10 mm thick mineral clay plaster yielded promising results in the cone calorimeter and successfully performed an intermediate scale test under standard fire conditions. Large scale test showed, that for a safe use, the connection of the clay boards has to be optimised. First investigations suggests, that with simple measures an effective system can be designed [8].

Based on this experimental and theoretical work, the fire safety concept of the first five-storey straw bale building in Germany was developed at iBMB [10]. It was built in Verden (Aller) with a fire alarm system in addition to the fire protection claddings and opened as information centre for sustainable building constructions (NZNB) in April 2015.

Figure 3. NZNB in Verden (Aller) [D. Scharmer]

Figure 4. Exhibition [NZBN, A. von Brill]

Recently, a new collaborative project started at iBMB with the aim of developing a multi-storey ETICS (external thermal insulation component system) with wood fibreboards. Involved are also the

‘Hochschule Magdeburg-Stendal’, ‘Fraunhofer WKI’ and industrial partners. The developing work is considering all construction elements influencing the fire behaviour of facades, e. g. insulation material, plaster and additional constructional measures like the arrangement of barriers.

Most of the described work focused on bio based building products and protective measures for building-class 4. Another current subject in Germany are timber buildings in building-class 5. Research work on this topic is planed in cooperation with Hochschule Magdeburg-Stendal and TU München [11].

As conclusion it can be noted, that research and development on fire safe use of bio based building products is going on and will provide new results, products and hopefully lead to new regulations.

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A UK engineering approach to mitigation of fire spread risks from timber frame construction sites

Danny Hopkin[1], Martin Milner[2], Simeon Anastasov[1]

[1] Trenton Fire Ltd., UK (danny.hopkin@trentonfire.co.uk)

[2] Milner Associates, UK

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The UK and timber

The UK has a long history of utilising timber as a construction material for buildings. For as long as timber has been used as a construction material, challenges have arisen regarding fire and the impact it has, not only on people within the building of origin, but also for those in the vicinity. A number of significant conflagrations have shaped the way the UK has historically regulated the use of combustible structural materials (such as timber), the most prominent being the Great Fire of London in 1666, which effectively eradicated the use of timber as a structural framing material for a number of centuries. It was not until 1991 that restrictions on the use timber as a framing material were lifted, as the UK transitioned from prescriptive to functional Building Regulations. Prior to this time, timber buildings were restricted to low rise buildings, typically for domestic (residential) uses.

Despite changes to the way buildings were regulated in 1991, this did not lead to an immediate increase in timber frame construction outside of those markets that had previously existed. This is because many building control and construction professionals remained sceptical whether taller timber buildings (typically 5-18m in height) could meet the functional requirements of the Building Regulations. Specifically, in relation to a taller timber building's ability to ensure that stability was achieved for a reasonable period.

The TF2000 test [1] in 1999 provided the tangible evidence necessary to install the confidence required for taller and larger timber buildings to be constructed. Since this time, it has become increasingly common for medium rise apartment buildings, etc., to be constructed from light timber frame construction and taller buildings to be constructed from materials, such as cross laminated timber (CLT).

Construction fires

The UK is not blessed with vast expanses of green belt land upon which new development can be undertaken. Instead, it is increasingly common for planning consent to be granted for developments that reinvigorate brownfield sites or require the demolition of existing buildings, ahead of the construction of new ones. This results in construction being undertaken in close proximity to established neighbourhoods and buildings that remain active whilst development work is ongoing.

Much UK construction is presently focussed on the delivery of residential buildings which, combined with constrained sites and the need to construct quickly, often results in light timber frame being the chosen construction method.

Since the TF2000, and as a bi-product of the UK's markets and constraints in terms of where new buildings can be reasonably constructed, an increased number of large light timber frame projects have been proposed within or in the vicinity of established neighbourhoods. Some of these sites have suffered significant fires which have had consequences beyond the immediate site affected:

- July 2006 – a fire in a six storey timber building under construction in Colindale leads to the collapse of the structure in under 20 minutes from ignition [2],
- January 2010 – 39 timber frame dwellings under construction in Peckham ignite, leading to fire spread to and the evacuation of houses nearby [3],
- September 2010 – a three storey timber frame care home partially completed in Basingstoke suffers a fire, with 100 fire fighters necessary to tackle the blaze [4].

During this spate of timber frame construction site fires, the London Assembly Committee on Housing and Planning [5] undertook a review of the risks associated with timber frame buildings during construction, leading to a plethora of recommendations. One of the most significant of these recommendations focussed on active promotion of mitigation measures which both reduce the likelihood of ignition and the potential for fire spread, should a fire occur.

UK guidance on space separation during construction

The STA (then UKTFA), in collaboration with fire engineering consultants FERMI and the Health & Safety Executive (HSE) embarked on a research programme to investigate the heat flux emitted from typical timber frame assemblies and those with 'enhanced fire performance' [6]. These experiments mimicked small rooms subject to arson and were also supported with additional 'wall ignitability experiments'. The experiments led to the definition of three categories of timber frame, defined as Class A, B or C, depending upon the propensity for fire spread and the heat flux emitted (Table 1).

Table 1. STA frame classifications and criteria

Class of frame	Type	Heat flux (kW/m^2) [a]	Comments on fire spread
A	Standard time frame	> 9.0	Rapid fire growth which breaks through walls.
B1	Reduced fire spread frames	7.0 – 9.0	Fire growth relatively limited to compartment, although flames extend out of the room.
B2		5.0 – 7.0	
B3		3.0 – 5.0	
C1	Fire spread resistance frame (with openings)	< 3.0	Fire spread limited to compartment with no breach of the floor or walls.
C2	Without openings		

[a] *Measured 4m away from the frame, at a height of 1.5m above floor level*

Based on the results of the experiments and informed by the criteria defining the different classes of frame (Table 1), the STA developed prescriptive guidance in the form of tables. These relate the size of a timber frame building to the separating distance required to prevent fire spread from the building of origin. The tables were developed based upon the common Boltzmann relationships, with the goal of preventing neighbouring properties from being exposed to a critical heat flux of 12.6 kW/m^2. As such, they are predicated on very simple rectangular geometries and initially (albeit subsequently updated) were solely focussed on light timber frame and precluded CLT, etc. Example tabulated outputs are provided in Figures 1 and 2.

Number of timber frame storeys	Emitter length (eL)						
	≤5m	≤10m	≤15m	≤20m	≤25m	≤40m	>40m
1	5.5	7.25	8.25	8.75	9.5	10.25	10.5
2	7.5	10.5	12.75	14.25	15.5	18	20.25
3	9	13	16	18	20	23.25	28.5
4	10	15	18.5	21.25	23.5	28.5	35.75
5	11	16.5	20.5	23.75	26.5	32.5	41.75
6	11.5	18	22.5	26	29	36	47.25
7	12.25	19	24	28	31.5	39.25	52.5

Figure 1. Separating distances for Class A frames

Number of timber frame storeys	Emitter length (eL) - B2 frame			
	≤5m	≤10m	≤15m	≤20m
1	5	5	5.25	5.5
2	5.25	7.25	8.5	9.5
3	6	9	10.75	12.25
4	6.75	10.25	12.75	14.5
5	7	11.25	14	16.25
6	7.25	12	15.25	17.75
7	7.5	12.75	16.25	19.25

Figure 2. Separating distances for Class B2 frames

The tabulated methods present significant progress in the management of the risks associated with timber frame construction sites and the impact fires have on surrounding areas. However, like much prescriptive guidance, they are intended for more 'common situations' and do not cater well for complex geometries or more unusual (uncommon) building situations. For this reason, fire engineering consultants are often engaged to review from a fundamental perspective what provisions are required to manage risks, should a fire occur on a construction site.

Performance based approaches

In developing the prescriptive tabulated methods outlined previously herein, a significant and valuable dataset was developed that can be adopted as a basis for fire engineering assessments and the proposition of appropriate risk mitigation solutions. A summary is provided in Table 2.

Table 2. Summary of fire engineering inputs for detailed assessments

Class	Emitter flux (kW/m^2)	Flame projection from elevation (m)	Flame height (m)
A	82		
B1	56.5		
B2	46	0.5	Building height + 20%
B3	37.5		
C1/C2	23.7		

For unusual geometries, in addition to the data contained in Table 2, configuration factors are required and can be challenging to establish. These are often evaluated by discretising the 'radiating surface' into a series of 'sub-panels' which are subsequently individually assessed and summed to establish the radiative heat transfer from one surface to another. This is often best achieved using bespoke software which solves the governing equations efficiently (Figure 3). The overarching aim is to ensure that a fire on a complex site (potentially comprising one complex building, or a multitude of smaller buildings) does not result in neighbouring properties receiving a defined critical heat flux. Solutions in terms of different arrangements of classes of frames can be evaluated in arriving at the most effective and efficient proposal, which is subsequently implemented on site.

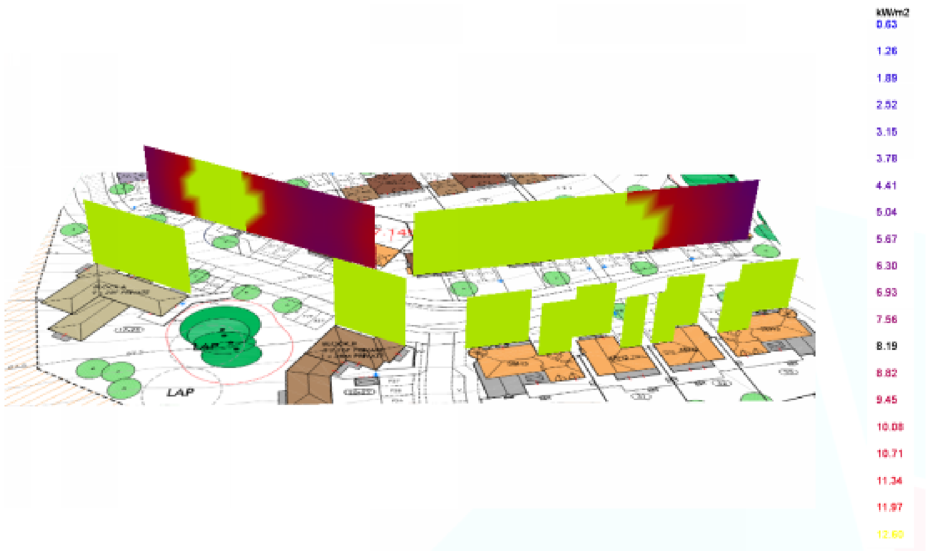

Figure 3. Radiation assessment for a complex site

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Total Fire Engineering as a Framework for Engineering Design of Combustible Construction

Neal Butterworth [1]

[1] Technical Leader, Arup fire engineering

Bio Based Materials (most noticeably wood) have been used as construction material for many centuries, but, for a variety of reasons, there is a resurgent desire to build from them. In particular, new glue technology and off-site manufacturing capability has meant that it is now practical and cost-effective to build high-rise timber buildings where the timber construction remains exposed. With this new capability and the time and cost savings that can be generated from eliminating a decorative finish, clients and architects are pushing boundaries with respect to building height and size and the amount of exposed timber.

However, it is not limited to timber, and Arup is noticing a trend to replacing conventional building materials with other bio-based materials such as cork, bamboo and straw or novel bio-based building components such as green facades

All of these materials are combustible, and therefore, fire is perceived as one of the most significant barriers to the adoption of bio based materials for construction. These barriers include legislation, project funding (from investors and lenders), insurance requirements, and mortgability and construction stage fire risks.

The barriers are real, but industry opinion is divided on whether their foundation is valid. In the context of timber construction some argue that the fire risks associated with exposed mass timber construction have been identified and can be mitigated by existing design methods (particularly for timber), whilst other argue that there are significant knowledge gaps and so the resulting risks associated with combustible construction are unacceptable.

This Paper / Presentation shall present Arup's view of how these barriers can be addressed as an independent firm of designers, planners, engineers, consultants and technical specialists. Our view is born from a desire to support the vision of others for timber (and other bio based materials), and the commercial drivers for its rise in demand, including architectural appearance, sustainability, speed of construction, weight of construction, cost etc. However we are also obliged to couple this with our understanding of structural fire performance; by which we mean the local and global response of the construction to the range of complex fires which can occur in a real building. This is a fascinating topic, and for combustible construction it means a whole new way forward seems possible with endless opportunity for new and robust methods for combustible construction.

Almost uniquely, profound questions about timber response to fire, are posed, yet entirely ignored for other structural materials. Yet it is our position that these questions, born out of the barriers and perceived risks, are entirely valid for any structural form. It is our position that one form of construction should not be held to an arbitrarily higher standard than any other. The individual risks for each form of construction need to be identified and addressed knowingly. This is a principle tenet which must be clearly defined as we seek new fire safe methods for combustible construction. Therefore a new design framework specifically for timber is not required; however, the design of timber under the existing framework is reviewed to establish how it can be applied.

Engineering a Solution

As engineers, we recognise that there is risk and uncertainty in building design, and importantly in construction and then in operation. This is true of all types of construction. Our role as engineers is to eliminate unacceptable risk by identifying uncertainty and mitigating it accordingly.

Arup proposes to achieve this by:

1. Practicing the philosophy of Total Fire Engineering:

This requires that all relevant fire design, construction and operation decisions are considered together and integrated into a whole by a well organised team.

2. Prioritising the fire safety goals:

Engaging with all stakeholders to identify and prioritise all relevant fire safety goals. This can include legislative requirements, funder and insurer requirements and other economic, environmental and social goals.

3. Identifying the project constraints:

Being an integrated part of the design team and working with them to identify the design, construction and operational objectives and constraints, fire hazards, occupant profiles and associated risks.

4. Design:

Designing the best possible fire safety solution to meet the fire safety goals within the constraints of the project and testing that solution robustly.

5. Execution

Ensuring that the fire safety solutions are specified, constructed, commissioned, handed over and operated correctly over their entire design life.

Fire Safe Design of Timber

One of the most important parts of the Design process is the assessment of our solutions, and the appropriateness of the assessment method that is adopted. Review of existing timber design methods and assessments establishes that their efficacy will change as structural for, design and construction method evolves. These empirical methods were created during the 1980s and 1990s, born out of single 3m to 4m long elements being tests in standard fire test furnaces. The desire to optimise, innovate and push the boundaries of timber construction then brings into question the efficacy of existing empirical and simplified / approximate assessment.

A review of the assessment methods that are currently available for exposed combustible construction concludes that new assessment methods are required to account for the fundamental differences between non-combustible construction and combustible construction that become important when large areas of combustible construction are left unencapsulated (i.e. exposed); namely the impact of burning construction on the fire severity and duration, and the question as to whether the construction will self-extinguish once the fire has burnt out. Structural design for 'burn out' (when all the contents of the compartment have been consumed by fire) is a fundamental precept of building fire safety design. It is a corner stone upon which all other aspects of the fire safe design are built.

Arup already has a comprehensive assessment method that is applicable to non-combustible construction, and this paper proposes a modification of that method for use for combustible construction. This ensures a consistency of standard and approach. The modification is an additional assessment to ensure that construction self-extinguishes following burnout of the combustible contents with the fire enclosure.

The knowledge required to implement the proposed assessment method is reviewed against existing knowledge and capability to identify gaps scientific knowledge and engineering application, and therefore define future research requirements.

Uniquely, this paper is presented from an engineering perspective, where uncertainty is the norm, and it is accepted that knowledge gaps can be mitigated through conservatism or limitations of application.

We do consider that such thorough requirements of many stakeholders for combustible construction, are equally true of any construction form, and we would like to see this same level of rigour applied well beyond timber buildings.

The future research requirements are presented in terms of those required as a minimum to enable the implementation of the proposed assessment method as well as those that can be conducted over time to eliminate conservatism and limitations.

Whilst we are proposing that the new, alternative assessment method is required when exposed combustible construction is being used, we are not saying that existing methods cannot be continued to be used. Approximate methods have their place, but they also have their limitations, and if they are to be used, they must be used knowingly and within their limitations. We suggest that methods based on a prescribed fire resistance standard and charring rates should only be used for situations where:

the exposed construction is in sufficiently low quantities that it does not significantly impact on the enclosure fire dynamics and it will self-extinguish when the combustible contents have been assumed (e.g. large compartments with only beam and columns being constructed from exposed timber), and/or

- a fire risk assessment is conducted to demonstrate that reliance placed on the fire resistance of the construction is sufficiently low (e.g. low rise, low value buildings).

Ultimately, this paper presents a comprehensive assessment method that can be used for exposed combustible construction. It is based on and consistent with the pre-existing Arup method that has been widely used for non-combustible construction such as steel and concrete.

Used correctly, it can contribute towards the industry relying on exposed combustible construction, safely; and help the industry move beyond expectations that are entirely ignored in any other form. A Total Fire Engineering approach enables a realistic bespoke assessment and defined outcomes.

Detailing in timber structures - Influence of convective heat transfer under fire exposure

René Stein[1]

[1] Technische Universität München, Chair for timber structures and building construction, research associate, Germany, r.stein@tum.de

Keywords: fire barriers, joint types, leakage rate, prefabricated elements, timber construction

The increasing application of bio-based materials, made of renewable raw and recycled materials, show their growing importance, mainly from the perspective of sustainability of building constructions. The fire resistance of building parts shall not influenced negatively by using bio-based materials inside or outside of wall or floor assemblies. Mainly fire protection aspects like the behaviour against fully-developed fires as well as the smoke gas potential have to be considered, in the case of using bio-based materials in timber constructions.

Normal framing methods in timber construction have voids between insulation and panels. If these voids are connected with those in floorings, hot gases and flames can spread into these spaces. Fire barriers restrict the passage of flames, hot gases and smoke and as a consequence an uncontrollable fire spread will be prevented.

For the evaluation of the fire behaviour of connections, the fire resistance of assemblies as well as insulation value and failure times of panels have to be calculated or tested. The fire resistance of separating walls and floorings can be calculated in accordance with the methods prescribed in EN 1995-1-2. This includes consideration of load-bearing capacity, insulation and integrity. Calculation methods can also be applied to element joints, e.g. the reduction of the insulation value of panels through different joint types.

The connections of building assemblies with separating function have to achieve a uniform fire resistance rating to the entire building element. The load-bearing structure and the panels shall not be exposed to fire through insufficient designed element joints. For the evaluation of the fire performance of integrated joint types the following system can be used:

a) Element-related joints

… will be generated in the single layers of assemblies according to the used material and construction method. The number and orientation of the joints depends on the usual cross-sections and panel dimensions.

b) Object-related joints

… will be generated at the boundary surfaces of the pre-fabricated assemblies. On the construction site the assemblies will be fixed together and object-related joints will change to:

b1) assembly-integrated object joints

b2) joints of assemblies

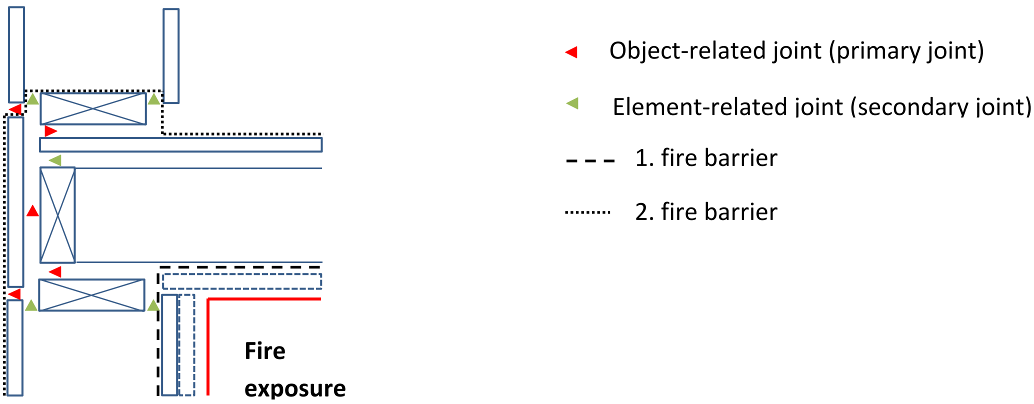

Figure 1. Element joints and fire barriers within a building connection.

To obtain well-designed timber structures convective heat transfer under fire exposure has to be taken into account. The convective heat transfer in closed conduits inside of the assemblies will be mainly influenced by the pressure and water content of fire gases as well as leakage rates and materials of the assemblies. Different joint types were tested under normal and fire conditions [1]. In subject to the leakage rates temperature peaks based on insufficient designed or executed joints will occur in layers behind the 300°C isotherm. Hereby an initial failure can be induced, which cannot be neglected in advanced studies.

To fulfill the separating function in the connection of building assemblies the narrow sides and fire-unexposed side of the connected assemblies have to be designed appropriate. Because of a possible fire exposure from both sides a robust design of two fire barriers will be endorsed. A simplified solution is the connection of the fire barriers with the internal and external layer of the core element. With the additional integration of the air respectively wind tightness function in such layers a smoke-proof construction can be realized.

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Notes

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