FIRE BEHAVIOUR OF WOOD-CLAD FACADES

TECHNICAL REPORT

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DBI

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EXECUTIVE SUMMARY

This report summarizes current knowledge on the fire behavior of ventilated wood-clad facades, to support fire safety engineers, architects, and construction professionals decision making process. It draws on literature reviews, historical fire incidents, and findings from the BioFacades:UpHigh project.

While wood façades provide aesthetic and potential environmental benefits, they also present fire risks due to wood's inherent combustibility. Key fire scenarios include flames ejecting from windows, ignition sources exterior to the building, and cavity spread in ventilated systems. Previous studies highlight that ventilated facades can significantly increase heat release and fluxes flux compared to non-ventilated or non-combustible ones. These findings underline the need to incorporate additional façade elements, such as fire barriers and deflectors, to help mitigate fire spread. Fire-retardant treatments can improve wood's fire performance but face durability challenges from leaching and weathering, requiring robust standards to ensure long-term outdoor use.

10 large-scale fire tests based on the European approach (large scale) method, were conducted as a part of the BioFacades: UpHigh project. The façade constructs were built of non-fire-retardant-treated wood cladding (thermally modified pine or non-thermally modified spruce) combined with steel plume deflectors to limit vertical fire spread. Tests varied in various aspects including deflector depth, cavity depth, cladding orientation, presence of cladding on the side wing, and size of the secondary openings. Key findings include:

- None of the façade constructions could limit the fire spread to the floor directly above the combustion chamber.
- Plume deflectors with sufficient depth could effectively limit vertical fire spread to the second floor above the combustion chamber on a single wall configuration. Upward flame spread in configuration with internal corner and lateral fire spread remain significant challenges.
- Ventilation cavities facilitate internal fire spread, while the tested fire stops could not limit the flame spread within a single floor's cavity.
- Heat fluxes at secondary openings indicate a significant risk of compartment breach via windows above the primary fire. However, this exposure is not solely attributable to the presence of wood cladding, as a significant thermal load originates from the compartment fire itself.
- Smouldering was observed in bio-based insulation exposed to high heat levels. Although burn-through was not detected during the 60-minutes of test, the continued smouldering behaviour introduces potential delayed fire risks that need to be addressed.
- Burning and falling parts from the wood cladding can pose secondary fire risks to occupants and firefighters. In the test context, distinguishing facade debris from test fuel remains challenging.
- Thermally modified wood showed similar performance to non-modified wood. More replicates on different scales are needed to confirm these results.
- Fire service operations must be considered in the early design phase, specifically in terms of accessibility, safety distances, and challenges posed by falling debris and smouldering insulation.

The results confirm that non-fire-retardant wood façades can be implemented safely, but they demand careful detailing, thoughtful mitigation strategies, and validation through performance-based testing. Several design

principles emerged as especially critical: ensuring adequate safety distances between buildings to reduce radiative heat transfer, installing plume deflectors with correct dimensions and placement, paying close attention to corners and joints, using non-combustible materials within cavities to limit hidden fire spread, and considering window geometry and placement to reduce vulnerability to flame impingement. Collaboration between architects, engineers, and fire consultants and fire services is essential in the design and approval process to ensure that both aesthetic ambitions and fire safety requirements are met.

In conclusion, non-FR-treated wood-clad facades can be implemented safely, with mitigation like plume deflectors, non-combustible linings, and fire stops, but risks of lateral spread, falling debris, and compartment breach persist. Despite these advances, several important knowledge gaps remain. Future research should further investigate how plume deflectors perform in internal corner configurations, evaluate the long-term durability of plume deflectors, and systematically assess the effectiveness of cavity fire stops. Further methods are also needed to reliably detect and mitigate smoldering in bio-based insulation materials. Finally, reduced-scale test methods and computational modelling tools could supplement costly large-scale experiments, providing a more practical means of assessing façade safety in a wider range of configurations.

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1. INTRODUCTION

1.1. Objective, scope, and limitations

The primary goal of this document is to summarize the current knowledge of fire behaviour in wood-clad facades, including results from the testing program during the project BioFacades: UpHigh. The reader is invited to refer to the testing reports for more details on individual BioFacades: UpHigh tests.

This report is intended to serve as a source of information for fire safety engineers, architects, and construction professionals, supporting the decision-making process during the building's design phase.

Project BioFacades:UpHigh was partly sponsored by Realdania and conducted in cooperation between DBI, NREP, CPH Village, Fælledby, and Frøslev Træ. The objective of the project was to demonstrate application of physical barriers (called plume deflectors) for limiting the vertical fire spread on façade cladding without fire-retardant (FR) treatment. The design of the façade constructions in the BioFacades:UpHigh project was informed by three real-world building cases, serving as representative scenarios for evaluating fire performance in practical applications.

It is evident that the façade fire behaviour cannot be discussed separately from the exposure conditions. The most assumed fire scenario involving a building's façade is a fire plume emerging from the room of fire origin through a window opening. The exposure conditions in such a scenario depend on many factors, including geometry of the room and window opening, the behaviour of the glazing in high temperatures, and the type and arrangement of burning fuels inside the room of fire origin. There is no simple answer to the question of how large fire would affect the façade in a real-life scenario. Nevertheless, the design fire scenarios are often specified in the regulatory framework for individual countries. The design fire reflects both the country's tolerance to risk and available means for mitigating hazards. In this report, regulatory aspects in different countries are mentioned only where necessary, but no extended discussion is provided. The report's primary focus is on the situation in Denmark.

Key findings and conclusions are highlighted in red boxes throughout the document to summarize critical observations and support design-related takeaways.

1.2. Role of façade in building fire safety and façade fire scenarios

The primary objective of fire safety measures in buildings is to protect human health and life against fire hazards. Other objectives include the protection of property, assets, business continuity, and the environment. Design, planning, construction, operation, inspection, and maintenance must ensure fire safety by utilizing materials suitable for their location and function, facilitating safe evacuation, maintaining structural integrity during fires, and limiting the spread of fire and smoke within and between buildings. Rescue services must have adequate means to perform rescue and extinguishing activities. Ongoing operational practices, regular inspections, and maintenance must also uphold fire safety throughout the building's lifespan.

One of the primary fire safety strategies is compartmentalization, which involves limiting fire and smoke for the time necessary to facilitate evacuation. It is accomplished with fire-resistant separating constructions that prevent fire from spreading from the compartment of origin to other compartments (fire sections or fire cells). Moreover, smoke management or control can be used in larger spaces and evacuation routes to separate individuals from smoke hazards.

The building's exterior creates vulnerability that can potentially undermine the strategy of compartmentalization. External wall and façade construction provides a potential path for fire spread from the room of fire origin to previously unaffected compartments. This may occur through windows or other openings (e.g., ventilation openings), at the façade-to-floor junction, or due to loss of integrity in the external wall. Moreover, façade burning can result in falling construction parts, which may impact fire and rescue service operations as well as the safety of people evacuating. A burning façade can also trigger secondary fires (in neighbouring buildings or nearby objects) due to high heat fluxes or the generation of burning particles.

The initial fire can originate from inside the building, outside, or from the façade construction itself (such as arson or faulty electrical installations). It is possible to reduce the likelihood of the façade being exposed to fire by, for example, requiring separation distances between parking spaces and buildings, or between buildings, and utilizing sprinkler systems. Nevertheless, the possibility of fire affecting a façade cannot be dismissed entirely. Typical scenarios that can result in fire exposure to the facades are:

- Emerging flames from the room of fire origin through a window opening.
- Burning of items in the proximity of the building – garbage containers, vehicles.
- Burning of items stored on the balconies.
- Thermal heat received from fires in nearby buildings.
- Firebrands from nearby buildings or wildfires.

Flame ejecting from the room of fire origin through a window is the most often considered fire scenario, usually represented in large-scale fire testing [1], [2], [3]. The length of the ejected flame depends on the width and height of the opening (e.g., broken glazing) and the burning rate inside the compartment [4], [5]. The burning rate in the post-flashover conditions will also be influenced by the area of the external compartment boundaries, in addition to the parameters already mentioned.

The materials used on the façade or for external walls, as well as the system configuration, can further contribute to fire spread and the generation of embers and falling debris. Combustible materials used on the façade (either cladding or insulation), if unprotected, can promote fire spread and involve large areas of the façade in burning. In addition, some materials are prone to melting [6] and dripping, which may support ignition of the lower parts of the façade [7].

Rapid and unrestricted fire spread increases the likelihood that the fire will breach the building's envelope, igniting items in previously unaffected compartments. This may occur due to increased heat flux to the external walls and windows, or simply because fire reaches more vulnerable features of the façade, thereby increasing the likelihood that one of these details will fail.

If present, the ventilation cavity also includes a path for fire spread. As noted in many publications, the narrow cavity results in extended flame heights and increased heat flux in the inner linings inside the cavity [8], [9]. If combustible materials are used on the interior surface, it is likely to intensify the burning rates.

2. BACKGROUND

2.1. Fire classification of façade materials

In Denmark, as in other European countries, the classification of construction products is based on the European Reaction to Fire classification system, as outlined in EN 13501-1 (Euroclasses). Generally, the prescriptive (also known as pre-accepted solutions in Denmark) class requirements for cladding depend on the building's use and height. In Denmark, for buildings with a top floor height of up to 22 m above ground level, rain screen cladding with a class B-s1,d0 rating should be used. However, evenly distributed smaller sections with a total area of no more than 20 % of the outer wall area can be made with material class D-s2,d2. Untreated wood cladding would typically be class D-s2,d0, whereas fire-retardant-treated wood cladding may reach B-s1,d0. Euroclasses are determined based on results from a family of tests. Classes B to D are assessed based on direct small flame impingement, as per EN ISO 11925-2, and the Single Burning Item (SBI) tests, as outlined in EN 13823. SBI, being the physically larger test of the two, is an intermediate-scale test that uses a corner configuration specimen with a height of 1.5 m. The short wing width is 0.495 m, and the long wing width is 1.0 m. The specimen is exposed to fire from a triangular gas burner with a heat release output of 30.7 ± 2.0 kW.

The use of wood facade cladding without FR-treatment is therefore effectively limited for multi-storey construction in Denmark. Deviations from the pre-accepted solutions can be approved on a project basis by a certified fire safety engineer. Sometimes, indicative ad hoc fire testing can be used to support the decision-making process during the fire safety design.

In some countries, large-scale façade fire tests, which allow for testing a semi-complete system, can also serve as a basis for approving the façade system. This provides an opportunity to use materials that do not meet the Euroclass requirements, provided that the complete façade system passes the large-scale façade test criteria. However, there is no single standardized test used in all European countries. The advantages of using large-scale façade tests, compared to intermediate-scale tests, are as follows:

- The heat exposure from the fire in large-scale tests is more representative to expected real-life scenarios.
- A more complete façade and external wall system can be tested in a large-scale test, including the ventilation cavity geometry, fire stops, and window detailing.
- Measurements of heat transfer inside the external wall are possible.
- Observations or falling parts are possible.

The fire tests in project BioFacades: UpHigh reported in this document used the principal test rig from the European approach to assess the fire performance of facades - large scale (referred to as *European approach* in this document) [10], although the tests did not strictly follow the European approach. A short description of the method and the deviations used in BioFacades: UpHigh is provided in section 3.1. The main advantages of the European approach, compared to other large-scale methods, are that the development process is well-documented, including repeatability and sensitivity to various parameters. The European approach also provides relatively high thermal exposure to the tested construction compared to other large-scale test methods [11].

2.2. Characteristics of wood as a combustible material

Wood is an organic, lignocellulosic material mainly composed of cellulose, hemicellulose, and lignin. In addition to its three main components, wood contains other substances, including resins, fats, alkaloids, and minerals. During the exposure to heat, wood undergoes thermal decomposition, releasing gases, vapors, tars, and forms char (see Figure 1). First, the free water in the cell cavities evaporates, followed by the release of chemically bound water. The moisture content of wood can significantly vary depending on factors such as wood species, environmental humidity, temperature, age, and the degree of thermal treatment. As moisture is lost, shrinkage occurs in the wood, resulting in varying degrees of contraction in the tangential and radial directions. This uneven shrinkage leads to cracking, which accelerates the drying process.

The thermal decomposition of hemicelluloses occurs between approximately 180 °C and 350°C, followed by the decomposition of cellulose at around 275 °C to 350°C. Lignin decomposes over a broader temperature range of 250–500°C. During pyrolysis, char formation occurs while volatile gases escape from the wood's porous structure to the surface. Given an ignition source and a nearly stoichiometric mixture of fuel gas and air, flaming combustion begins. The oxidation of volatile gases results in a significant release of heat. The heat feedback from the flame, especially by the thermal radiation, accelerates pyrolysis, generating sufficient combustible gases to sustain the fire. This feedback is eventually limited due to the insulation provided by the char layer, resulting in a decrease in the burning rate.

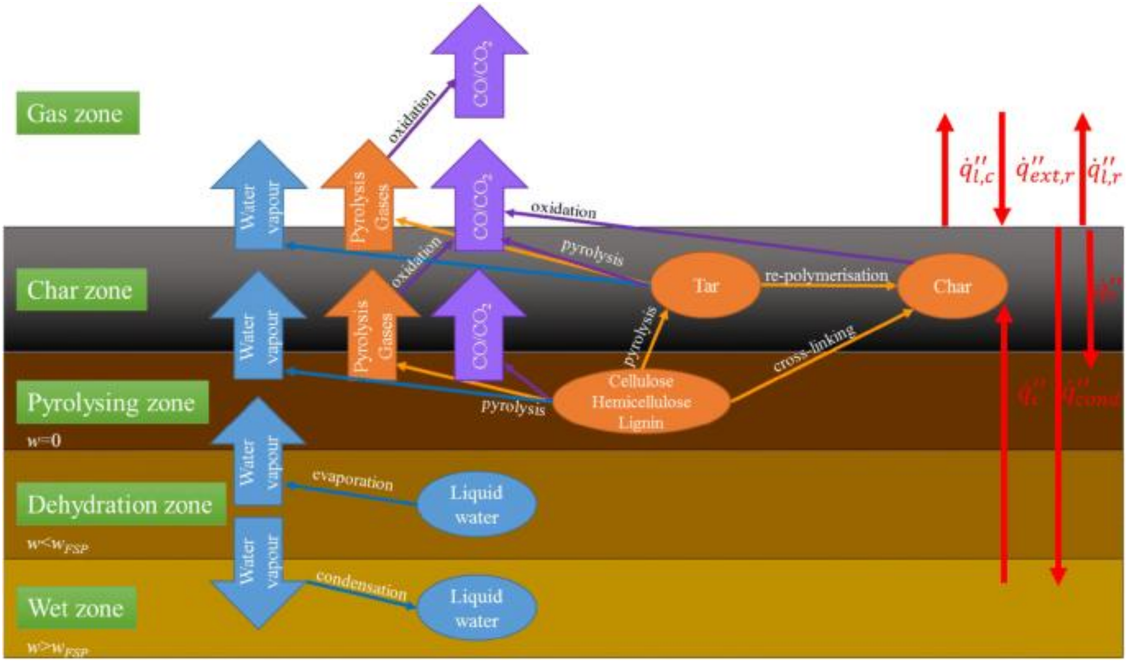


Figure 1: Chemical and physical processes within a burning timber sample [12]

As the charring progresses, the char undergoes oxidation at elevated temperatures, releasing heat until only ash remains. The charring rate of wood is a critical factor in assessing the fire resistance of timber structures. It represents the speed at which the charred layer progresses into the material when exposed to fire. Generally, denser wood species exhibit slower charring rates due to their compact structure. Under exposure to the standard cellulosic fire temperature-time curve (according to ISO 834), charring rates typically range from approximately 0.8 mm per minute for light, dry softwoods and around 0.4 to 0.5 mm per minute for dense, moist hardwoods, reflecting the influence of wood type and moisture content on fire behaviour [12].

Flaming vanishes depending on the availability of combustible material and the energy balance of heat generation and losses. Due to the porous structure of wood, the material tends to smoulder after the flames have vanished. Smouldering can be described as flameless combustion, sometimes accompanied by glowing. It can be very persistent, although the heat release is much smaller than in a flaming combustion. Depending on the circumstances, a smouldering fire can transition to flaming and vice versa.

Thermal modification and aging can influence the flammability and burning characteristics of wood. Table 1 compares the fire performance of three different wood specimens: PS-Virgin (i.e., non-thermally modified Pinus Silvestris), PS-TM-New (i.e., new thermally modified Pinus Silvestris), and PS-TM-Aged (i.e., aged thermally modified Pinus Silvestris with an estimated weathering time of 7 years. The tests were done under different heat flux exposures in the cone calorimeter [13]. The virgin specimen took the longest to ignite (43 s), while both thermally modified samples ignited faster (35.3 s and 35.7 s). The critical heat flux for ignition was lowest for the aged sample (14.5 kW/m²). The new thermally modified sample had the highest peak heat release rate (151.3 kW/m²), while the virgin sample had the lowest (141.2 kW/m²). A similar trend can also be observed in the intermediate-scale Single Burning Item test, where thermally treated samples exhibit higher fire growth rates and total heat release rates, indicating worse fire behaviour compared to the virgin samples. However, there is effectively no difference between the flammability classes of these materials according to the European reaction to fire classification[13]. Up to three repeated tests were done in the cone calorimeter; however, no information is given on the number repeated tests in SBI.

Table 1: Results from Cone-Calorimeter Tests with Pinus Silvestry with virgin, thermally modified (TM), and additionally aged samples. Table reproduced from reference [13]

Parameter	PS-Virgin	PS-TM-New	PS-TM-Aged	Heat flux exposure
Specimen thickness (mm)	43	43	42	Constant 35 kW/m²
Specimen initial mass (g)	191.4	159.7	175.0	
Time to ignition (s)	43	35.3	35.7	
Total heat release (MJ/m²)	97.4	106	111.2	
Peak heat release rate (kW/m²)	141.2	151.3	148.5	
Critical heat flux for ignition (kW/m²)	17.7	17.5	14.5	Varying

In a different study, cone calorimeter tests were conducted at DBI using Scots pine wood also used as façade material in the Biofacades:UpHigh project. Both thermally treated and virgin (untreated) wood samples were tested at a heat flux of 25 and 50 kW/m² (sample thickness of 22 mm). As shown in Figures 2 and 3, the time to ignition at both heat flux levels is very similar between the two types of wood. Although the average peak mass loss rate for the thermally treated wood is higher than that of the virgin wood, one of the virgin wood tests exhibited a peak mass loss rate exceeding the average peak of the thermally treated samples. Therefore, it is difficult to draw a definitive conclusion regarding which wood type has a consistently higher peak mass loss rate. In the mass loss rate curves, the second peak appears earlier and persists longer in the virgin wood samples compared to the thermally treated ones. This secondary peak is typically attributed to thermal feedback when the heat wave reaches the lower part of the sample. The observed differences are likely due to variations in the thermal inertia between the two material types.

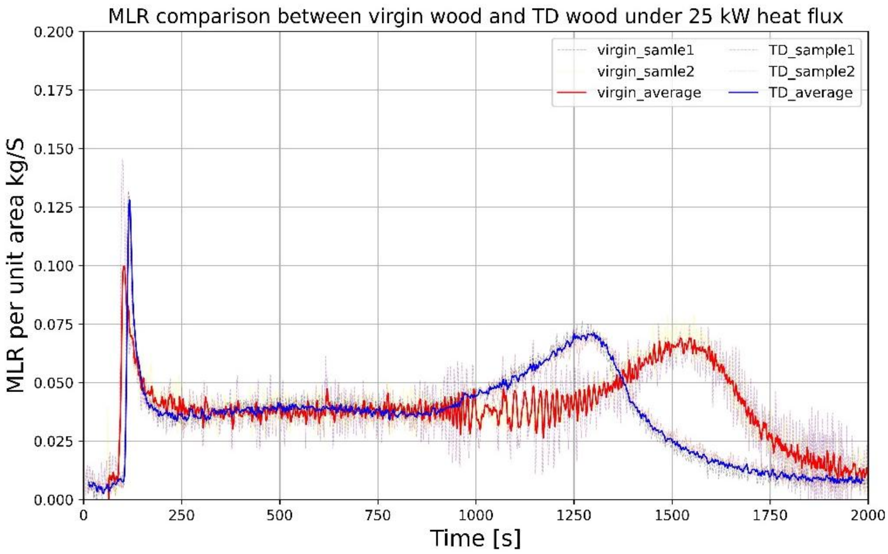


Figure 2: Comparison of mass loss rates between virgin (red) and thermally treated (blue) Scots pine under 25 kW/m² heat flux in cone calorimeter tests conducted at DBI.

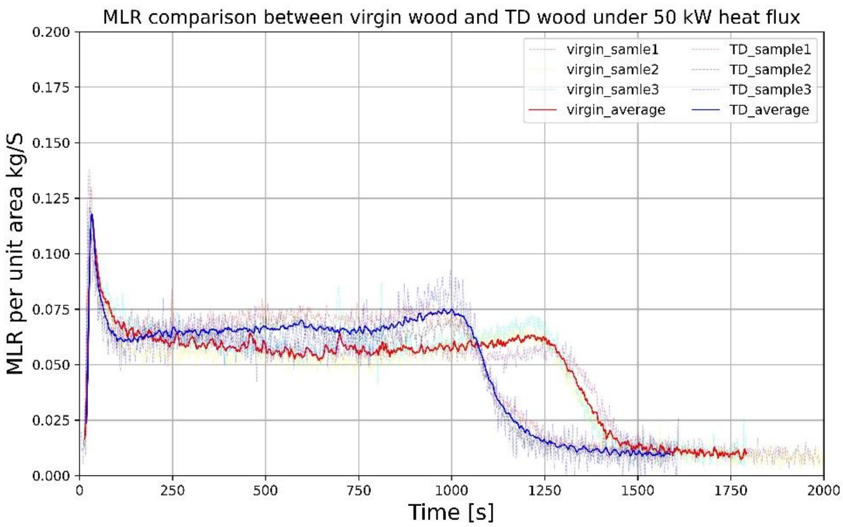


Figure 3: Comparison of mass loss rates between virgin (red) and thermally treated (blue) Scots pine under 50 kw/m² heat flux in cone calorimeter tests conducted at DBI.

A similar indication that thermally modified wood performs slightly worse compared to non-thermally modified wood (given all the other parameters, e.g. species, board dimensions and orientation etc. are the same) is based on manufacturers Frøslev Træ A/S data. The summary of two sets of SBI tests provided by is given in Table 2.

Table 2: SBI test results based on data provided by company Frøslev Træ A/S, board thickness 21 mm. Vertical and horizonal orientations of the cladding boards in the test.

	ThermoWood Sature (thermally modified)	Frøslev Sature Fyr (untreated Pine)	Number of Tests
FIGRA 0.2MJ – Vertical	332.7 W/s	309.6 W/s	1
FIGRA 0.2MJ - Horizontal	398.0 W/s	361.4 W/s	3
THR - Vertical	12.2 MJ	15.5 MJ	1
THR - Horizontal	12.4 MJ	17.1 MJ	3

Due to the inhomogeneity of wood, it is suggested that the conclusion about the performance should be based on a larger number of repeated tests.

Small-scale fire tests indicate that thermally modified wood performs slightly, if at all, worse than unmodified wood. However, an increased number of repetitions across all scales is needed for conclusive results.

2.3. Structure of wood-clad facades and fire behaviour

Wood cladding profiles and connection joints come in a wide variety, including tongue-and-groove, shiplap, board-on-board, and open joint cladding. Illustrations of the cladding types are provided in Figure 4.

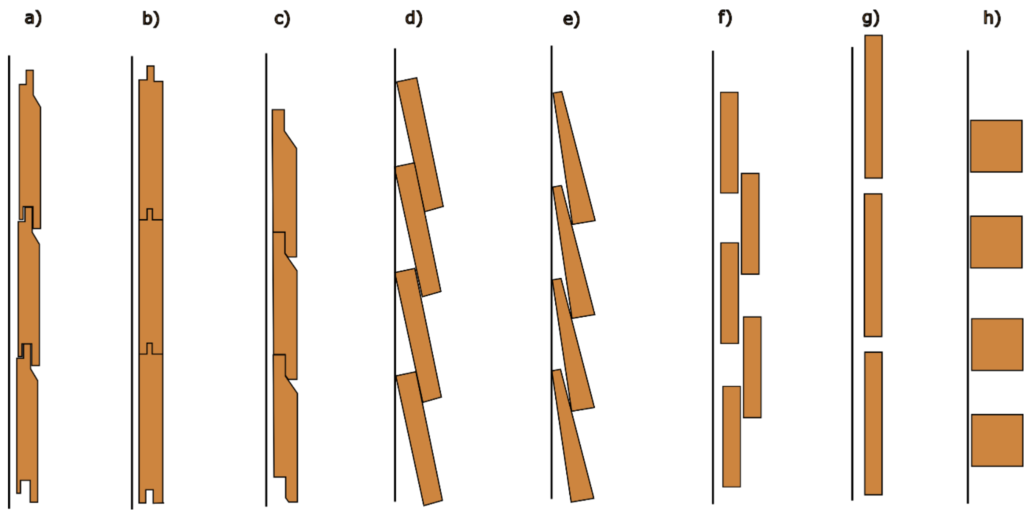
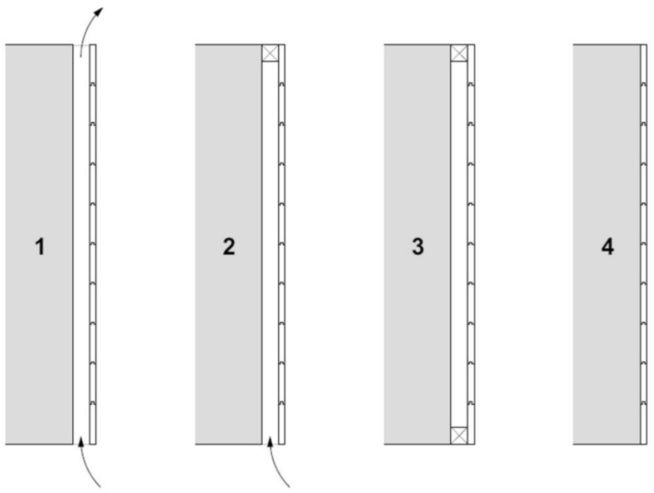


Figure 4: Typical wood cladding connection types: a) and b) tongue and groove c) shiplap d) square edge e) feather edge f) board-on-board g) open joint h) lamellae

Wood-clad facades are often rear-ventilated because this method significantly improves the long-term durability, performance, and moisture control of the facade system. Rear-ventilation enables air circulation behind the wood cladding, facilitating the rapid evaporation of moisture resulting from rain, condensation, or humidity. This significantly reduces the risk of moisture-related problems such as mold growth, wood rot, and structural deterioration. In ventilated façades, there is a distinction between fully rear-ventilated façade claddings (with openings at both the top and bottom) and partially rear-ventilated façade claddings, as illustrated in Figure 5. Facades without rear ventilation are less frequently used, primarily due to concerns regarding their long-term durability.



1 Fully rear-ventilated façade cladding

2 Partly rear-ventilated façade cladding

3 Non rear ventilated façade cladding with void

4 Non rear-ventilated façade cladding without void

Figure 5: Overview of structural designs of wooden façades [14]

However, rear ventilation poses additional fire safety challenges because it allows fire to spread through the cavity and measures are necessary to limit the spread of the fire inside ventilation cavity. A typical design principle is the arrangement of non-combustible external wall linings, and fire stops in the void cavities, see Figure 6. In case of non-FR wood cladding, fire stops are also crucial to limit the fire spread on the façade surface.

The cladding profiles can be arranged in vertical, horizontal, or both orientations. Vertical arrangement typically requires two layers of battens, whereas the horizontal arrangement requires one layer.

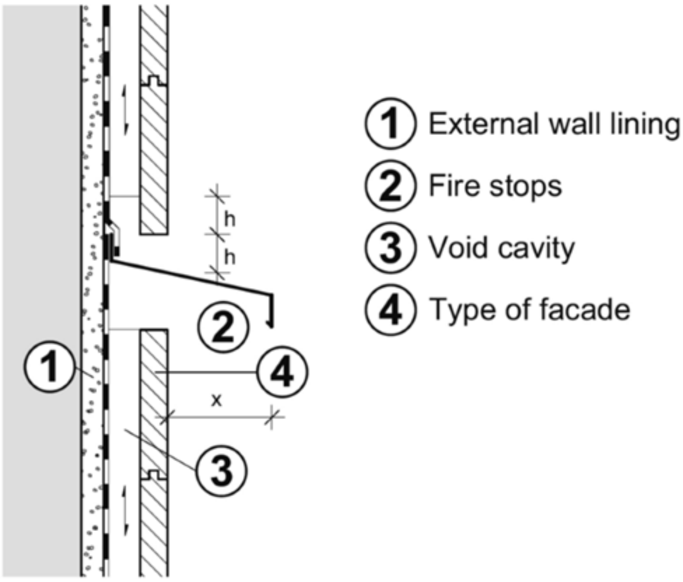


Figure 6: Typical structural design of wooden façades [14]

2.4. Summary of findings of previous work on wood clad facades

This section presents a brief summary of conclusions drawn from large-scale tests conducted with ventilated wood facades. It is worth noting that the list below is based on results from various test methods.

1) The total energy released from a ventilated plywood "façade" was nearly 2 times higher for a ventilated façade compared to a non-ventilated façade. [15]
2) The ventilated plywood façade produced approximately twice the total heat flux at the center of the fictitious window opening located one floor above the combustion chamber, compared to a non-combustible façade. Specifically, the non-combustible façade exhibited heat flux values between 30 and 40 kW/m^2, whereas the ventilated plywood façade reached significantly higher levels, ranging from 60 to 65 kW/m^2. The ventilated plywood façade also resulted in much higher temperatures measured at the centre of the fictitious window opening located two floors above the combustion chamber, compared to plywood façade without a cavity and an inert façade. [15]
3) When up to 33% of the façade area was covered with wood cladding without FR-treatment, the constructions managed to pass the SP FIRE 105 test requirements. When 60% of the façade area consisted of wood cladding without FR-treatment, the test resulted in failure. The failure criterion was charring observed near the window opening at the second floor. [16]
4) Fire barriers serve two main purposes: first, they block ventilation cavities to prevent fire from spreading via the chimney effect; second, they shield the wooden façade above by keeping flames and heat at a distance, reducing the risk of ignition. [17]
5) The dimensions and design of the horizontal projection in front of the façade cladding depend primarily on the type of formwork used for the timber façade. [14]
6) Under high temperatures, steel sheet fire barriers expand, which can cause gaps to form between the fastening points. Thus, a rigid connection is crucial. [14]
7) When façades include internal corners, additional construction measures are necessary to meet safety objectives due to the increased flame lengths in corner. [17]
8) Horizontal fire shield (similar to plume deflector) with extension of 0.8 m outside the façade and located directly above the combustion chamber opening, did limit the fire spread on 100 % wood-covered façade, effectively fulfilling SP 105 Fire tests requirements. [16]
9) Interior linings of the ventilation cavity should preferably be non-combustible. [14]
10) In general, a closed cladding system or cladding with a lower cavity depth has shown improved fire performance in terms of its fire spread. [14]
11) Formation of gaps on the cladding and between the cladding boards promotes the fire spread and hence negatively influences the fire behaviour of the façade system. [14]

2.5. Notable historical fire incidents with wood-clad facades

A list with an excerpt of other notable fire incidents with wood-clad facades is provided in Table 3. Due to the limited documentation of minor incidents in the literature, the list represents fire incidents with severe consequences.

Table 3: Excerpt of notable fire incidents with wood cladding facades

Date	Location	Building type	Facade	Soure
07/08/2021	Bergen, Norway	4-storey residential block	Wooden balconies/facade	[18]
18/09/2019	Clapton, London, UK	five-storey residential block	Wood cladding facade	[19]
09/09/2019	Worcester Park, London, UK	four-storey residential block	Wooden-framed and wood-clad	[20]
09/06/2019	Barking, London, UK	6-storey residential block	Wooden balconies/facade	[21]
31/12/2017	Manchester, UK	12-storey tower block	Wood cladding facade	[22]

Two example fire incidents are described in more detail below. The following examples illustrate worst-case fire incidents involving buildings with wood-clad facades, where, in addition to the material choice, the geometry also played a significant role. These cases underscore the fire risks associated with combustible exterior materials and emphasize the importance of implementing effective fire safety measures.

Bergen (Norway), 2021

On the morning of Saturday, August 7, 2021, a fire broke out in a four-story block building with 24 flats in the Lone district of Bergen, Norway. The building was designated as social housing for individuals undergoing drug rehabilitation. Kebony® wood cladding (typically classified D-s2,d0) was applied to the balconies, facades, and walkways of the building. The used wood material was impregnated with a mixture of furfuryl alcohol and a catalyst, followed by a heating and drying process that permanently enhances its durability.

Each apartment featured a balcony on the southwest side of the building, all enclosed by tight-fitted Kebony® balustrades. The partitions between balconies and the cladding on the façade walls were also constructed from the same material. An opening above the partitions separated the balconies on the same floor (see Figure 7). The cladding was also used for the galleries on the northeast side of the building, both on the façade wall and in the dense railings.

Figure 7: Wood-cladding balconies on the south side of the building before the fire [18]

The incipient fire most likely started on the balcony of a ground-floor apartment. The fire department was alerted at 02:17 through the automatic alarm system triggered by the activation of the sprinkler system inside the building. Eleven minutes later, the fire service arrived at the scene, observing a fully developed fire consuming the entire south side of the building, with flames spreading across the roof. By 03:15, all occupants (24 residents and one security guard) had been safely evacuated **[23]**. Figure 8 shows the fire development about two hours after the fire alarm.

Figure 8: Municipal apartment building fire on 7th of August 2021 in Bergen, Norway (Southside, two hours after fire alarm) [23]

A comprehensive report on the incident has been published in **[18]**. The fire properties of the materials used on the balconies and walkways, together with the geometry of these structures, appear to have played a decisive role in the rapid development of the fire. A significant amount of property was also stored on the balconies, which was not considered in the fire concept. Material testing of the undamaged cladding revealed that aging and low moisture content had a negative impact on its fire properties. At the same time, the building design and especially the balconies, enabled a rapid fire spread on the wood cladding. Ultimately, the investigation highlighted that material choice and geometric influences are crucial factors in the fire-safe design of wood-cladding facades.

Barking Riverside Fire, London (UK), 2019

On June 9, 2019, a serious fire occurred at Samuel Garside House, Barking, recorded under London Fire Brigade (LFB) Incident Number 072738-09062019 **[21]**. The fire was first reported to the LFB at 15:29 on June 9, 2019 and affected a residential block containing 79 flats. The first fire engine arrived at the scene at 15:36 and found that the timber-clad balconies, spanning from the ground floor to the roof, were fully alight (see Figure 9). The incident escalated quickly, and by 15:39, the fire officer on scene requested ten fire engines and an aerial ladder platform to tackle the growing blaze. The fire was brought under control at 18:04 when it was declared "surrounded," meaning it was contained but not fully extinguished. A final stop message, indicating that the fire had been fully extinguished, was sent at 21:02.

Figure 9: Barking Riverside fire - Entire section of balconies burning [24]

The emergency response involved approximately 63 people evacuating the building, with many doing so before the arrival of the fire brigade. Despite the scale and intensity of the fire, there were no human fatalities. However, three cats perished in the fire. Two residents were treated on-site by paramedics for smoke inhalation, but their injuries were not life-threatening, and they were released after precautionary checks.

The damage caused by the fire was extensive, particularly to the balconies and external areas of the building. A 20-metre-long section of timber-clad balconies running from the ground floor to the roof was completely destroyed. The fire also caused significant internal damage to several flats. Two flats were utterly destroyed, while another two flats suffered 90% fire damage. Other flats experienced partial destruction, with 30-50% of their interiors damaged. In addition to the internal destruction, the fire reached the roof, causing damage in void spaces beneath the weatherproofing layer.

The fire investigation determined that the blaze originated on the second-floor balcony of a flat. The interconnected design of the wooden balconies allowed the fire to spread rapidly upwards and across the building's exterior.

Previous fire incident underscores that fire safety in wood-clad facades fundamentally depends on materials properties, facade geometry, compartmentalization and the fire scenario itself. Cladding around the balconies poses a specifically high hazard.

3. PROJECT BIOFACADES: UPHIGH

3.1. Test method

A testing program of 10 large-scale façade tests was performed as part of the project BioFacades:Uphigh in 2023 and 2024. The project was funded by Realdania and five partners: NREP, CPH Village, Fælledby, Frøslev Træ, and DBI. The tests were conducted at the DBI testing facilities in Hvidovre, Denmark. The testing program exclusively focused on wood cladding without FR-treatment, with the steel plume deflectors as the primary strategy for limiting vertical fire spread.

The test method was roughly based on, although not precisely followed, the European approach to assess the fire performance of facades method "large scale" (referred to in this text as European approach) [10]. When the tests were planned and conducted, the European approach was still in its development stage and was not yet a standardized method. The European approach is composed of a corner configuration façade, with a main face and a return wing, as shown in [10]. The combustion chamber is placed at the lower part of the main face, see Figure 10. A wooden crib with a mass of 350 ± 20 kg (resulting in approx. 1.0 × 1.1 × 1.5 m^3), placed inside the combustion chamber, is used as the fuel source. The minimum height of the façade above the top edge of the combustion chamber opening is 5.5 m. A secondary opening of 1.2 × 1.2 m^2 is located on the main face 1.5 m above the top edge of the combustion chamber. Thermocouples are used to measure temperatures at external to the cladding surface, inside the ventilation cavity, and in mid-depth of the insulating layer. The thermocouples are placed in a horizontal line 4.5 m above the top edge of the combustion chamber and two columns – 2.75 m from the corner on the main wall and 1.45 m from the corner on the return wing (see Figure 10). During the time this report is written, the method suggested using the following pass/fail criteria:

1) Vertical fire spread - external or internal temperature rise of 700 K on the horizontal thermocouples row placed 4.5 m above the top edge of the combustion chamber for 30 seconds.
2) Horizontal fire spread - external or internal temperature rise of 700 K on the vertical thermocouple columns for 30 seconds.
3) Burning parts – if a falling part burns for more than 30 seconds after reaching the ground.
4) Falling parts - Two levels of falling part criteria are suggested. Level 1 is stated when any falling part exceeds 1 kg. Level 2 is stated when any falling part exceeds 5 kg.

More information on the test method can be found in reference [25].

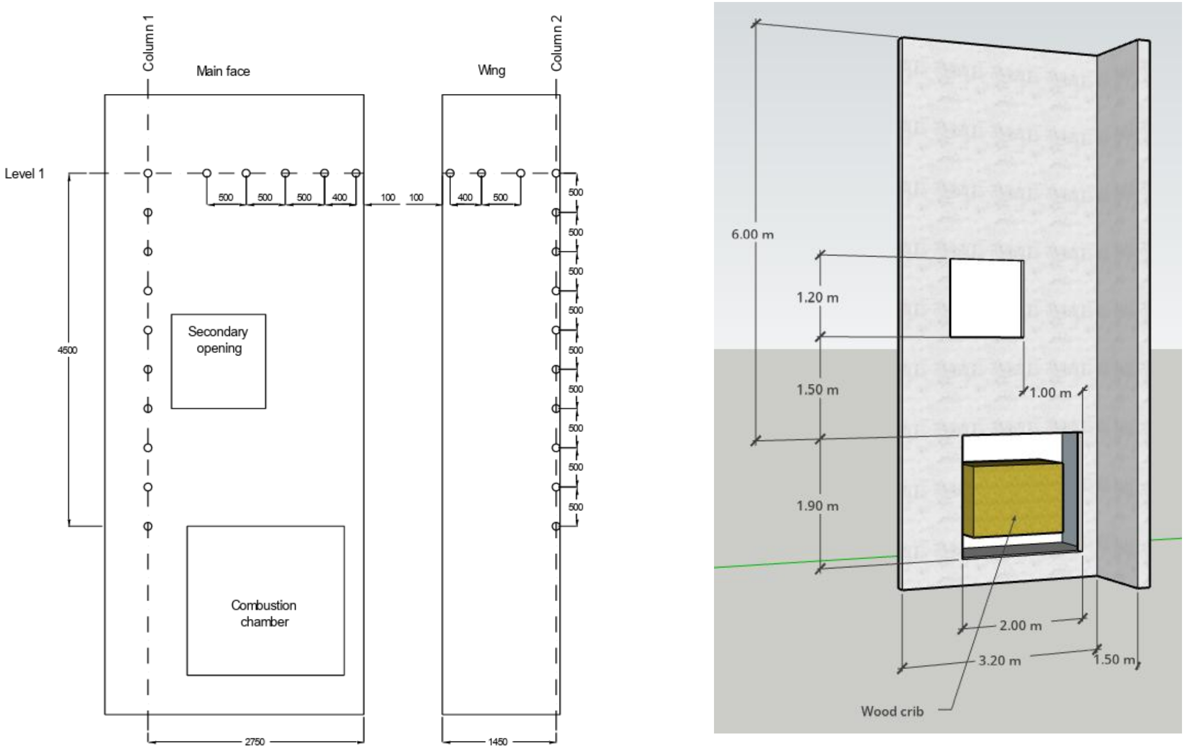


Figure 10: Thermocouple positions required according to the European approach and sketch-up of the test rig

A list of Large- and intermediate-scale façade tests used around Europe are listed in Appendix B. The European approach (large-scale) has been demonstrated to cause a significant thermal impact on the façade surface. It produces taller flames and higher local temperatures (measured with plate thermometers) compared to large-scale SP Fire 105, LEPIR 2, NFPA 285, and CAN/ULC-S134 methods. It is also concluded that the European approach may be representative of a severe real fire [11].

European approach to assess the fire performance of facades (large-scale) creates relatively high heat exposure to façade compared to many other large-scale tests. There are indications that the heat exposure in this test is representative of severe real-life fires.

Danish fire safety regulations neither specify a large-scale façade test method for system certification nor provide for indicative testing in multi-storey building projects; hence, these test results cannot be used for classification of the construction for use in a pre-accepted solution framework. For the context of this project, the method was used as an ad hoc or demonstration test, and the results were intended to support engineering decision-making. The deviations from the originally proposed method were implemented in the BioFacades:UpHigh tests. These deviations were based on the design of the individual building projects for which the corresponding tests are intended. The most significant differences between the European approach and tests performed for BioFacades: UpHigh project include:

- The return wing was not clad with the façade solution in many of the tests. Nevertheless, in those cases, the supporting structure made of aerated concrete was maintained in the test setup.
- The secondary opening size was different in different tests.

- A weighing load cell to measure the mass of the falling parts was not used in the tests, due to technical challenges.
- The starting time of the test is defined as the moment when the wood crib is ignited, instead of a 380 K increase at any of the thermocouples at 4500 mm above the combustion chamber.

As many other fire test, the European approach is not originally intended to provide information of constructions behaviour in a “realistic” fire scenario, but rather it is a method for ranking the constructions. The deviations applied here prohibit direct comparison between BioFacades: UpHigh test results and results from other similar tests.

The summary of the tested constructions and the test results done in the BioFacades: UpHigh project are presented in APPENDIX A. Some of the constructions in APPENDIX A, are designated as “high” and some as “low” constructions. In this context, “high” constructions refer to the façade construction for the second floor, which is complete and includes the plume deflector at the top of the façade. “Low” construction means that the second-story façade is not built in its full height, and it typically would not include a plume deflector at the top. The reason for using “low” constructions was to minimize the risk of damage to the exhaust system in the testing laboratory.

3.2. Cladding materials used in Biofacades: Uphigh project

In the 10 tests conducted at DBI, thermally modified pine (tests 1-2 and 5 -10) and thermally non-modified spruce (tests 3 and 4) were used as cladding material.

A brief material study was done prior the Biofacades: UpHigh tests. In this pre-testing thermally treated wood is ThermoWood® class D (also referred to in this document as thermal D) from Frøslev with dimensions of 21 × 120 mm was compared to its not-thermally treated counterpart. The photos of both samples are given in Figure 11. This product is derived from Scots pine (Pinus sylvestris) and is a softwood commonly used in the construction industry. The thermal modification process applied to the raw Scots pine enhances its stability and durability. This process, known as the ThermoWood® process, was developed by the Technical Research Centre of Finland (VTT) [26]. During thermal modification, the timber is treated with steam, which not only protects the wood but also drives the permanent structural and chemical changes within it.

The thermal D wood, in a 21 mm profile mounted on D-s2, d0 wood battens and A2-s1, d0 gypsum, has been classified with a fire reaction rating of D-s1, d0.

Figure 11: (left) Raw wood of Scots pine, (right) Thermal-D wood.

In pre-testing samples the density of the thermal-D wood was measured to be 420 kg/m^3, whereas the untreated raw pine wood had a density of 490 kg/m^3. The moisture content was around 4% for thermal-D wood after 48 h in the conditioning room. For comparison, typical moisture content in construction-grade untreated softwood is about 8-12% but can reach up to 20% in unconditioned or freshly sawn timber. This aligns with the general rule of thumb that ThermoWood has approximately 50% lower moisture content than untreated wood under similar environmental conditions. For comparison the density and moisture content for the BioFacades:UpHigh tests are given in the individual test reports (measured density was 441.5 ± 49.5 kg/m^3 for thermally treated pine and 470 kg/m^3 for non-thermally treated spruce). The pre-testing results of the mass loss cone calorimeter are previously provided in Figure 2 and Figure 3.

The thermal conductivity of the wood materials is reported in Figure 12 to provide insight into their heat transfer characteristics, which is a relevant parameter when considering the fire performance of façade claddings. In principle, lower thermal conductivity means that the material transfers heat slower, potentially delaying heat penetration to underlying layers and influencing the ignition and fire spread behaviour of the system. This may be particularly important for ventilated façades where thermal insulation and cavity detailing play a role in fire development. The overall fire behaviour of full-scale system depend on many factors, and hence the thermal conductivity may have only a minor role in it. The overall fire behaviour depends on a combination of factors such as cladding geometry, ventilation cavity design, combustibility of surrounding materials, and the presence of fire barriers.

The thermal conductivity of thermal-D wood was found to be approximately 0.10 - 0.11 W/(m·K) between 18 °C and 85 °C, in contrast to raw wood material which increases from 0.125 to 0.15 W/(m·K) within the same temperature range, as illustrated in, see Figure 12.

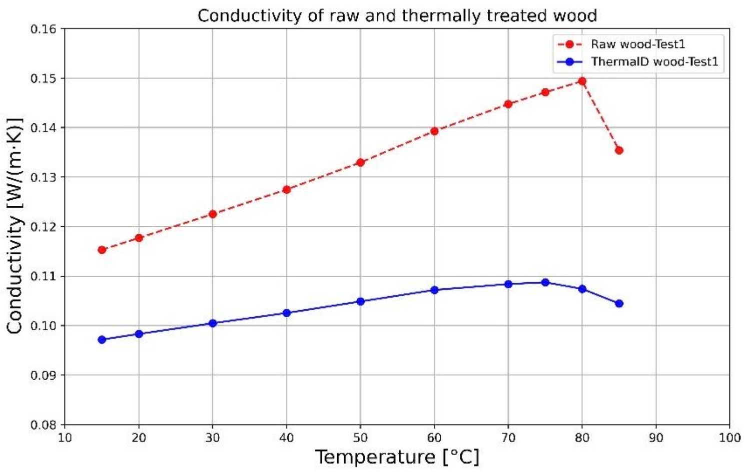


Figure 12: Conductivity of raw wood and thermal-D wood.

3.3. Flame spread and heat release from wood cladding

3.3.1. Thermal exposure on the façade and horizontal deflector

The thermal exposure received on the surface of the façade is crucial to the flame spread. This is related to the configuration of the façade system. There are three distances that can significantly affect the shape of the ejecting flame. They are illustrated in the Figure 13 below.

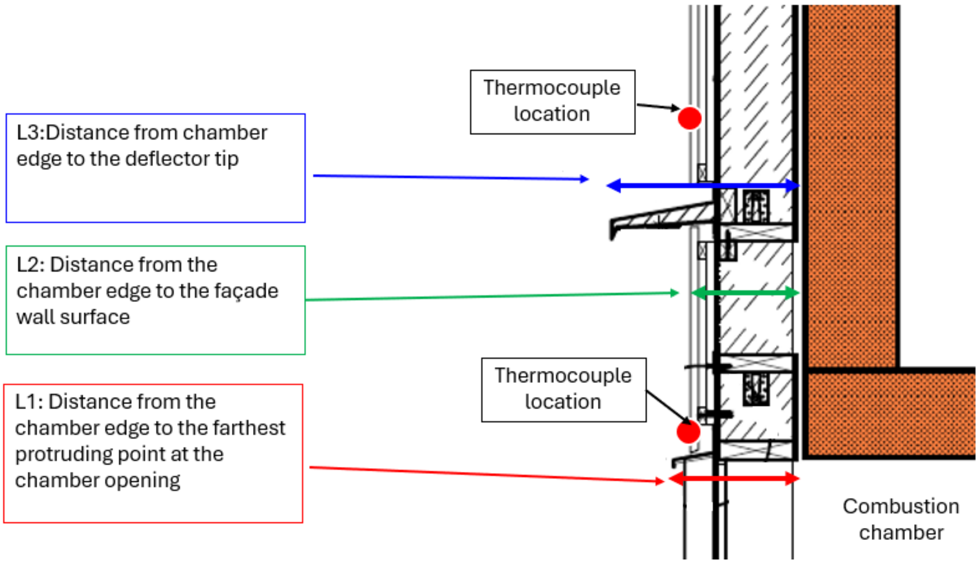


Figure 13: Distances in the Façade system.

The thermocouple temperature measured directly above the combustion chamber is strongly influenced by the distance L1. Generally, a larger L1 corresponds to a lower measured temperature, as the flame is directed further away from the façade, while a shorter L1 results in a higher temperature. As shown in Figure 14, the temperature recorded just above the combustion chamber across the ten tests (with the thermocouple location indicated in Figure 13) follows a power-law relationship with the distance L1, defined as the distance from the chamber edge to the farthest protruding point at the chamber opening. This finding quantitatively demonstrates the importance of geometrical parameters of façade design. The temperatures at 2 minutes were selected to assess the initial thermal exposure to the façade surface prior to ignition. This early-phase temperature reflects the direct flame impingement from the crib fire, isolated from the added heat contribution of burning façade materials.

It is important to note that this relationship applies only to the specific thermocouple location discussed. A larger L1 does not guarantee compliance with test criteria. Rather, L1, together with L2 and L3, should be viewed as critical design parameters that require careful consideration and should not be overlooked in the design process.

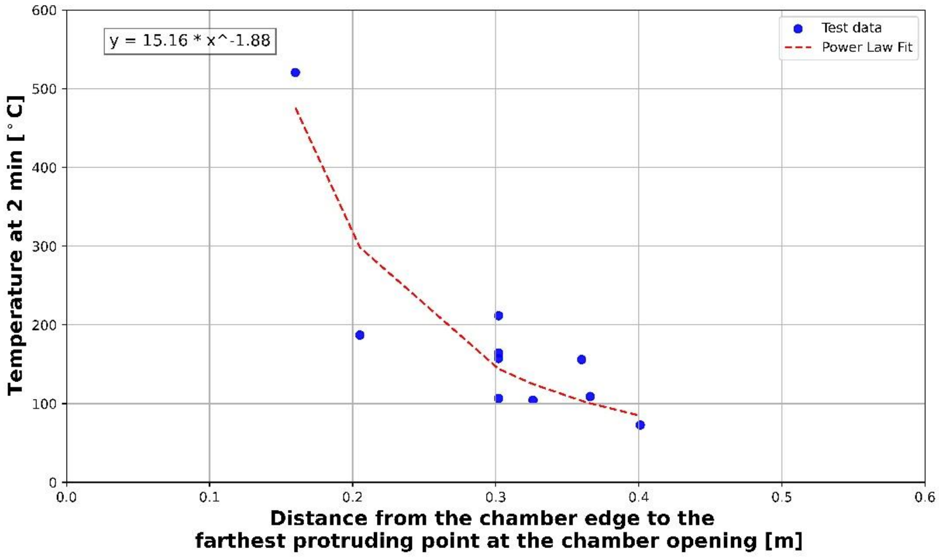


Figure 14: Temperatures on the façade at 2 min right above the chamber.

It is evident that the thermocouple temperatures recorded higher up on the first floor and further along the façade are influenced not only by L1, but also by L2 and L3. However, due to the limited number of tests conducted in this study, it is not possible to establish a clear quantitative relationship between the measured temperatures and the distances L2 and L3. Nonetheless, the temperature results on the first floor from the ten tests—including the corresponding values of L1, L2, and L3—are provided for reference in Table 4.

Table 4: Temperatures measured on the first floor of the façade at 2 min.

Parameter	Test1	Test2	Test3	Test4	Test5	Test6	Test7	Test8	Test9	Test10
L1: Distance from the chamber edge to the farthest protruding point at the chamber opening	205	160	366	401	360	302	302	302	326	302
L2: Distance from the chamber edge to the façade wall surface	175	159	315	330	284	288	288	288	292	288
L3: Distance from chamber edge to the deflector tip	375	365	639	654	540	587	587	587	489	587
Temperature on the façade at 2 min on the 1st floor	263	836	96	85	399	140	156	152	169	142

3.3.2. Burning area on the façade

The total burning area during and after the test was determined based on the videos and photos. Additionally blue light imaging method [27] was employed during the test, enabling a better visualization of areas through flames, and determining the extent of burning areas that might otherwise have been obscured at certain times. Figure 15 - Figure 19 illustrate the progression of flame spread and the corresponding increase in burnt area on wood façades in the 10 tests. Color-coding is used, ranging from red (indicating the early test phases) to light yellow (representing the later stages), to illustrate the progression of burnt area. The timeline from test's initiation to when flames spread to the specific façade area is represented in mm:ss. The areas without such a time mark remained unburnt throughout the entire test.

For example Tests 3 and 4 are presented in Figure 16. In Test 4, the entire ground floor area, which is on the same level as the combustion chamber, was engulfed in flames by 25:00. Conversely, in Test 3, a small area on the ground floor remained unburnt. The flame spread to the first floor more rapidly in Test 4, with the first area above the deflector covered in fire at 07:00, compared to 11:00 in Test 3. Additionally, while only about 42% of the first floor's total area was burnt in Test 3 by the time marker 59:00, Test 4 experienced complete burning of the entire first floor area by time marker 15:00. By the 36:28 mark in Test 4, flames had reached the second floor, in contrast to Test 3, where the fire was confined to the first floor for the duration of the test. The progression of the flame spread in the conducted tests highlights significant differences in fire behaviour across different configurations.

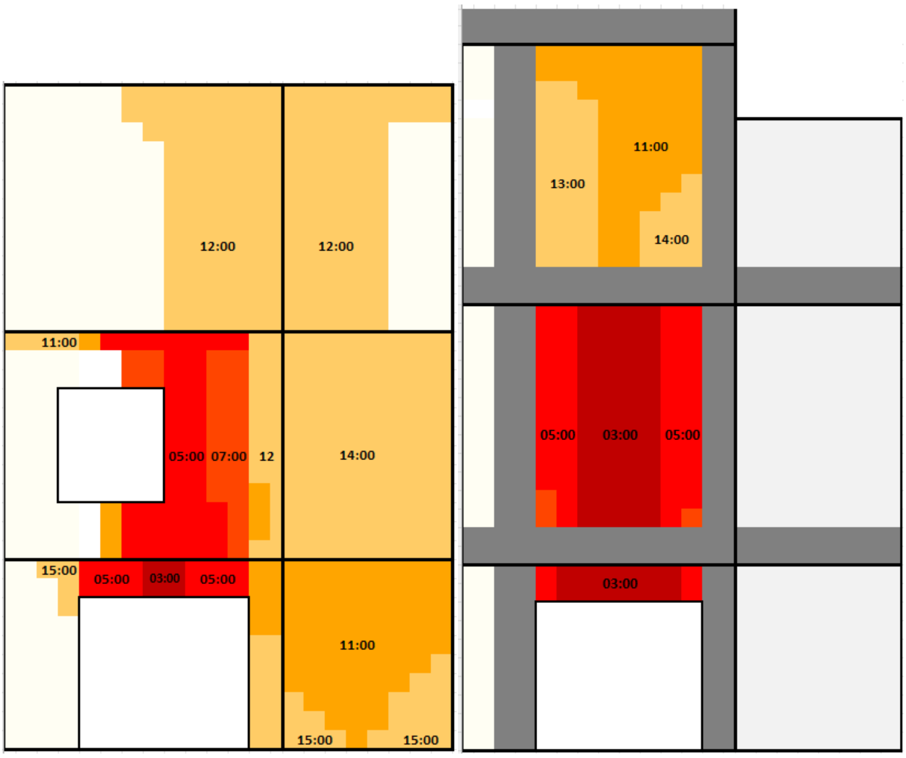


Figure 15: Flame spread in Test 1 (left) and Test 2 (right).

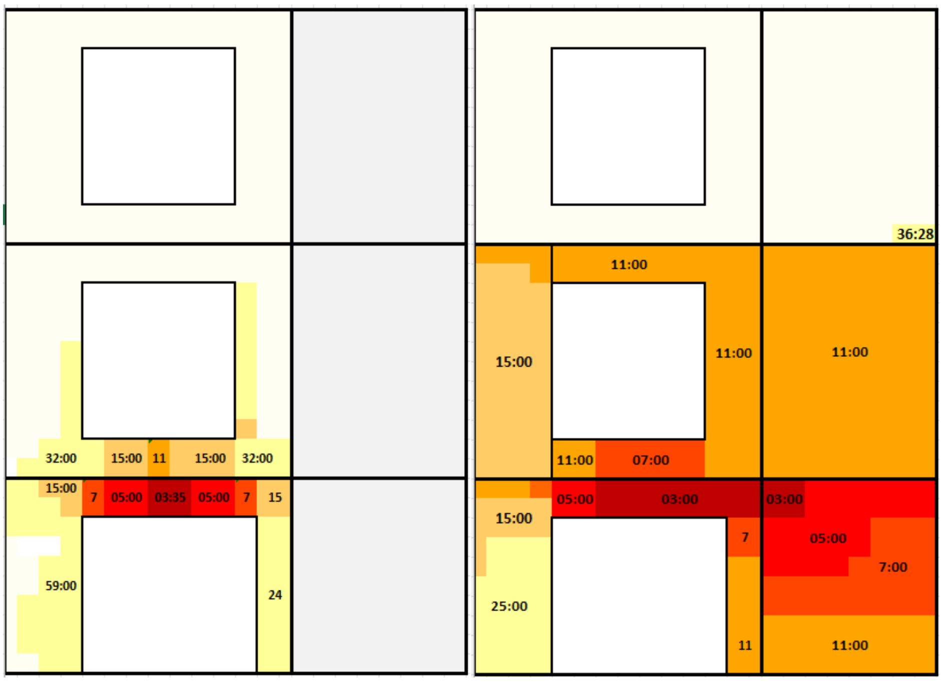


Figure 16: Flame spread in Test 3 (left) and Test 4 (right).

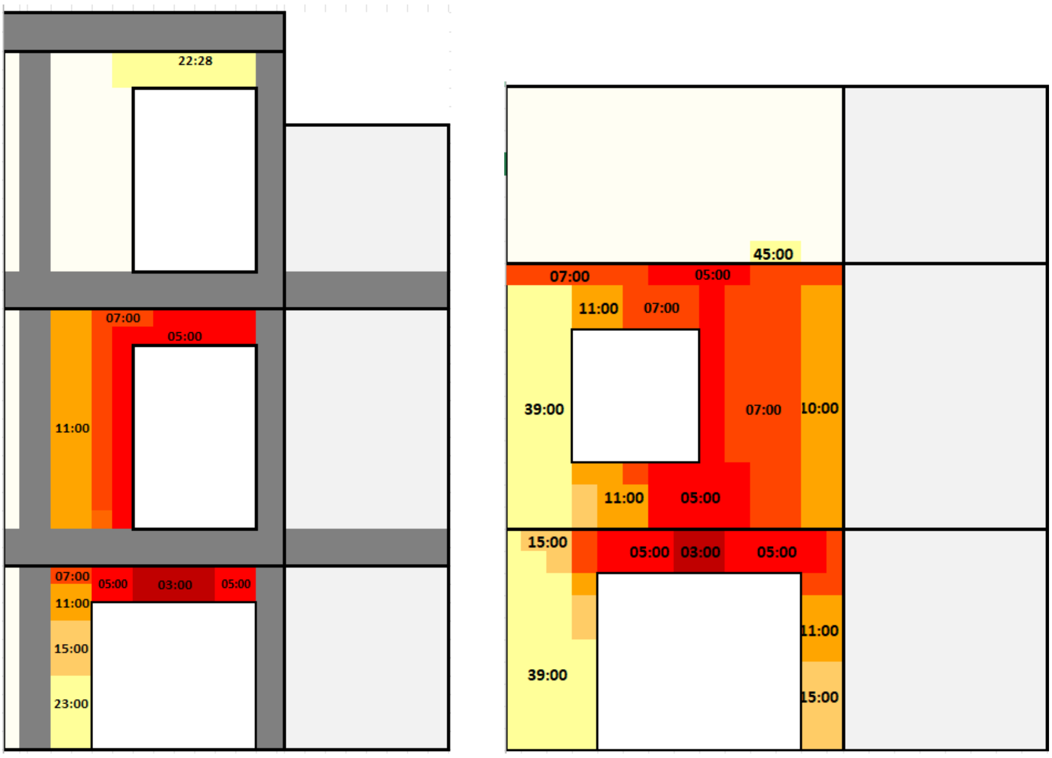


Figure 17: Flame spread in Test 5 (left) and Test 6 (right).

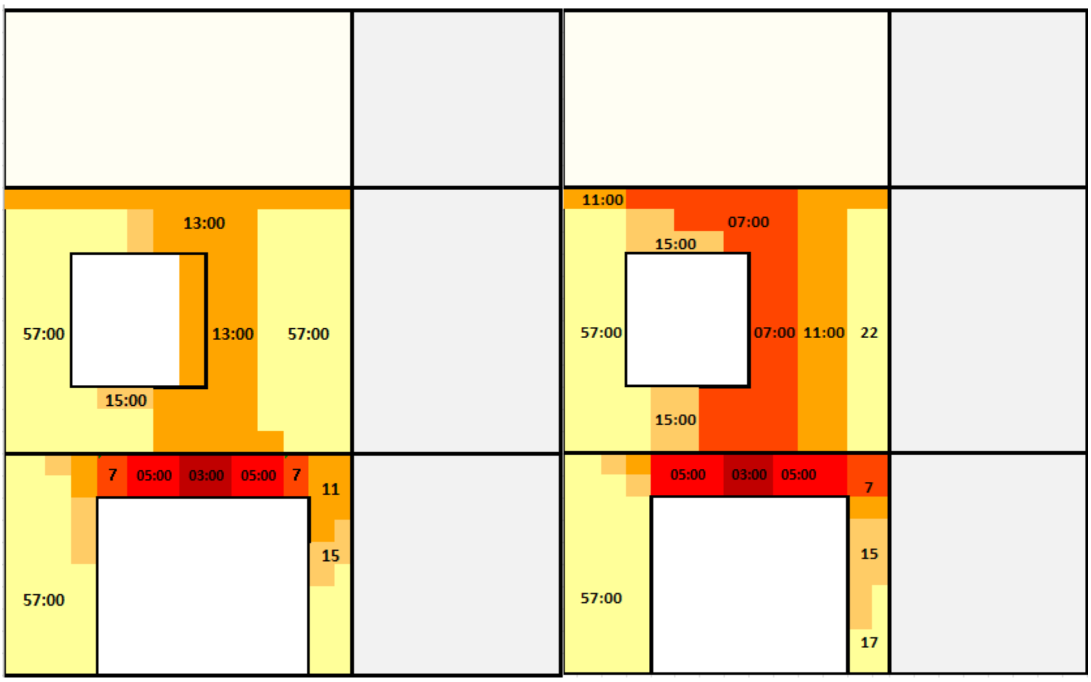


Figure 18: Flame spread in Test 7 (left) and Test 8 (right).

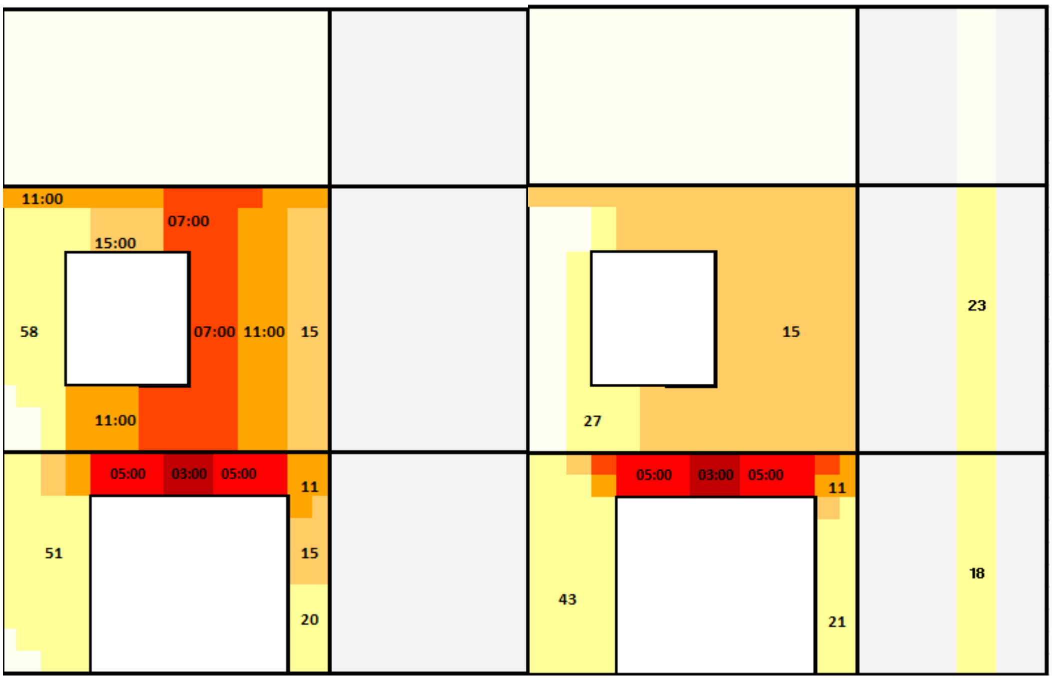


Figure 19: Flame spread in Test 9 (left) and Test 10 (right).

In tests 9 and 10, the plume deflector design was improved based on the observations of the previous tests the improvements were as follows: increasing the height of the "nose dip" to 50 mm, the deflectors were filled with mineral fibre insulation and the vertical distance between the plume deflector and upper cladding was increased to 50 mm (refer to Appendix A). In test 10, shown in Figure 19, the side wing was partly covered with non-combustible board with the width of 1002 mm. Despite this separation distance provided by the non-combustible board, the side wing did ignite at 19 minutes on the ground floor and 23 minutes on the first floor. The upward fire spread to the second floor was not observed in this case.

Based on observations and comparison of the burning areas on the façade across the ten tests, we can identify several key design factors that significantly influence external fire spread. These factors should be carefully considered during façade design and in the fire safety assessment of façades as follows:

1) The upward flame spread is influenced by the presence, depth, and profile of horizontal/vertical deflectors, along with the three distances (L1, L2, and L3) illustrated in Figure 13.
2) The upward fire spread did not extend to the 2nd floor with plume deflectors extending outside the cladding for 305 mm and more. An exception was test 9, where even a 207 mm plume deflector was sufficient to limit the flame spread.
3) A larger area of wood cladding on the first floor (i.e. smaller secondary window opening size) generally contributes to a higher risk of vertical fire propagation.
4) Wood cladding on the side wing increased the risk of upward fire spread compared to non-combustible alternatives. In Test 10, a non-combustible board covering 1 m of the side wing contributed to preventing upward fire spread. However, the impact of board width should be further studied using a wider clad section.
5) The orientation and layout of wood panels on the façade.
6) Openings or gaps in the façade cladding systems, such as ventilation cavities and incomplete seals around window frames, can act as channels for flame entry and fire spread.
7) Failure according to the lateral fire spread was observed in all except one test. The exception was test 2, in which the façade consisted of a vertical metal construction, providing a physical barrier to lateral fire spread. A similar construction was also present in test 5 and it could be argued that the horizontal fire spread in that case was called only due to the positioning of the thermocouples. It must be noted, that the test constructions in BioFacades:UpHigh were designed with the focus on the upward fire spread, not for lateral fire spread.

3.3.3. Fire spread inside the ventilation cavity

It was not possible to visually observe the presence of flames inside the ventilation cavity during the tests. Nevertheless, thermocouples were placed inside the ventilation cavity to measure the temperature rise due to hot gases and flames.

Only constructions in Test 1 and Test 10 used fire stops inside the ventilation cavity. The locations of the cavity fire stops in both tests are presented in Figure 20. In test 1 FB Cavity barrier was installed at around mid-height of the artificial window opening, directly above and below the artificial window opening and at the lower part of the second floor. In Test 10 Tenmat brandshield EI was installed at the height of the top of the artificial window opening, and the location was based on the observations done in Test 9.

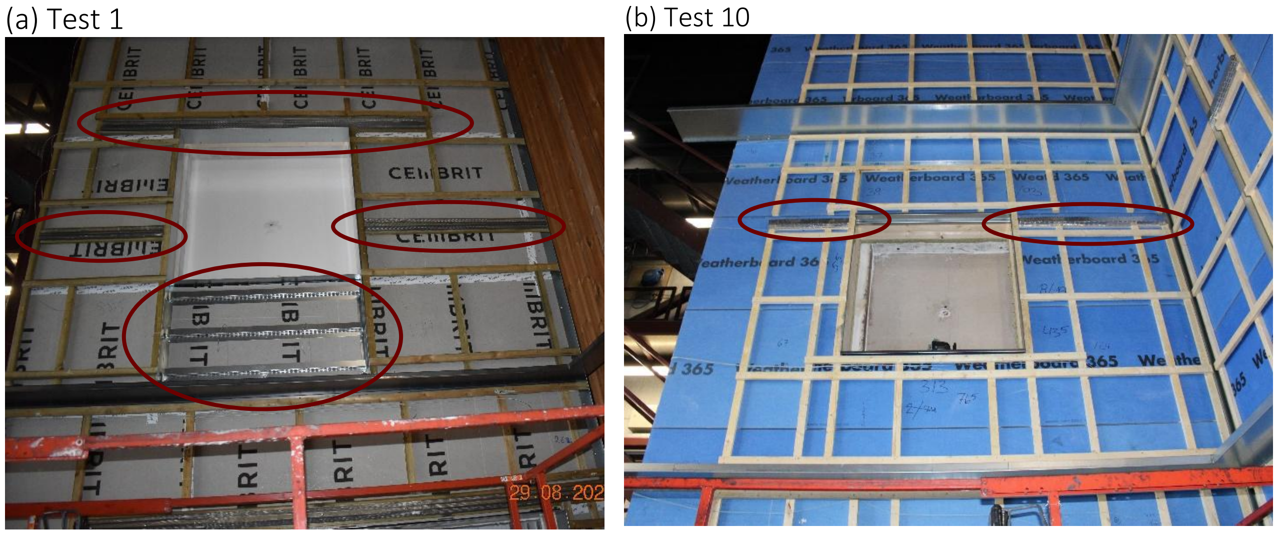


Figure 20: Distribution of the ventilation cavity fire stops in test 1 and test 10

The locations for presenting the temperature measurements inside the ventilation cavity are chosen as follows: below the second plume deflector, above the second plume deflector, and at the top of the façade. All locations are on the main face and are presented in Figure *21*. The temperatures measured inside the cavity are presented in Figure 22, representing the highest temperatures measured from a few thermocouples (two in most cases) in the selected locations on the main face.

In most of the tests, the temperatures below the second plume deflector (on the first story of the façade), reached levels high enough to be considered as burning. The only exception is Test 3, where the temperatures were below 250˚C; however, as can be seen in the individual test report, the ventilation cavity temperatures increased above 700˚C in the lower parts of the first floor. The intensity of external burning in Test 3 was relatively low, and the damaged area was small compared to other tests (see Figure 16). In all other tests, the temperatures below the second plume deflector exceeded 800˚C, indicating the presence of flames at some point during the test. In Test 10, a sharp temperature rise, indicating flame spread, was observed later compared to other tests (at approximately 16 minutes). This may be attributed to the strategic distribution of cavity fire stops, although further evidence is required to support this claim.

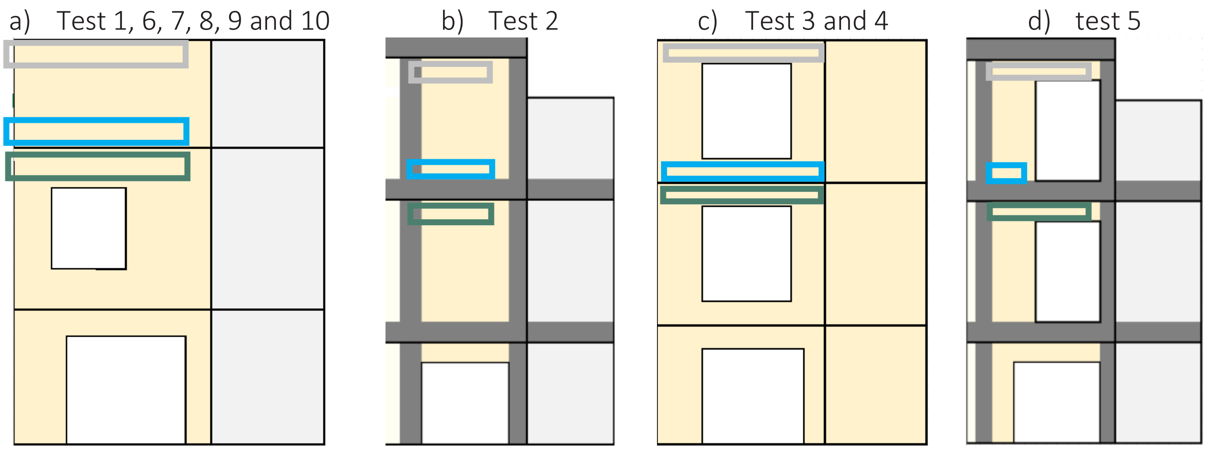


Figure 21: Selected locations for presenting the ventilation cavity temperature measurements. Green – below second plume deflector; blue – above the second plume deflector; grey – top of the facade

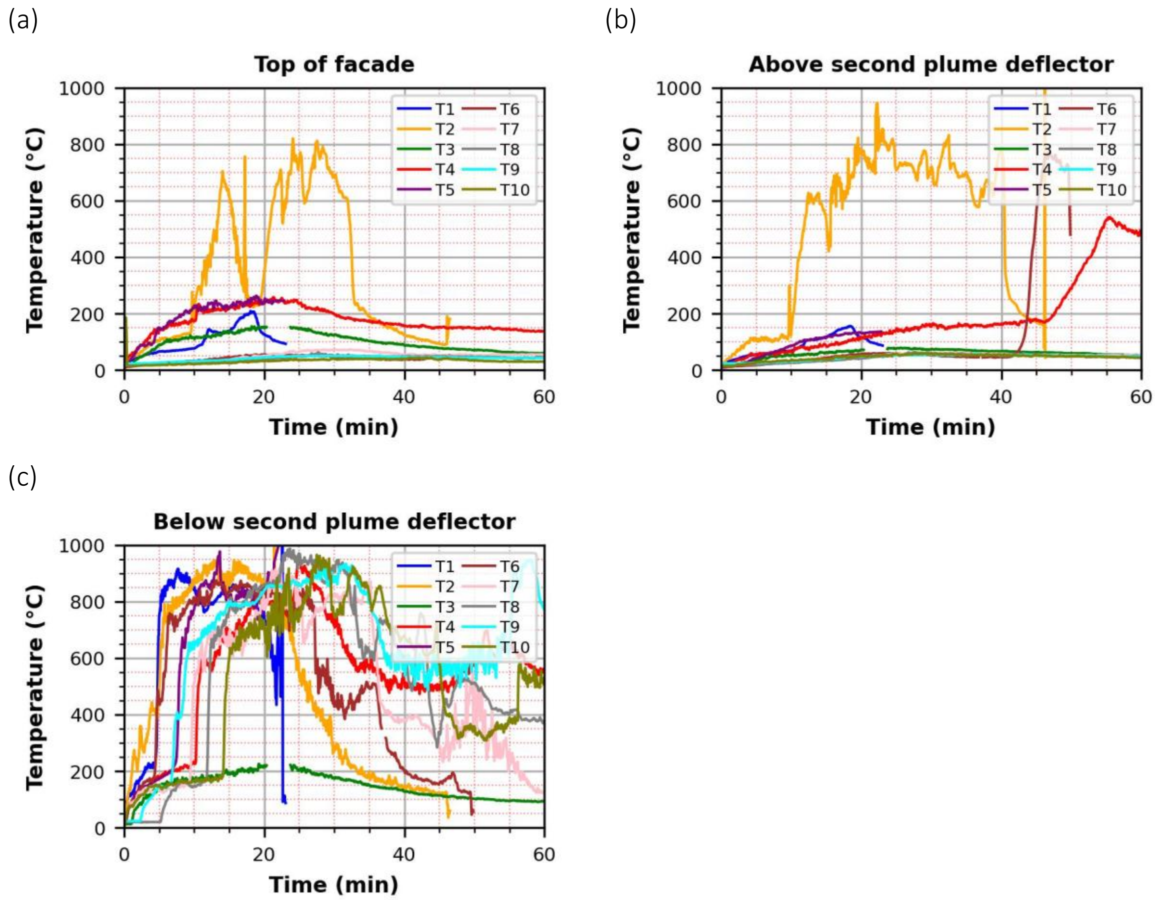


Figure 22: Highest temperatures measured in various locations inside the ventilation cavity (a) top of the façade (second story); (b) top of second plume deflector (second story) (c) below the second plume deflector (fist story)

However, no significant benefit for fire stops is observed in Test 1, indicating that other important factors beyond the mere presence of cavity fire stops are at play. The quantity of the fire stops does not substitute for the quality of the design. Test 1 utilized a large number of fire stops, resulting in negligible effect. In many of the tests, the ventilation cavity temperatures on the first floor rose earlier at the higher positions - below the second plume deflector - compared to lower parts on the same floor. In Test 10 the cavity stops location is elevated to the upper window edge along the entire main wall -so slightly higher compared to Test 1. No cavity barriers were placed below the window opening, as it was deemed to be unnecessary.

There are indications that strategically placed cavity fire stops may prolong the time to flame spread inside the ventilation cavity space. However, it is unclear how significantly this factor contributes to limiting the external fire spread.

On the second floor, the measured temperatures seldom reached those indicating the presence of flames. An exception to this is Test 2, where the cavity temperatures already reached over 600˚C at 10 minutes, indicating the presence of flames. In Tests 4 and 6, the cavity temperatures significantly increased in the second half of the test, when the wood crib had already burned out. This indicates the importance of continuing to observe the test specimen also after the burn-out of the crib. It is worth noting that no vertical fire spread fail criteria was reached in Test 4, despite the temperatures rising to around 550˚C indicating risk of fire spread.

3.4. Fire spread between the compartments

Fire entering compartments in the floors above the compartment of fire origin may occur through the window, due to a burn-through of the façade, or due to fire spread between the façade and horizontal separation. The modes are described in Figure 23 and described below.

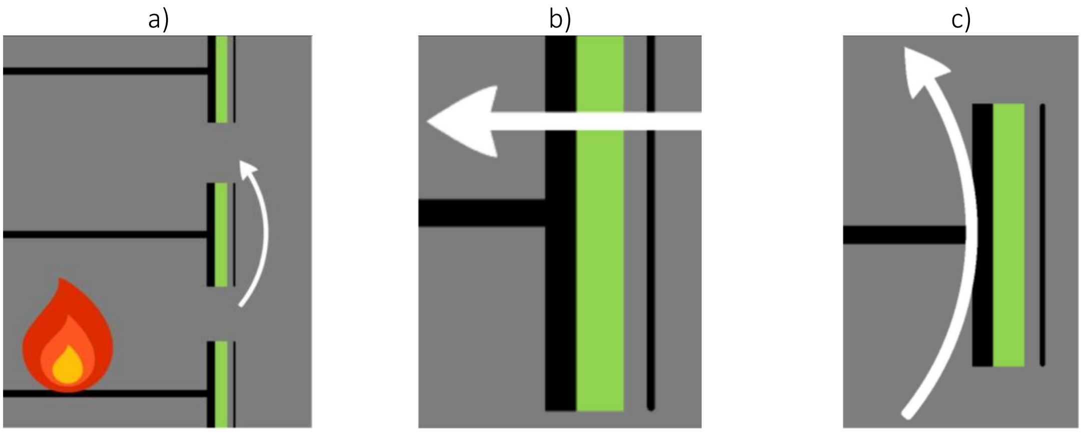


Figure 23: Modes of external fire spread between the compartments a) Through the window opening b) Burn through the façade c) fire spread between the façade and the horizontal separation.

Through the window opening: When an externally venting plume flows up along a façade, it exposes any window in its vicinity to radiative and convective heat. A substantial exposure can occur several meters above the fire of fire origin. Hence, there is a risk of fire spread to the storey above just by radiation through the upper window or by the plume entering the upper room through an open or broken window. The risk of this fire spread mechanism is present regardless of the type of façade system and flammability of the materials used round-robin tests done on inert façade during the development of the European approach (large scale) showed temperatures up to 700 °C at the window opening above the burning chamber [28]. Nevertheless, the risks are higher if a combustible façade contributes to the burning.

Burn through the façade: The risk of burn-through of the façade must be considered, especially for light-weight facades. Burn-through is closely related to the risk of fire spread in solid materials but may also be triggered by the fall-off of components resulting in exposure to material layers with low fire resistance. Penetrations through the facade (e.g. for ventilation or other technical installations) are particularly vulnerable in relation to fire spread through the façade structure.

Fire spread between the façade and the horizontal separation: The risk of fire spread between façade and internal horizontal separations is primarily, but not only, relevant for balloon-framing façade systems, where the exterior wall extends continuously past the floor levels. Unlike platform framing, the floor structure does not act as a natural barrier to fire propagation within the wall cavity or between the façade and interior spaces. This poses the risk of fire spreading between the façade and the horizontal separation.

The Biofacades:Uphigh test series in parts addressed the fire spread through the window and burn-through the façade. Nevertheless, it did not address the issue of fire spread between the façade and the horizontal separation. This would require inclusion of the horizontal separation in the test, as well as having actual external wall construction (rather than aerated concrete).

3.4.1. Fire spread through the window opening

The total heat flux to the surface was measured at the centre of the secondary opening (artificial window opening) using water-cooled heat flux meters. These measurements were conducted only for those tests, where the fictitious window placement on the main façade followed the method described in **[10]**, i.e., the artificial window opening is placed asymmetrically 1.5 m above the upper edge of the combustion chamber.

The total heat fluxes and the temperatures are presented in the Figure 24. The peak total heat fluxes vary between approximately 20 and 30 kW/m^2 (although instantaneous spikes of up to 40 kW/m^2 are observed), with the lowest values measured in Test 7 and 10. In principle, this heat flux is sufficient to ignite most of the combustible materials at the window level. The individual test reports also contain temperature measurements taken from the heat flux sensors, which are used to check the cooling efficiency achieved with water. The peak temperature observed in all tests was 42˚C (Test 10), however, in most tests, the peak temperature was below 35˚C.

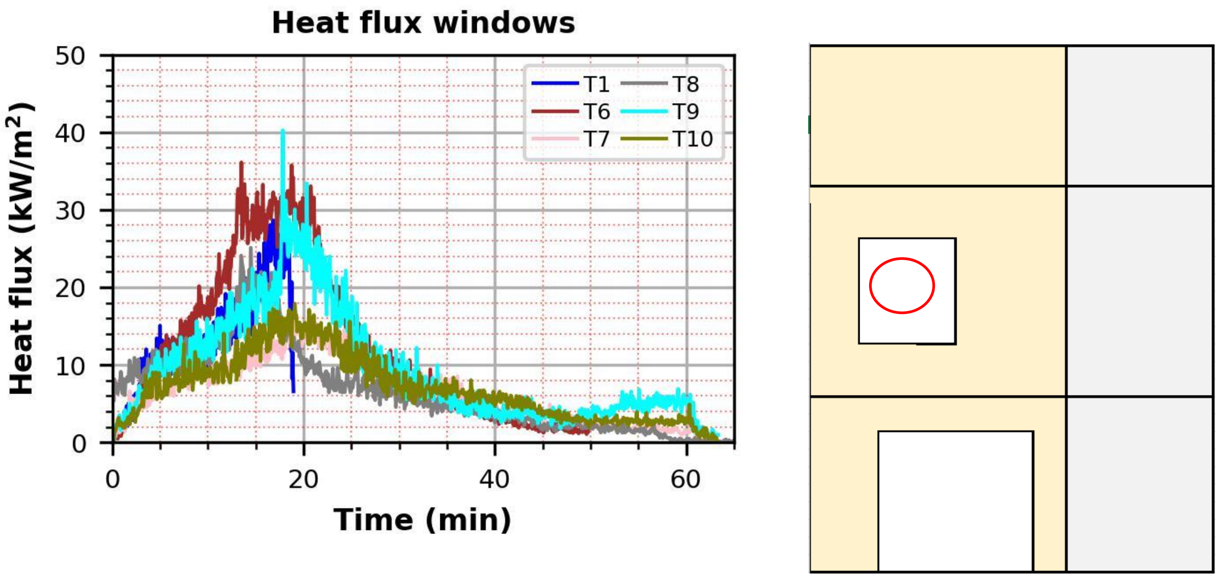


Figure 24: Total heat fluxes measured at the center of the artificial window opening.

Part of the thermal exposure at the centre of the fictitious window opening comes from the combustion chamber and part from the burning wood cladding. Separation of the contributions from the two sources would allow evaluating the contribution of risks associated with the wood-clad façade in comparison with a non-combustible façade. To separate the fire source contribution, test results with non-combustible facades should be explored. Reference **[29]** provides results from three tests with a similar configuration of fuel, but a non-combustible façade. The plate thermometer temperatures at the window centre are shown to reach a maximum of approx. 500˚C at around 25 minutes. Nevertheless, the comparison between the total heat flux in kW/m^2 units (measured in Biofacades:Uphigh) and plate thermometer temperatures in ˚C units (provided in [29]) require significant assumptions, specifically regarding gas-phase temperatures in the proximity of the plate thermometer. In SP Fire 105 large scale test the heat flux at the centre of fictitious window on the floor directly above the combustion chamber is approximately 35 kW/m^2 for non-combustible façade and approximately 65 – 70 kW/m^2 for ventilated plywood façade [15].

In most real building designs, it is expected that windows will be placed directly above one another. The total heat fluxes would then be expected to be higher compared to asymmetric placement, as in these presented tests.

Small and intermediate scale tests has indicated that the area of the fallen out glazing of the outermost pane of modern 3 pane windows, when exposed to high heat conditions (estimated to be up to 55 kW/m^2), is very small [30].

The heat flux on at the centre of window can reach up to 30 kW/m^2, indicating a risk of fire spread through the window. It is unclear what would be the heat flux for a non-combustible façade in the same setup.

3.4.2. Burn through the façade

In this report, the burn through the façade is primarily examined in relation to the use of bio-based insulation in wood-framed wall cassettes. Wood fibre insulation was used in Test 3 and Test 4, and paper-in-blow insulation was used in Test 6, Test 7, and Test 8. The insulation was covered from the outside with the windboards (detailed information is available in the individual test reports).

Figure 25 presents the temperature distribution inside the insulation layer of the Test 4. This test was chosen because it contains the most temperature measurements in the insulation layer. The curves illustrate measurements taken at various positions and depths within the façade assembly, including 50 mm from the façade, the centre of the ventilation layer, and different points within the insulation. Two layers of wood fiber insulation boards with a size of 1220 × 565 × 120 mm and a nominal density of 50 kg/m^3 were placed in the prefabricated cassettes. Two layers of wood fibre-based windbreaker boards 12 mm with a nominal density of 235 kg/m^3 were mounted on the construction wood C24 of all three cassettes. An aluminum membrane layer with nominal thickness of 0.43 mm was mounted on top of the windbreaker.

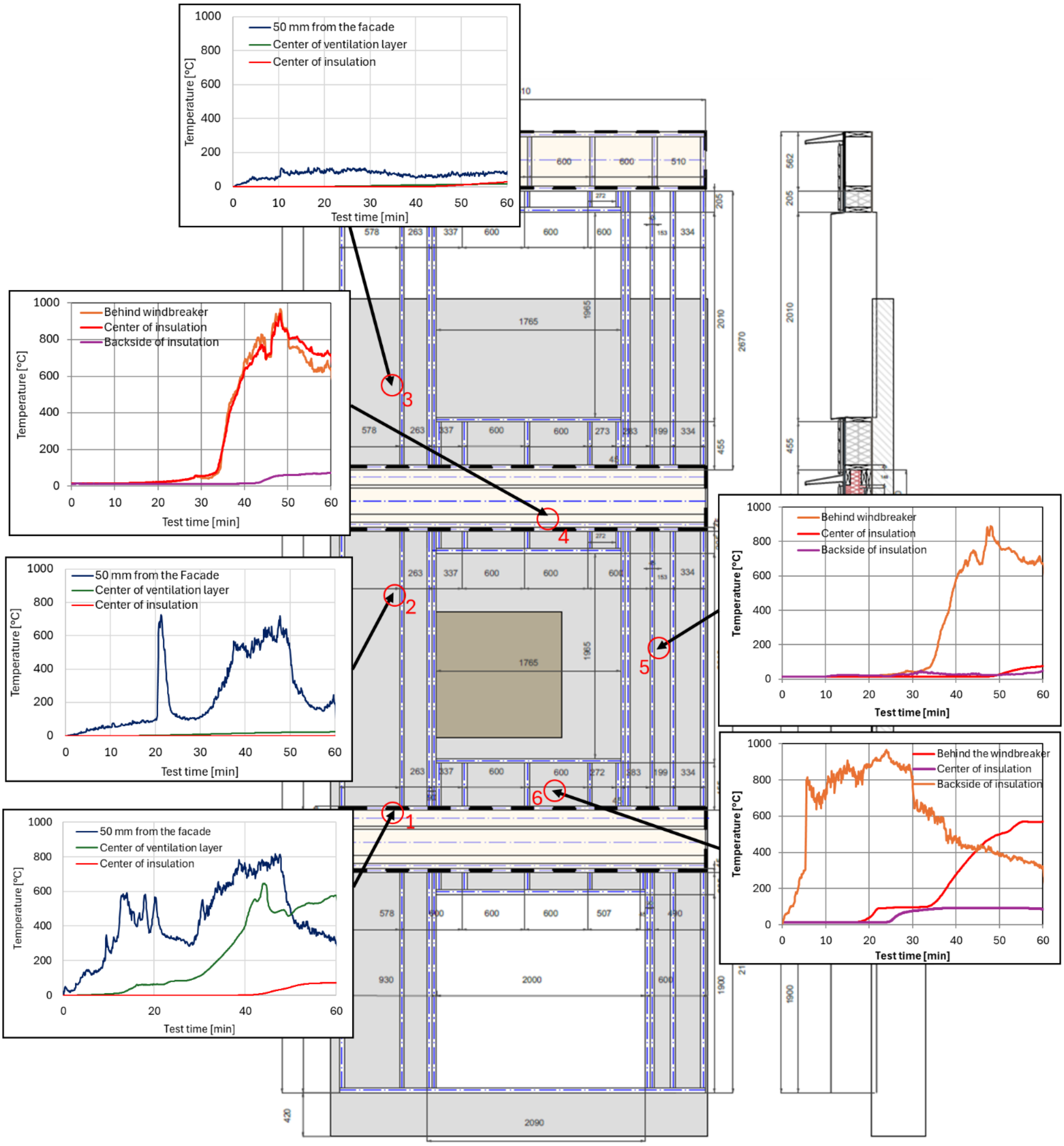


Figure 25: Temperatures inside the construction, Test 4

Temperatures recorded between the window and burning chambers (Pos. 1) indicate a rapid and intense fire exposure, with values reaching up to 800°C behind the windbreaker within the first five minutes. In contrast, the temperature at the center of the insulation stabilizes at approximately 100°C after 20 minutes, primarily due to water evaporation. Five minutes later, the backside of the insulation begins heating up, maintaining a plateau of 100°C until the end of the test.

The temperature trends suggest that convective water vapor flow facilitates rapid heat penetration. However, the latent heat of water evaporation acts as a temporary heat sink, delaying further temperature increase. Around the 35-minute mark, as the remaining water in the insulation evaporates completely, the temperature rises significantly, reaching approximately 600°C. The continued temperature increase suggests a smouldering wave propagating from the front to the back of the insulation. This was further confirmed upon removal of the insulation after the test.

The heating behaviour of the construction at the top left of the first flame detector (Pos. 2) follows a similar pattern, though with lower temperature exposure due to its greater distance from the burning chamber. The temperature reaches approximately 800°C only after 50 minutes. However, smouldering is observed in the centre of the insulation after approximately 40 minutes. The backside of the insulation experiences delayed heating, eventually reaching a maximum temperature of 100°C. Overall, the combustible insulation exhibits smouldering velocities of approximately 5-10 cm/h. Despite this, the temperatures at the backside of the insulation remain relatively low, effectively preventing burn-through for the first 60 minutes of the test. Generally, the temperature exposure along the sides of the burn chamber axis is significantly lower than at the centre. This results in a delay or even prevention of smouldering initiation in the combustible insulation.

The results demonstrate that combustible insulation can effectively prevent early burn-through of the façade. Throughout the test, all temperatures behind the insulation remained within the criteria outlined in EN 13501-2, with a maximum temperature rise of 180 K. Different windbreakers were used between the insulation and the ventilation gap. Since temperature measurements behind the windbreaker were not consistently collected across all tests, and the heat exposure levels varied significantly, it is difficult to assess the windbreaker's contribution to fire performance accurately. Generally, a non-combustible windbreaker acts as an additional protective layer, shielding the cassette structure from direct thermal attack. However, in the area approximately 1 meter around the combustion chamber, the fire intensity was extremely high, resulting in burn-through in all tests—regardless of the windbreaker material. Consequently, smouldering was observed in all tests that included bio-based insulation materials.

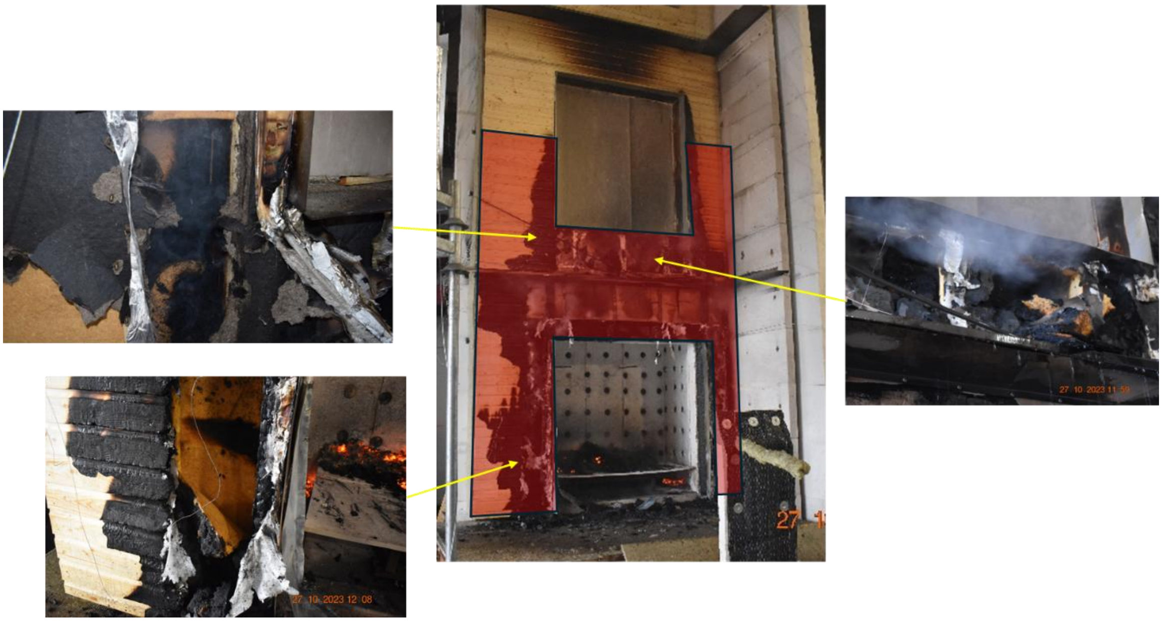


Figure 26: Areas affected by smoldering insulation (Test 3)

Since the test was stopped after 60 minutes, assessing the smouldering behaviour in the BioFacades: UpHigh testing programme was not possible. In general, the smouldering behaviour presents a potential risk of delayed compartment breach, which could occur several hours after the test if the smouldering is not detected and extinguished. This can be confirmed by examining several areas that were affected by smouldering insulation after disassembling the construction. For this reason, it is crucial to enable effective firefighting measures. Thorough assessment of smouldering behaviour requires an extended observation period—potentially up to 15 hours. In contrast, the BioFacade:UpHigh tests were typically concluded after 60 minutes, limiting the ability to evaluate long-duration smouldering phenomena fully.

Bio-based insulation materials are prone to smouldering, a slow, flameless combustion that can pose additional fire safety risks.

Additionally, all tests were evaluated in terms of fire spread within the materials. According to the European approach, the failure criterion is reached if any external or internal thermocouple positioned on columns 1 and 2 (see Figure 10) exceeds a temperature rise above its initial temperature of 700 K on average over a period of 30 seconds during the assessment time. The maximum temperatures measured inside the middle of the insulation layer are listed in Table 5. The failure criterion was reached in Tests 3 and 9. It is worth noting that the number of internal thermocouples located at mid-depth of the insulation varied significantly between the tests and thus did not follow the requirements of the European test method. The results in Figure 25 show clearly that high temperatures in the centre of the insulation can also be expected elsewhere.

Table 5: Temperatures measured at the middle of the insulation layer

Test	ΔT max (˚C)	Position	Time (min)	Number of TCs placed at the middle of the insulation layer
1	41	I.3.7	20	4
2	84	I.3.6	22	2
3	819	I.3.8	60	3
4	144	I.3.8	60	8
5	72	I.3.3	22	3
6	81	I.3.4	30	5
7	72	I.3.5	50	5
8	70	I.3.4	48	5
9	956	I.3.4	60	5
10	302	I.3.7	50	9

3.5. Fire spread between the buildings

3.5.1. Heat flux in front of the facade

According to Danish building regulations BR 18, guide to Chapter 5 – Fire, Chapter 8: Demonstration (Eftervisning in Danish), the incoming radiation to adjacent buildings should not exceed 15 kW/m^2. The source of heat is radiation from flames and hot gases, considering a potential risk of a fully developed fire. Moreover, elevated heat flux levels in front of the façade can significantly hinder firefighting operations. Firefighters' tolerance to radiant heat with personal protective equipment is generally considered to range between 5–10 kW/m^2 [31].

Three stations for measuring incident radiation heat flux were used in the Biofacades:UpHigh tests. The positions are given in Figure 27 (denoted as HF 1, HF 2, and HF 3)[1]. Each heat flux measurement station included a plate thermometer (as used in fire resistance testing) and a gas phase thermocouple. In addition, HF1 also included a water-cooled heat flux sensor measuring total heat flux (combination of radiation and convection). The positions are denoted as follows (for the purpose of clarity in this report, the position naming is not consistent with the naming used in the individual test reports):

HF 1: 3 m away from the façade (except test 1, where the distance was 2 m), facing the centre of the combustion chamber opening (which results in approximately 1.4 m above the floor level at the fire testing facilities). This position is equipped with a plate thermometer, gas phase thermocouple and water-cooled heat flux sensor.

HF 2: 5 m away from the façade, at a height of 2.5 m from the floor. This position is equipped with a plate thermometer and gas phase thermocouple.

HF 3: 5 m away from the façade, at a height of 4.5m from the floor. This position is equipped with a plate thermometer and gas phase thermocouple.

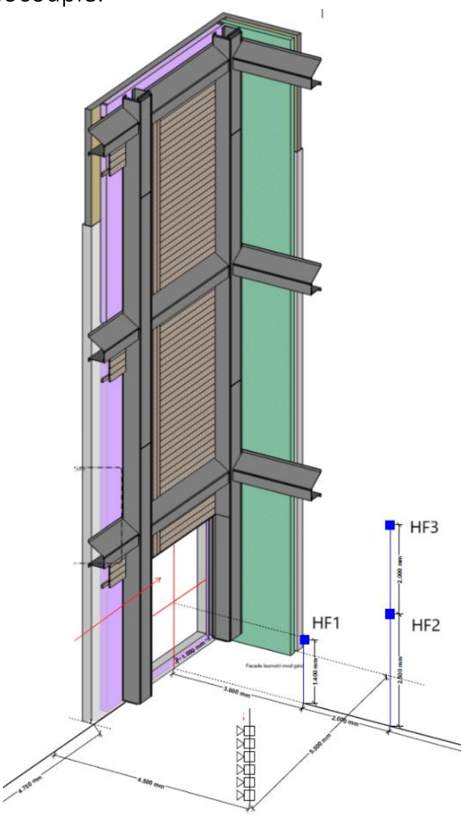


Figure 27: Heat flux station positions

The methodology outlined in reference **[32]** was used to calculate the incident radiation based on the temperature measurements with plate thermometers. The validity of the calculation was ensured by comparison with the heat flux sensor used at the station “HF1”. The incident radiation comes from both the main fuel source (i.e., wood crib inside the combustion chamber) and the burning of the façade cladding.

[1] For the clarity purposes of this report, the position labeling here is changed and does not match labeling in test reports.

The heat fluxes in position HF 1 are presented in Figure 28 along with the temperature measured inside the combustion chamber. The total heat flux (combined radiation and convection) at a distance of 3 m in front of the façade main wall reached its peak of around 45 kW/m^2 (construction 4). Other tests showed significantly lower heat flux levels, between 25 and 35 kW/m^2. In test 1, the heat flux was measured 2 m in front of the façade, showing relatively high peak values of about 60 kW/m^2. Nevertheless, it did not match with the calculations based on plate thermometers and likely can be attributed to technical error during the measurement process. This measurement position HF1 is likely to be little influenced by the burning of the façade itself, but more likely to be directly influenced by the wood crib. As shown by the Figure 28 (b), the chamber temperatures were also one of the highest in Test 4 (along with Test 7 and 9), indicating the influence of the wood crib to the measurements.

(a) (b)

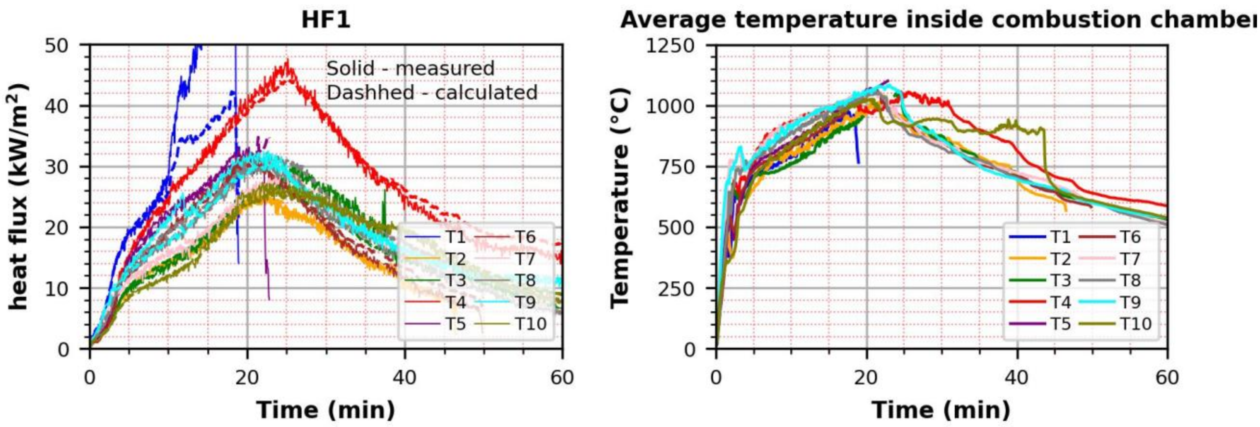


Figure 28: (a) Heat fluxes on the station "HF1". Solid lines show values measured by heat flux sensor and dashed lines show calculated values from plate thermometer measurements (b) temperatures measured inside the combustion chamber

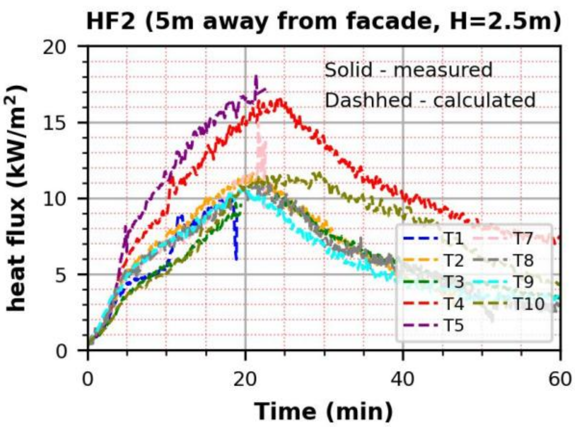


Figure 29: Heat fluxes on the station "HF2". Test 6 excluded because of faulty measurement.

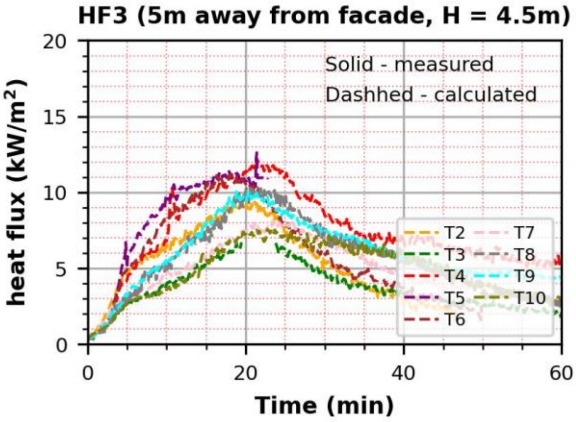


Figure 30: Heat fluxes on the station "HF3". Test 1 excluded because of faulty measurement.

The calculated incident radiation at the distance of 5 m in front of the façade main wall reached its peak of 17 kW/m^2 (Test 4 and Test 5) for the height of 2.5 m above the floor and 10 – 12.5 kW/m^2 (Test 4, Test 5 and Test 6) for the height of 4.5 m above the floor. This data is presented in Figure 29 and Figure 30.

Test 4 yielded one of the highest heat fluxes among all stations. It must be noted that the combustion chamber temperatures are also the highest in Test 4 (along with Test 7), potentially indicating a more severe fuel load during the test. The other contributing factor may be the presence of a cladded side-wing in Test 4 and the fact that the density of the non-thermally-modified spruce, used in Test 4 and 3, was slightly higher compared to that of the pine used in other tests. Nevertheless, Tests 4 and Test 5 can be considered as outliers of the overall trend.

In stations HF2 and HF3, tests without cladded return wing showing the highest heat fluxes are test 5 and test 6. It is unclear, which factors has influenced the fact that these constructions exhibited the highest heat fluxes.

A 7-test program had previously been done by RISE as part of the development of the European approach for assessing the fire performance of facades [29]. The total heat flux was measured 1.3 m in front of the façade main wall (lightweight concrete) at the mid-height of the combustion chamber. The peak total heat flux in those tests was measured at about 40 – 60 kW/m^2. Although significant assumptions are required to compare this result with the measurements from the BioFacades: UpHigh project (due to the different distances between the heat flux sensors and the combustion chamber opening), it can be roughly considered comparable.

The performed tests indicated that the external heat flux 5 m away from the facades can exceed 15 kW/m^2. Estimated significant contribution to this heat flux is related to the wood crib used as the fuel source in the test.

The performed tests indicated that the external heat flux 5 m away from the facades can exceed 15 kW/m^2. Larger safety distances can significantly lower the risk of fire spread to neighboring buildings and improve firefighting measures.

3.5.2. Formation of burning parts

According to the European approach to assessing the fire performance of facades, the failure of the burning parts criterion occurs when a falling part burns for 30 s or longer after hitting the ground. It is suggested by the developers of the method to leave this pass/fail criterion as a stand-alone criterion and allow for each regulator to decide if this could be included in regulations [10].

Out of 10 tests performed in Biofacades: UpHigh project, the failure time ranged from 4 minutes to 25 minutes, with an average of 16.3 minutes and a median of 18.5 minutes. Video snapshots from selected tests are given in Figure 31.

Figure 31: Formation of burning parts at the based of the façade rig

A peculiar characteristic of fire tests with wood cladding facades is that the wood crib itself produces burning parts. In some cases it is difficult to similar to distinguish if the burning part is produced by the wood crib or the façade. This creates problems with the identification of a failure.

> The results indicate that that the formation of burning parts is a problem for non-FR-treated wood clad facades. The risks associated with the burning parts should be taken into consideration while developing fire safety strategy.

3.6. Formation of falling construction parts

According to the European approach to assessing the fire performance of facades, falling parts are divided into level 1 (any falling part exceeding 1 kg in mass) and level 2 (any falling part exceeding 5 kg in mass). The measurements according to the method should be done with a weighing load cell platform with an accuracy of ± 50 g. Visual equipment shall be used to assess the size and test time.

The weighing load cell platform was not used in the Biofacades:UpHigh tests and the failure according to the falling parts level 1 and level 2 was not identified during the test. In all tests, formation of falling burned parts of the wood cladding were observed. It is difficult to evaluate if the individual parts had been larger than 1 kg in mass, however the total mass of the fallen cladding observed at the end of the tests was considerable. The reader is welcome to observe the test videos to support the decision-making process.

Examples with photos and video snapshots showing parts in selected tests are provided in Figure 32.

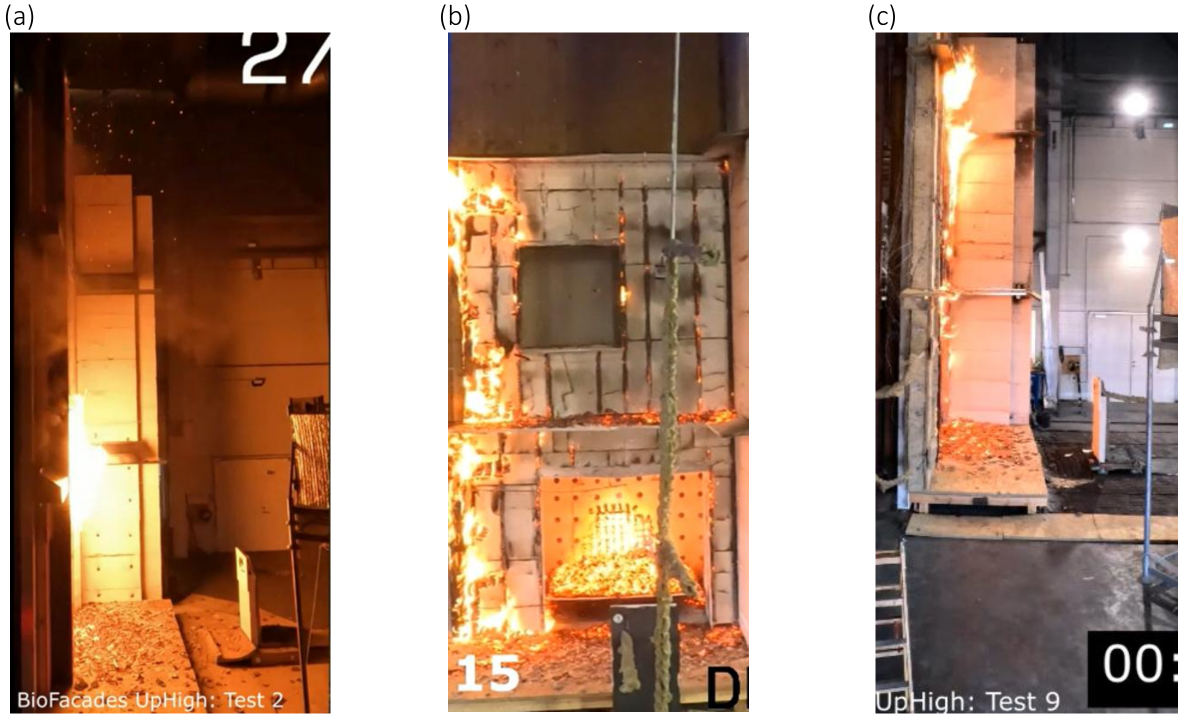


Figure 32: Falling parts near the end of selected tests (subjectively evaluate worst cases from all 10 tests). (a) test 2 (b) test 8 (c) test 9

4. FUTHER CONSIDERATIONS

4.1. Effectiveness and durability of fire-retardant treatment

Fire retardants (FR) suppress fire spread in timber products through different mechanisms. They can be impregnated into the wood to slow flame spread and promote char formation or remain on the surface, acting as a protective barrier. FRs used for timber cladding are categorized into two types: additive and reactive. Additive fire retardants are applied via dipping, spraying, vacuum, or brushing but do not chemically bond with the wood, making them more prone to leaching over time. Reactive fire retardants, on the other hand, chemically interact with the wood, making them more durable but also more expensive. Additionally, FRs are classified as organic or inorganic. Another fire protection method involves fire-proof coatings, which are either intumescent or non-intumescent [33].

Historically, aluminium, boron, halogens (such as bromine), and more recently, phosphorus and nitrogen have been identified as effective fire retardants for wood. Today, most conventional fire-retardants no longer contain halogens, although boron remains in use. Boric acid has low resistance to leaching but is raising health and environmental concerns—similar to formaldehyde. From an environmental perspective, nitrogen and phosphorus have emerged as promising and highly effective alternatives. Overall, all these treatments increase the hygroscopicity of wood, and leaching of the flame-retardant chemicals remains an issue for ensuring long-term fire protection in outdoor applications [34].

Two key mechanisms impact the durability of FR-treated wood products. The first involves the potential for high moisture content, which can lead to the migration of fire-retardant chemicals within the wood and the formation of salt crystallization on its surface. The second concern is the reduction in fire performance due to the loss of fire-retardant (FR) chemicals through leaching [16].

The durability of reaction to fire performance is evaluated according to EN 16755:2017. The producer can select the weathering method to be performed according to the accelerated procedure (with a choice between three methods) or natural weathering (as specified in EN 927-3). The natural weathering should last for at least one year, while the accelerated weathering allows for a reduction in time to 6 weeks. The producer can also select if the test procedure follows intermediate-scale SBI test or small-scale cone calorimeter method (exposed to 50 kW/m^2). The preferred combination, deemed to be the most representative, is natural weathering and SBI test for sample comparison. Although this may be more time and resource-demanding compared to given alternatives. Reference [35] suggest that the accelerated weathering methods are roughly comparable to the 1-year field weathering. However, the fire technical properties of fire retarded wood cladding keep reducing over a longer period in natural weathering, resulting in significantly reduced fire technical properties in 10 years.

A study [36] on the fire performance of impregnated wood subjected to natural aging showed that even limited outdoor exposure of only a few weeks resulted in a measurable decline in fire performance when tested at the material scale in Cone Calorimeter. Additionally, significant inconsistencies were found in the base material's fire performance, even before exposure, likely due to variability in the fire-retardant treatment process.

According to the Danish Building Regulations, BR18, Chapter 5, Fire, the fire safety of the building must be maintained throughout its service life. The lack of effective methods further compounds the problem of assessing the fire performance of materials installed, meaning potential reductions in reaction to fire properties could go unnoticed.

Fire retardants can enhance the fire behavior of wood-clad facades. However, their long-term effectiveness is challenged by chemical leaching.

4.2. Fire service operations

Although passive fire protection measures can slow the spread of fire, enabling effective firefighting operations is crucial for wooden facades. Emergency services must have adequate opportunities to rescue people and animals, as well as assist in evacuation. It must also be ensured that the necessary extinguishing work can be carried out and that significant fire spread between fire units is limited. The emergency services' response options must be considered early in the design process, see Figure 33. In cases where deviations from prescriptive regulations or traditional response methods are not suitable, agreement with the local authorities must be ensured.

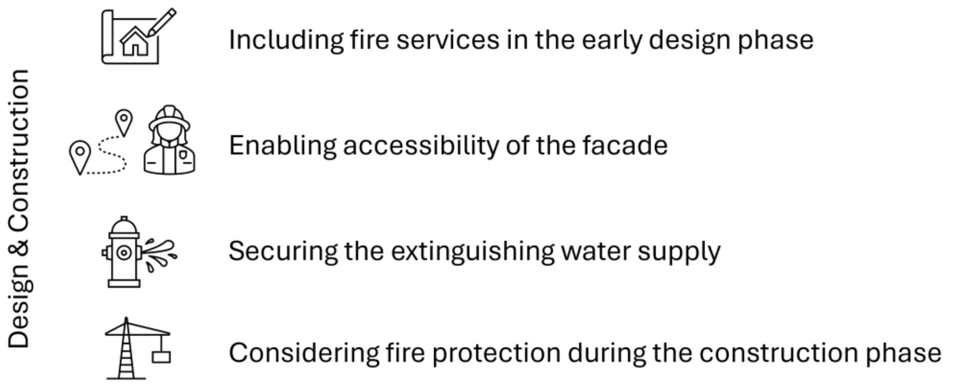


Figure 33: Measurements in the design and construction phase to enhance fire service operations on wood-clad facades

The standard procedure for firefighting operations on wood facades is visualized in Figure 34. One essential condition for effective fire service operations is accessibility. Therefore, buildings and the surrounding areas must be designed to accommodate the deployment of emergency response vehicles, equipment, and personnel. This can be achieved by access roads and fire rescue areas to reach the building effectively. Aerial ladders are effective for optimally reaching the façade in the event of a fire. However, providing fire roads to all sides of the building is often impossible, so accessibility is limited to operations from the ground.

Research findings have shown that the early use of handheld nozzles can effectively slow down fire spread, ideally combined with firefighting operations from the interior. It could be shown that a vertical spray distance of up to 25 m at a distance of 9.6 m ($\alpha \approx 69°$) can be reached with a B-size nozzle, as specified in EN 15182-2, at a pressure of approximately 10 bar. Consequently, a corridor and a sufficient water supply must be ensured. Nevertheless, wind influences can significantly affect the water throw height. Even if an initial ground-based attack can substantially limit the spread of the fire, dismantling the wood cladding may remain challenging, as accessibility is limited to openings and balconies [37]. It is therefore advisable to also carry out effective firefighting measures from inside the building in the event of a fire in the façade area.

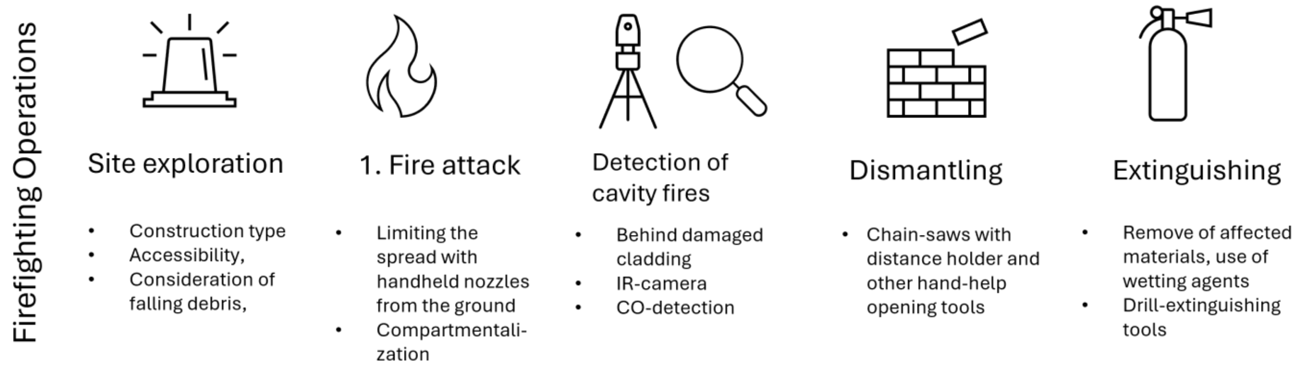


Figure 34: Standard procedure for firefighting operations on wood-clad facades

The use of combustible insulation, such as a windbreaker or cavity insulation in exterior walls, can facilitate smouldering fires, posing an additional challenge to firefighting efforts. Accessibility, detection, and opening the construction are key factors in controlling and extinguishing cavity fires. The results of the BioFacades: UpHigh project showed that smouldering of combustible insulation occurred mainly in the initial phase in areas where the cladding exhibited significant charring (see Figure 35). Additionally, detection tools such as infrared (IR) cameras and carbon monoxide monitors can be utilized to detect cavity fires more effectively.

Figure 35: Charred areas after test (left) and dismantled areas, where smoldering was observed (right) in Test 3

After detecting, opening the affected construction becomes necessary to fight smouldering fires, primarily when combustible insulation materials are used. Standard hand tools (fireman's axe, nailing tool, TNT tool, Halligan tool) can be used. However, they are time-consuming and require a high level of staff deployment. The results from the research project HoBraTec demonstrated that electrical or motorized chainsaws have been opted for the quick dismantling of cladding materials [38]. A significant advantage of these devices is that they are typically part of the standard equipment; therefore, they are widely available, and fire services are accustomed to them. An additional distance holder is recommended to limit the cutting depth. Additionally, special firefighting tools such as water mist lances or drill-extinguishing equipment can support the firefighting of cavity fires [39]. When opening the structure, it should be borne in mind that a sudden supply of oxygen can lead the insulation to a transition from smouldering to a flaming fire [40]. The insulation should be removed extensively around the visible smouldering areas. Extinguishing water that is dispensed into the construction often only reaches the surface of the insulation material. Additionally, the discharge of extinguishing water into the construction can cause considerable damage. After removal, the insulation should be stored in a fire-safe place in case of a possible reignition [41].

Emergency services must have adequate opportunities for firefighting operations on wood-clad facades. Additional challenges such as smouldering of bio-based insulation materials must be considered.

5. CONCLUDING REMARKS AND FUTURE OUTLOOK

5.1. Fire technical conclusions

This report has examined the fire behavior of wood-clad facades without fire-retardant treatment through a review of literature, historical incidents, and test results from the BioFacades: UpHigh project. The findings highlight several critical factors influencing facade fire performance, including material properties, geometrical configuration, the presence of ventilation cavities, and design details such as deflectors and fire stops.

Key takeaways include:

- General: The BioFacades: UpHigh project included large scale ad hoc / demonstration tests with significant deviations from the originally proposed European approach method. The test results provided here cannot be directly compared with other tests, following more closely to the originally proposed method.
- Flammability: Wood is inherently combustible and prone to both flaming and smouldering combustion. Thermally modified wood exhibited similar fire behavior in small scale tests and slightly worse behavior in intermediate scale SBI, compared to non-thermally modified samples. Aged thermally treated wood shows lower critical heat flux for ignition compared both to new thermally treated and non-thermally treated wood. The number of small and intermediate scale tests in different studies is limited, however considering the inhomogeneity of wood a higher number of test replicates is recommended to draw stronger conclusions.
- Vertical fire spread: In all tests, the first-floor wood cladding above the combustion chamber ignited, and in many cases it was almost completely burned by the end of the test. The tested plume deflectors were not capable of protecting the 1st floor cladding against the flames from the combustion chamber.
- Vertical fire spread: Strategically placed horizontal deflectors significantly reduced risks of vertical flame spread to the 2nd floor above the combustion chamber. Geometrical parameters such as the depth of deflectors and distances to facade surfaces (L1, L2, L3) were shown to be crucial in thermal exposure management. Plume deflectors extending outside the cladding of 305 mm and more showed a good potential to limit vertical fire spread. In one test a 207 mm plume deflector was sufficient.
- Vertical fire spread: Internal corner configuration presents an increased risks of upward fire spread. However, in most of BioFacades: UpHigh tests only a single cladded wall was used (opposed to having also cladded the return wing). There is a limited understanding of how to design a plume deflector for an internal corner configuration.
- Vertical fire spread: A strategy of introducing a 1 m horizontal separation distance (ensured by a non-combustible board) on the side wing was investigated in test 10. The test did not result in vertical fire spread, despite the ignition of 0.426 m cladding strip on the side wing on the first floor. Although the strategy seems promising, further testing with a wider cladding strip on the side wing is recommended.
- Lateral fire spread: The Biofacades: UpHigh tests did not intent to demonstrate approaches for limiting the lateral fire spread.
- Ventilation cavities: While beneficial for moisture control and durability, façade ventilation cavities create a path for fire spread. The presence and type of cavity fire stops were shown to influence the timing of internal fire spread, though their effectiveness is context dependent. At the moment, there is no evidence on how the flame spread through the ventilation cavity of a single individual floor can be effectively stopped by cavity fire stops. However, the proposed design the plume deflectors are

provide a constant physical obstacle also in the ventilation cavity, hence limiting the cavity fire spread between the floors.

- Burning and falling parts: The formation of burning and falling parts was observed in all tests, presenting risks of secondary fires to building occupants and firefighters.
- Window interaction and compartmentation breach: In the present test conditions for project BioFacades:UpHigh the peak heat fluxes to the window openings reached levels capable of igniting combustible materials. Therefore, it demonstrates the risk for potential fire spread through window. It is unclear how significant contribution comes from the wood cladding and how much of the contribution comes from the fuel (wood crib) used in the test method.
- Bio-based insulation materials used behind the cladding were found to be prone to smouldering combustion. While they did not lead to immediate burn-through within the 60-minute test duration, smouldering persisted and could pose a delayed risk of compartment breach. The onset of smouldering was typically observed in areas exposed to the highest external thermal load. This underlines the importance of considering not just flaming fire resistance but also smouldering behavior in material selection and fire safety design.
- Fire retardant treatment: While fire-retardant treatments can significantly improve fire performance, their long-term effectiveness may be influenced by environmental factors such as moisture and UV exposure. Currently standards exist for demonstrating durability through artificial or natural weathering and consecutive testing at small or intermediate scale. Ensuring durability under outdoor conditions remains an important consideration in ongoing product development.
- Operational concerns: Fire service operations face several challenges when dealing with wooden facades, including limited access, risk of smouldering insulation, and the difficulty of dismantling facade layers during intervention.

Overall, the report confirms that non fire-retardant treated wood-clad facades can present significant fire risks if not carefully designed and detailed. However, with appropriate mitigation strategies, such as physical barriers, non-combustible cavity materials, fire stops, and robust fire service planning, wood can still be a viable material in sustainable architecture.

5.2. Design phase conclusions

The results from the BioFacades: UpHigh fire tests provide practical guidance for documenting and achieving an acceptable level of fire safety when using timber cladding. These findings support a performance-based approach, where compliance is demonstrated through full-scale testing and careful design consideration, rather than relying solely on pre-accepted solutions.

A number of key design parameters have been identified as critical in controlling the spread of fire and ensuring the robustness of timber-clad façades:

- Façade fire spread: The project showed that plume deflectors may not effectively prevent ignition of the cladding on the floor directly above the fire floor. In some cases it would be possible to prevent ignition to the 2nd floor above the fire floor.
- Safety Distances: Greater separation distances to adjacent buildings and property boundaries are advisable—often exceeding those in prescriptive codes—to limit the risk of fire spread between structures.
- Flame Barrier Configuration: The effectiveness of flame deflectors (plume deflectors) is highly

dependent on their geometry, material, surface treatment, and fastening methods. Their role in redirecting flames away from the façade is central to preventing vertical fire spread.

- Wood Cladding Design: The profile, orientation, species, density, and treatment of timber cladding significantly influence ignition, flame spread, and smouldering behaviour. Selection should be based on tested configurations.
- Corners and Joints: Special attention is required at internal corners and joint assemblies, where fire behaviour may differ from flat surfaces. These should be addressed through targeted testing or conservative detailing.
- Window Geometry and Placement: The size and vertical alignment of windows affect the potential for flame impingement and radiative exposure to upper stories. Windows located directly above fire sources are especially vulnerable.
- Façade Protrusions and Detailing: Architectural features such as recesses, cornices, and downpipes can alter flame trajectories and thermal exposure patterns. These should be designed to avoid concentrating heat or creating secondary ignition points.
- Cavity Design and Material Selection: The choice of wind barrier and insulation, as well as the placement of cavity fire stops, plays a critical role in limiting hidden fire spread within ventilated façades.

Collaboration between architects, fire engineers, and façade specialists is essential to ensure that both aesthetic and safety objectives are met.

5.3. Knowledge gaps and future work

BioFacades:UpHigh testing program and the accompanying analyses highlight several critical knowledge gaps and areas for future research.

A significant challenge lies in interpreting and contextualizing the BioFacades: UpHigh results in relation to real-life scenarios or other national façade fire test standards, such as SP FIRE 105, BS 8414 or DIN 4102-20. Future work should aim to systematically compare plume deflector performance in different test scenarios. In real building configuration, windows are typically vertically aligned above each other, which likely results in heat fluxes to the glazing and interior of the building, compared to the asymmetrical configurations tested in BioFacades: UpHigh tests.

In most BioFacades: UpHigh tests, the return wing was not clad with the façade construction. Having cladding on the return wing is an integral part of the European approach test method, and it can be reasoned that having clad return wing would increase the likelihood of vertical fire spread. In BioFacades: UpHigh project, the test method was regarded as ad hoc or demonstration test and the results are evaluated on project basis for buildings without internal corners. Nevertheless, it must be highlighted that the European approach is developed, like most other fire tests, to provide data for ranking different constructions, rather than simulating probable "real-life" fires. Due to this significant deviation from the originally proposed method, results from BioFacades: Uphigh test programme cannot be directly compared with European approach test data. Future work should focus on the evaluation of methodologies for protecting a corner, e.g. with non-combustible boards or special design corner detailing of plume deflectors.

Computational Fluid Dynamics (CFD) simulations represent a promising supplement to large-scale testing but are not yet ready to replace physical experiments. At present, there is limited experience with applying CFD for modelling European approach test setup, which makes systematic validation challenging. Current models are able to capture general trends in flame heights, heat fluxes, and temperature distributions, yet they also produce both over- and underestimations[42]. Future work should therefore aim to build a more extensive validation database against which CFD can be benchmarked. Over time, such models could become valuable tools for exploring façade design variations, such as the influence of plume deflector geometry or corner detailing, that would otherwise require numerous costly full-scale tests. Moreover, it can also help understanding the fluid dynamics in corner configuration and hence the effect of the design of the corner (e.g. necessary width of a non-combustible board in corner). The future work may also include the development of reduced scale test methods for evaluating plume deflector designs or materials.

While it was evident that geometrical parameters such as L1 influence temperatures measured near the façade on the first floor, the current data set is too limited to establish robust quantitative relationships. More extensive parametric studies are necessary to determine how these spatial configurations modulate flame impingement and thermal exposure, thereby informing façade design guidelines. The omission of a weighing load cell to capture falling parts' mass limits the conclusions drawn about compliance with Level 1 and 2 falling parts criteria. Future tests should incorporate robust weighing mechanisms to accurately identify both the origin and characteristics of falling debris, especially to distinguish façade material from wood crib components.

Test 10 suggested that strategically placed cavity fire stops may delay flame spread inside the ventilation cavity. However, no definitive conclusion can be drawn without further controlled studies. The influence of fire stop positioning, material type, and integration with façade details warrants systematic examination. Specifically, their efficacy in limiting internal versus external fire spread remains unclear.

The 60-minute observation window was insufficient to assess the smoldering potential of bio-based insulation fully. The European approach suggests a test duration of 6 hours (ISO 16733) and 15 hours (DIN 4102-4) for smoldering assessment, respectively. However, these extended large-scale tests are resource-intensive and costly. Therefore, there is a clear need to develop alternative testing methodologies at small- or medium-scale that can reliably predict large-scale smouldering behaviour. This could include the use of advanced numerical modelling techniques to extrapolate smouldering dynamics, offering a more feasible and cost-effective approach for routine assessments.

Research should prioritize the development of both more durable fire-retardant treatments for wood and field-applicable testing or monitoring solutions. To capture realistic aging effects, the loss of fire performance durability should also be evaluated under large-scale test conditions that reflect real-world exposure and assembly details.

Furthermore, the long-term reliability of plume deflectors and cavity barriers depends on their correct installation. The loss of performance of plume deflector and consequent necessity for maintenance is unknown at this stage. Future work should consider protocols for quality assurance during construction and periodic inspection methodologies.

REFERENCES

[1] J. Anderson *et al.*, “European approach to assess the fire performance of façades,” *Fire and Materials*, vol. 45, no. 5, pp. 598–608, Aug. 2021, doi: 10.1002/fam.2878.

[2] *SP FIRE 105, External wall assemblies and facade claddings, Reaction to fire, Issue No: 5*, Sept. 09, 1994.

[3] *BS 8414-1:2020. Fire performance of external cladding systems - Test method for non-loadbearing external cladding systems fixed to, and supported by, a masonry substrate*.

[4] P. H. Thomas and M. Law, “The projection of flames from burning buildings,”

[5] S. Yokoi, “Study on the Prevention of Fire-Spread Caused by Hot Upward Current”.

[6] N. Jones *et al.*, “Burning behaviour of rainscreen façades,” *Journal of Hazardous Materials*, vol. 403, p. 123894, Feb. 2021, doi: 10.1016/j.jhazmat.2020.123894.

[7] L. Schiøtt Sørensen and K. Dahl Hertz, “Fire safety challenges of external foam plastic insulated buildings,” in *Abstract from Nordic Fire & Safety Days*, Lyngby, Denmark, 2019.

[8] K. Livkiss, S. Svensson, B. Husted, and P. van Hees, “Flame Heights and Heat Transfer in Façade System Ventilation Cavities,” *Fire Technol*, vol. 54, no. 3, pp. 689–713, May 2018, doi: 10.1007/s10694-018-0706-2.

[9] J. E. Mendez, D. Lange, J. P. Hidalgo, and M. S. McLaggan, “Effect of cavity parameters on the fire dynamics of ventilated façades,” *Fire Safety Journal*, vol. 133, p. 103671, Oct. 2022, doi: 10.1016/j.firesaf.2022.103671.

[10] *Finalisation of the European approach to assess the fire performance of façades SI2.825082. 1st edition*. Publications Office of the European Union, 2024.

[11] J. Sjöström, D. Brandon, A. Temple, J. Anderson, and R. McNamee, “External fire plumes from mass timber compartment fires—Comparison to test methods for regulatory compliance of façades,” *Fire and Materials*, vol. 47, no. 4, pp. 433–444, June 2023, doi: 10.1002/fam.3129.

[12] A. I. Bartlett, R. M. Hadden, and L. A. Bisby, “A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction,” *Fire Technol*, vol. 55, no. 1, pp. 1–49, Jan. 2019, doi: 10.1007/s10694-018-0787-y.

[13] D. Hopkin, M. Spearpoint, Y. Kanellopoulos, C. Gorska, and C. Mayfield, “Multi-Scale Characterisation of the Fire Hazards of Timber Cladding,” *Fire*, vol. 8, no. 2, Art. no. 2, Feb. 2025, doi: 10.3390/fire8020035.

[14] T. Engel and N. Werther, “Structural Means for Fire-Safe Wooden Façade Design,” *Fire Technol*, vol. 59, no. 1, pp. 117–151, Jan. 2023, doi: 10.1007/s10694-021-01174-2.

[15] L. Boström, C. Skarin, M. Duny, and R. McNamee, “Fire test of ventilated and unventilated wooden facades,” SP Technical Research Institute of Sweden, 2016:16.

[16] B. Östman and L. Tsantaridis, “Fire Scenarios for Multi-storey Façades with Emphasis on Full-Scale Testing of Wooden Façades,” *Fire Technol*, vol. 51, no. 6, pp. 1495–1510, Nov. 2015, doi: 10.1007/s10694-015-0508-8.

[17] M. Teibinger, I. Matzinger, and P. Schober, “Experimental study of the fire performance of wooden facades,” *MATEC Web of Conferences*, vol. 9, p. 02004, 2013, doi: 10.1051/matecconf/20130902004.

[18] E. Aamodt *et al.*, *Analyse av brann i kommunalt boligbygg i Bergen 7. august 2021*. 2023. Accessed: Dec. 03, 2024. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-64223

[19] “Clapton flats fire: Woman rescued during ‘suspicious’ blaze,” Sept. 17, 2019. Accessed: July 29, 2025. [Online]. Available: https://www.bbc.com/news/uk-england-london-49725761

[20] H. Champ, “Insurance sector monitoring investigation of Worcester Park fire probe,” Housing Today. Accessed: July 29, 2025. [Online]. Available:

https://www.housingtoday.co.uk/news/insurance-sector-monitoring-investigation-of-worcester-park-fire-probe/5101549.article
[21] “Full Report Samuel Garside House, 2 De Pass Gardens, Barking Riverside, Barking, IG11 0FQ. Borough of Barking and Dagenham,” LFB Incident Number: 072738-09062019.
[22] “Manchester fire was spread by wooden balconies | Daily Mail Online.” Accessed: July 29, 2025. [Online]. Available: https://www.dailymail.co.uk/news/article-5224271/Manchester-fire-spread-wooden-balconies.html
[23] E. Aamodt, A. Steen-Hansen, O. Ers, and . H., “Learning From Fire Incidents -- Analysis of a devastating fire in a building with municipal housing in Norway,” in *Book of Extended Abstracts for the 32nd European Safety and Reliability Conference*, Research Publishing Services, 2022, pp. 1156–1163. doi: 10.3850/978-981-18-5183-4_R21-01-401-cd.
[24] R. Booth and R. B. S. affairs correspondent, “Experts had warned of fire risk at Barking block of flats,” *The Guardian*, June 19, 2019. Accessed: Mar. 11, 2025. [Online]. Available: https://www.theguardian.com/uk-news/2019/jun/19/experts-had-warned-of-fire-risk-at-barking-block-of-flats
[25] J. Anderson *et al.*, “Assessment of fire performance of facades using large fire exposure, draft revision 6,” 18 2022.
[26] “ThermoWood handbook.” Accessed: Oct. 20, 2025. [Online]. Available: https://asiakas.kotisivukone.com/files/thermowood.palvelee.fi/tiedostot/web_thermowood_handbook.pdf
[27] Christopher M. Smith, Matthew Hoehler, “Imaging Through Fire Using Narrow-Spectrum Illumination,” July 2018, [Online]. Available: https://link.springer.com/article/10.1007/s10694-018-0756-5
[28] ÉMI NON-PROFIT LIMITED LIABILITY COMPANY FOR QUALITY CONTROL AND INNOVATION IN BUILDING, “Comparative document on the analysis of large-scale Round Robin tests on inert facade,” Project: SI2.825082, Apr. 2024. Accessed: Sept. 15, 2025. [Online]. Available: https://www.ri.se/en/expertise-areas/projects/european-approach-to-assess-the-fire-performance-of-facades
[29] J. Sjöström, J. Anderson, F. Kahl, L. Boström, and E. Hallberg, “Large scale exposure of fires to facade - Initial testing of proposed European method,” RISE Research Institutes of Sweden AB, Borås, RISE Report 2021:85, 2021.
[30] H. Bengtsson, A. A. A. Awadallah, I. Pope, L. Giuliani, and L. S. Sørensen, “Experimental study of the post-flashover fire performance of multi-pane low-energy windows,” *Glass Struct Eng*, vol. 10, no. 3, p. 20, Sept. 2025, doi: 10.1007/s40940-025-00305-3.
[31] J. Geng, S. Guo, Z.-W. Gao, Z. Wang, and W.-Q. Peng, “Influence of radiation mode and intensity on the protective performance of firefighting boots,” *Journal of Loss Prevention in the Process Industries*, vol. 87, p. 105247, Feb. 2024, doi: 10.1016/j.jlp.2024.105247.
[32] A. Häggkvist, J. Sjöström, and U. Wickström, “Using plate thermometer measurements to calculate incident heat radiation,” *Journal of Fire Sciences*, vol. 31, no. 2, pp. 166–177, Mar. 2013, doi: 10.1177/0734904112459264.
[33] C. Hill, M. Kymäläinen, and L. Rautkari, “Review of the use of solid wood as an external cladding material in the built environment,” *J Mater Sci*, vol. 57, no. 20, pp. 9031–9076, May 2022, doi: 10.1007/s10853-022-07211-x.
[34] P. Sauerbier, A. K. Mayer, L. Emmerich, and H. Militz, “Fire Retardant Treatment of Wood – State of the Art and Future Perspectives,” in *Wood & Fire Safety*, L. Makovicka Osvaldova, F. Markert, and S. L. Zelinka, Eds., Cham: Springer International Publishing, 2020, pp. 97–102. doi: 10.1007/978-3-030-41235-7_14.

[35] B. Östman and L. Tsantaridis, "Durability of the reaction to fire performance for fire retardant treated (FRT) wood products in exterior applications – a ten years report," *MATEC Web of Conferences*, vol. 46, p. 05005, 2016, doi: 10.1051/matecconf/20164605005.

[36] K. Wilkens Flecknoe-Brown, N. Johansson, F. Engström, and H. Psajd, "Fire Performance of Impregnated Wood Subjected to Natural Aging in the Swedish Climate," in *Conference Proceedings*, Lund, Sweden, June 2024.

[37] J. Lange *et al.*, "Experimental Investigation on Firefighting Procedures for Multi- Storey Wooden Façades," in *Proceedings from the 4th International Symposium on Fire Safety of Facades 2024: 10-12 June 2024. Lund, Sweden*, in RISE rapport 2024:45. June 2024. [Online]. Available: https://www.ri.se/en/fire-safety-of-facades-fsf/conference-proceedings

[38] "HoBraTec: Schlussbericht zum Vorhaben "Optimierung der Brandbekämpfungsmethoden und -techniken für Gebäude in moderner Holzbauweise [Final report of the project 'Optimization of firefighting methods and techniques for buildings in modern timber construction'], 09/2024 (to be published)."

[39] "HoBraTec - Optimierung der Brandbekämpfungsmethoden und -techniken für Gebäude in moderner Holzbauweise (engl. 'Optimization of firefighting methods and techniques for buildings in modern timber construction'), Final Report," 2024.

[40] P. Sudhoff and J. Åström, "Smoldering-to-Flaming Transition of Bio-based Insulation Materials," in *Book of Abstracts*, in RISE Report 2024:49. Lund, June 2024. doi: 10.23699/yns7-3n56.

[41] P. Bachmeier, "Empfehlungen der Arbeitsgemeinschaft der Leiterinnen und Leiter der Berufsfeuerwehren und des Deutschen Feuerwehrverbandes: Löschmaßnahmen bei Bränden von Holzfaserdämmung," Fachausschuss Vorbeugender Brand- und Gefahrenschutz der deutschen Feuerwehren (FA VB/G), München, 2024–01.

[42] G. Zhao, J. Anderson, A. Dragsted, S. Hostikka, and K. Livkiss, "Numerical Investigation of Thermal Exposure on External Walls in the Harmonized European Approach to Assess the Fire Performance of Façades," *Fire and Materials*, vol. 49, no. 7, pp. 1026–1044, Nov. 2025, doi: 10.1002/fam.70001.

[43] J. Zhang, M. Delichatsios, and M. Colobert, "Assessment of Fire Dynamics Simulator for Heat Flux and Flame Heights Predictions from Fires in SBI Tests," *Fire Technol*, vol. 46, no. 2, pp. 291–306, Apr. 2010, doi: 10.1007/s10694-008-0072-6.

[44] V. Dréan, R. Schillinger, and G. Auguin, "Fire exposed facades: Numerical modelling of the LEPIR2 testing facility," *MATEC Web of Conferences*, vol. 46, p. 03001, 2016, doi: 10.1051/matecconf/20164603001.

[45] *ISO 13785-1:2002 Reaction-to-fire tests for façades Part 1: Intermediate-scale test*, 2019.

[46] T. Hakkarainen and T. Oksanen, "Fire safety assessment of wooden facades," *Fire Mater.*, vol. 26, no. 1, pp. 7–27, Jan. 2002, doi: 10.1002/fam.780.

APPENDIX A – SUMMARY OF THE BIOFACADES: UPHIGH TEST RESULTS

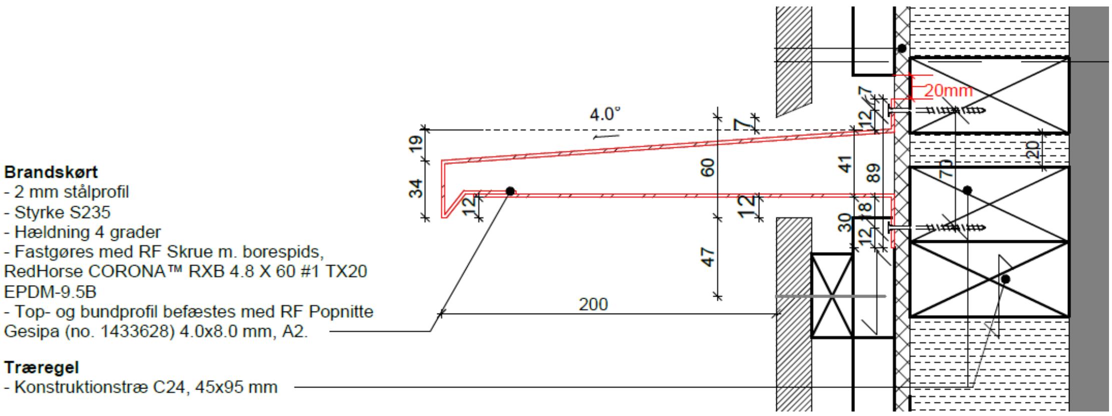
Table 6 presents the main construction parameters and failure times of BioFacades: UpHigh project tests. Table 7 presents photos of the construction and plume deflectors before and after the tests as well as a summary of the construction. The detailed construction description and results are available in testing reports issued by DBI.

Table 6 main façade defining parameters and test results for the project BioFacades: Uphigh

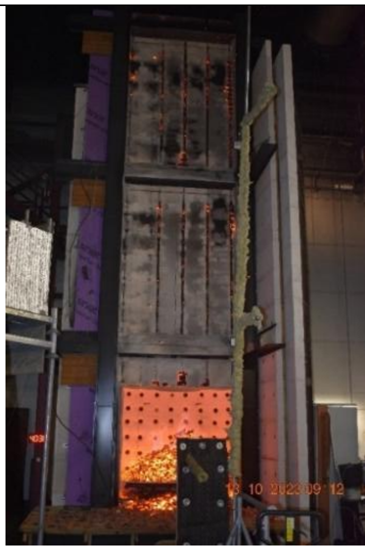
Test no.	Depth of plume deflector (mm)	Return wing cladding	Secondary opening dimensions (mm)	Cladding orientation	Cladding wood [1]	Cavity depth (mm)	Construction type	Vertical fire spread failure time (min)	Failure time and mode (min)[2]
1	200	yes	1200 × 1200	V	TM pine	50	high	11	10 (HFS) 12 (BP)
2	207	no	none	V and H	TM pine	50	high	4	11 (BP)
3	324	no	1765 × 1965	H	NTM spruce	25	high	no failure	56 (HFS) 23 (BP)
4	314	yes	1765 × 1965	H	NTM spruce	25	high	no failure	4 (HFS) 25 (BP)
5	264	no	1500 × 2300	V and H	TM pine	25	high	21[3]	10 (HFS) 6 (BP)
6	305	no	1200 × 1200	V	TM pine	50	low	49[3]	19 (HFS) 16 (BP)
7	305	no	1200 × 1200	V	TM pine	50	low	no failure	38 (HFS) 21 (BP)
8	305	no	1200 × 1200	V	TM pine	50	low	no failure	31 (HFS) 21 (BP)
9	207	no	1200 × 1200	V	TM pine	44	low	no failure	42 (HFS) 23 (BP)
10	307	partial	1200 × 1200	V	TM pine, treated with water-borne top-coat	50	low	no failure	22 (HFS) 24(BP)

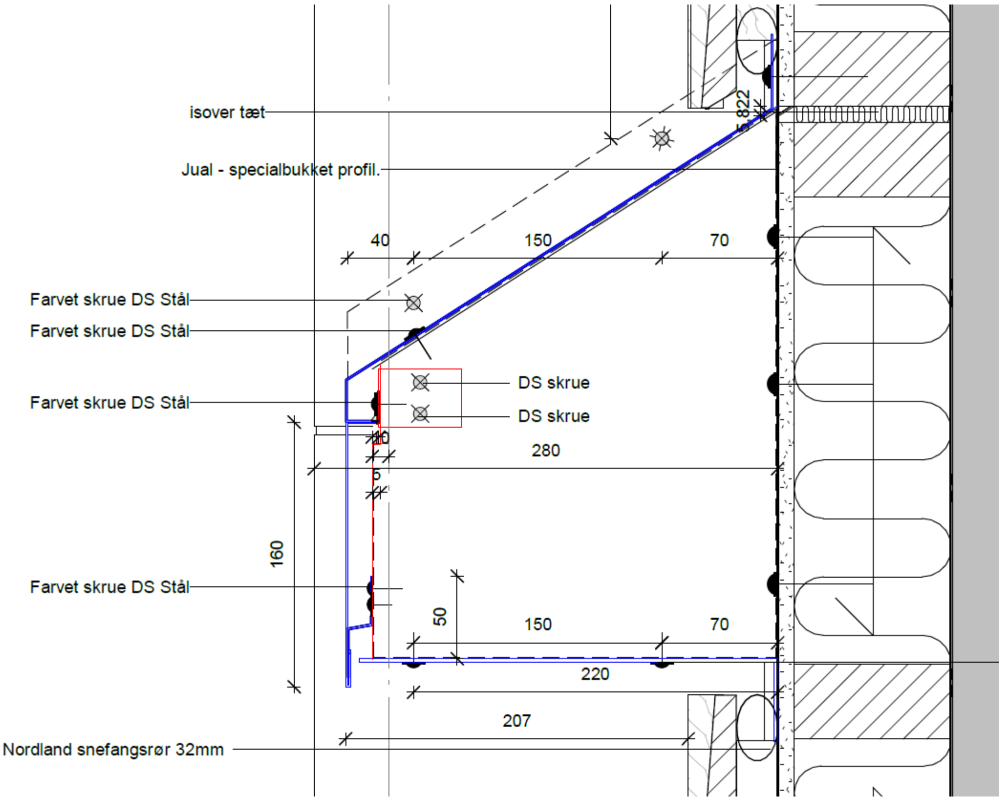
[1] TM – thermally modified; NTM – non-thermally modified
[2] VFS – vertical fire spread; HFS – horizontal fire spread; BP – burning parts; FP – falling parts
[3] Based on visual observations, not temperature measurements

Table 7 Photos of test specimens prior and after the test and the plume deflector

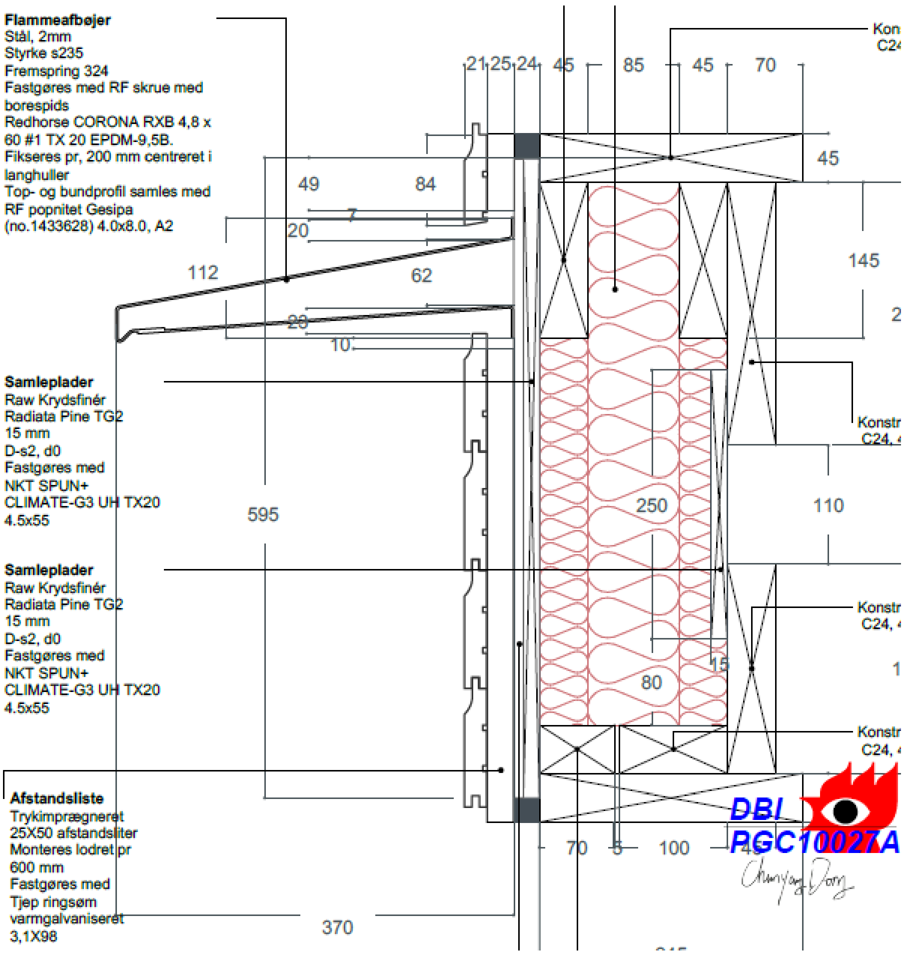
No	Prior the test	After or late stage of the test
Test 1		
		

Test 2

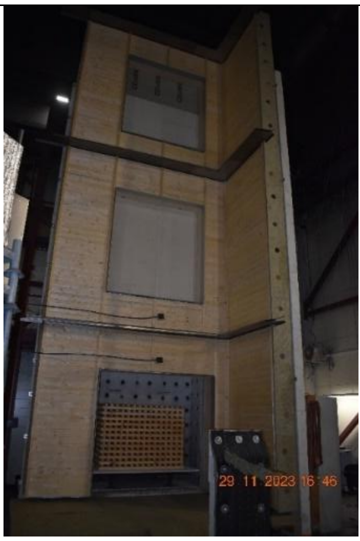



isover tæt
Jual - specialbukket profil.
Farvet skrue DS Stål
Farvet skrue DS Stål
Farvet skrue DS Stål
Farvet skrue DS Stål
DS skrue
DS skrue
Nordland snefangsrør 32mm
40
150
70
280
160
50
150
70
220
207
10
22

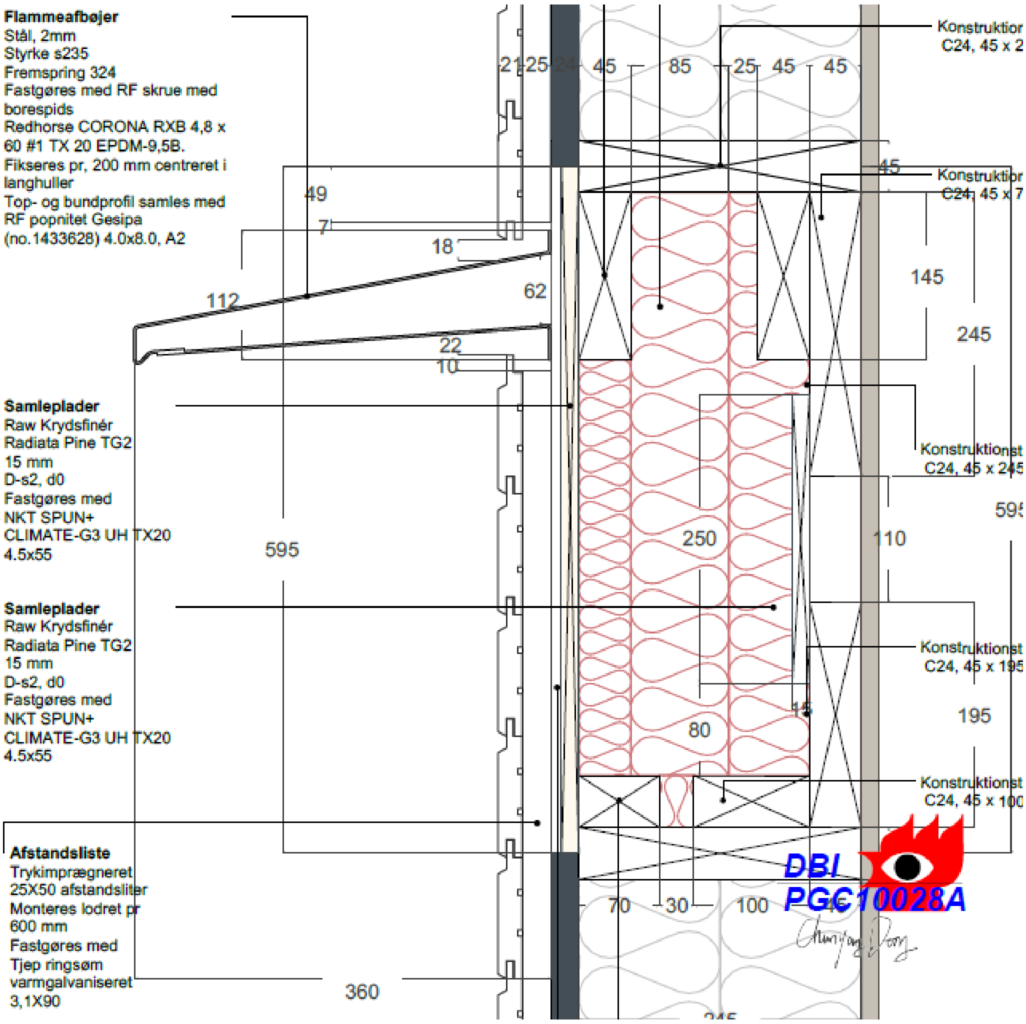
Test 3


Flammeafbøjer
Stål, 2mm
Styrke s235
Fremspring 324
Fastgøres med RF skrue med borespids
Redhorse CORONA RXB 4,8 x 60 #1 TX 20 EPDM-9,5B.
Fikseres pr, 200 mm centreret i langhuller
Top- og bundprofil samles med RF popnitet Gesipa (no.1433628) 4.0x8.0, A2
Samleplader
Raw Krydsfinér
Radiata Pine TG2
15 mm
D-s2, d0
Fastgøres med
NKT SPUN+
CLIMATE-G3 UH TX20
4.5x55
Samleplader
Raw Krydsfinér
Radiata Pine TG2
15 mm
D-s2, d0
Fastgøres med
NKT SPUN+
CLIMATE-G3 UH TX20
4.5x55
Afstandsliste
Trykimprægneret
25X50 afstandsliter
Monteres lodret pr
600 mm
Fastgøres med
Tjep ringsøm
varmgalvaniseret
3,1X98
21 25 24 45 85 45 70
45
49
84
20
112
62
145
595
250
110
80
15
70 5 100
370
DBI
PGC10027A

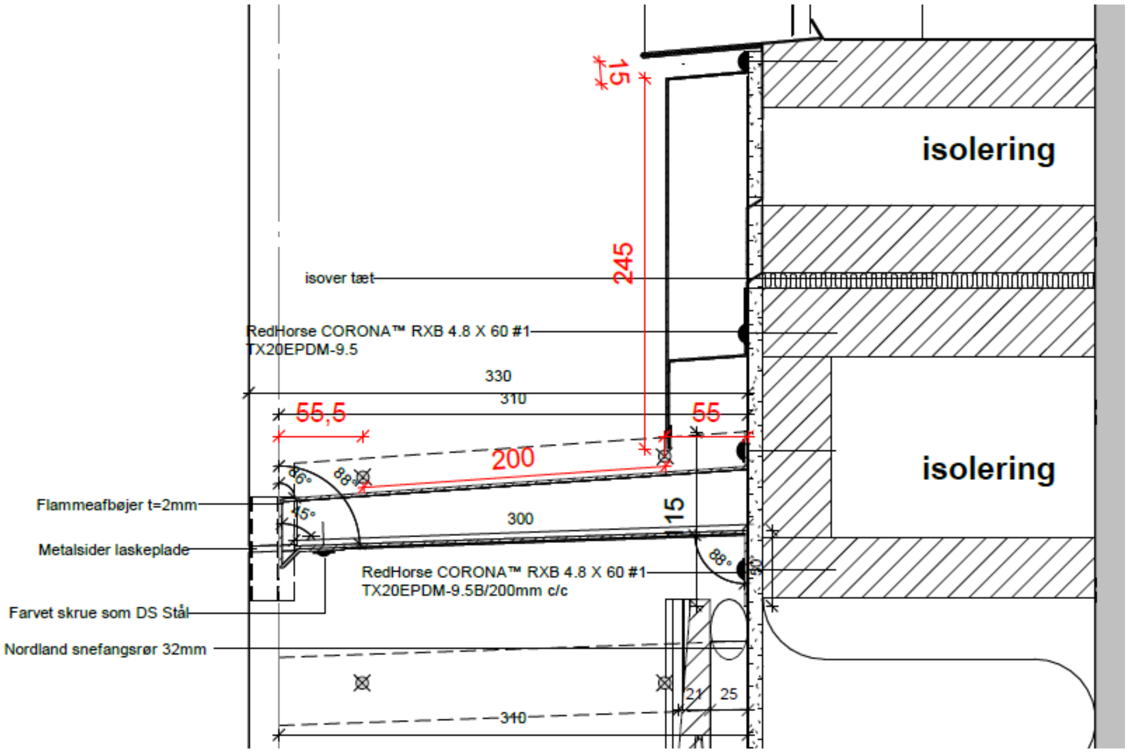
Test 4


29 11 2023 16 46

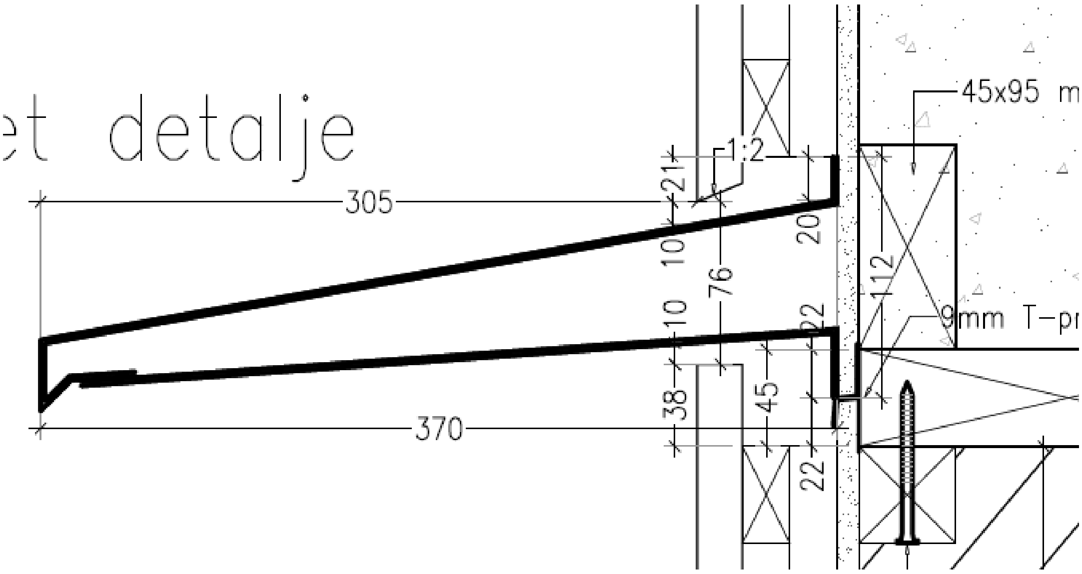

30 11 2023 10 59


Flammeafbøjer
Stål, 2mm
Styrke s235
Fremspring 324
Fastgøres med RF skrue med borespids
Redhorse CORONA RXB 4,8 x 60 #1 TX 20 EPDM-9,5B.
Fikseres pr, 200 mm centreret i langhuller
Top- og bundprofil samles med RF popnitet Gesipa (no.1433628) 4.0x8.0, A2
Samleplader
Raw Krydsfinér
Radiata Pine TG2
15 mm
D-s2, d0
Fastgøres med
NKT SPUN+
CLIMATE-G3 UH TX20
4.5x55
Samleplader
Raw Krydsfinér
Radiata Pine TG2
15 mm
D-s2, d0
Fastgøres med
NKT SPUN+
CLIMATE-G3 UH TX20
4.5x55
Afstandsliste
Trykimprægneret
25X50 afstandslister
Monteres lodret pr
600 mm
Fastgøres med
Tjep ringsøm
varmgalvaniseret
3,1X90
Konstruktior
C24, 45 x 2
Konstruktior
C24, 45 x 7
Konstruktionst
C24, 45 x 245
Konstruktionst
C24, 45 x 195
Konstruktionst
C24, 45 x 100
DBI
PGC10028A
21
25
45
85
25
45
45
49
7
18
62
112
22
10
45
145
245
595
250
110
595
195
80
70
30
100
360

Test 5



isolering
isolering
15
245
isover tæt
RedHorse CORONA™ RXB 4.8 X 60 #1
TX20EPDM-9.5
330
310
55,5
55
200
300
15
Flammeafbøjer t=2mm
Metalsider laskeplade
RedHorse CORONA™ RXB 4.8 X 60 #1
TX20EPDM-9.5B/200mm c/c
Farvet skrue som DS Stål
Nordland snefangsrør 32mm
21
25
310

<table>
<tr><td rowspan="2">Test 6</td><td></td><td></td></tr>
<tr><td colspan="2">
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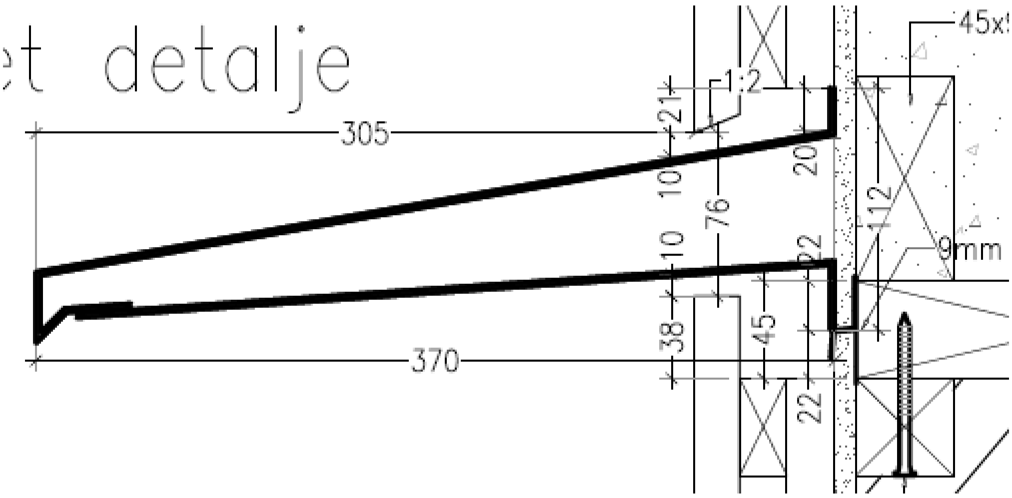
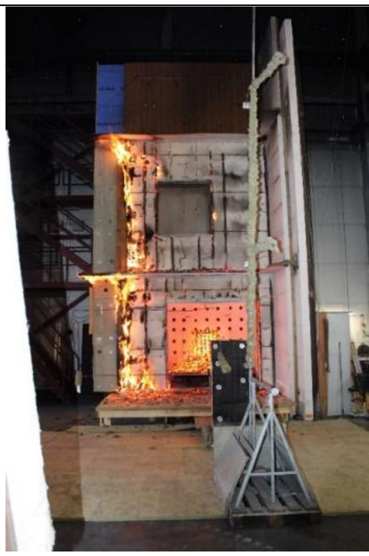
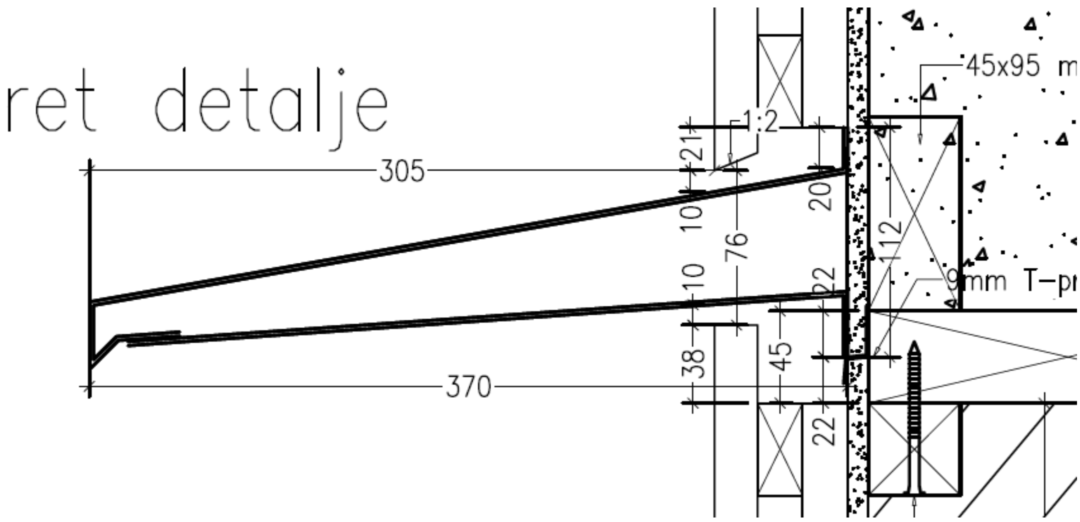
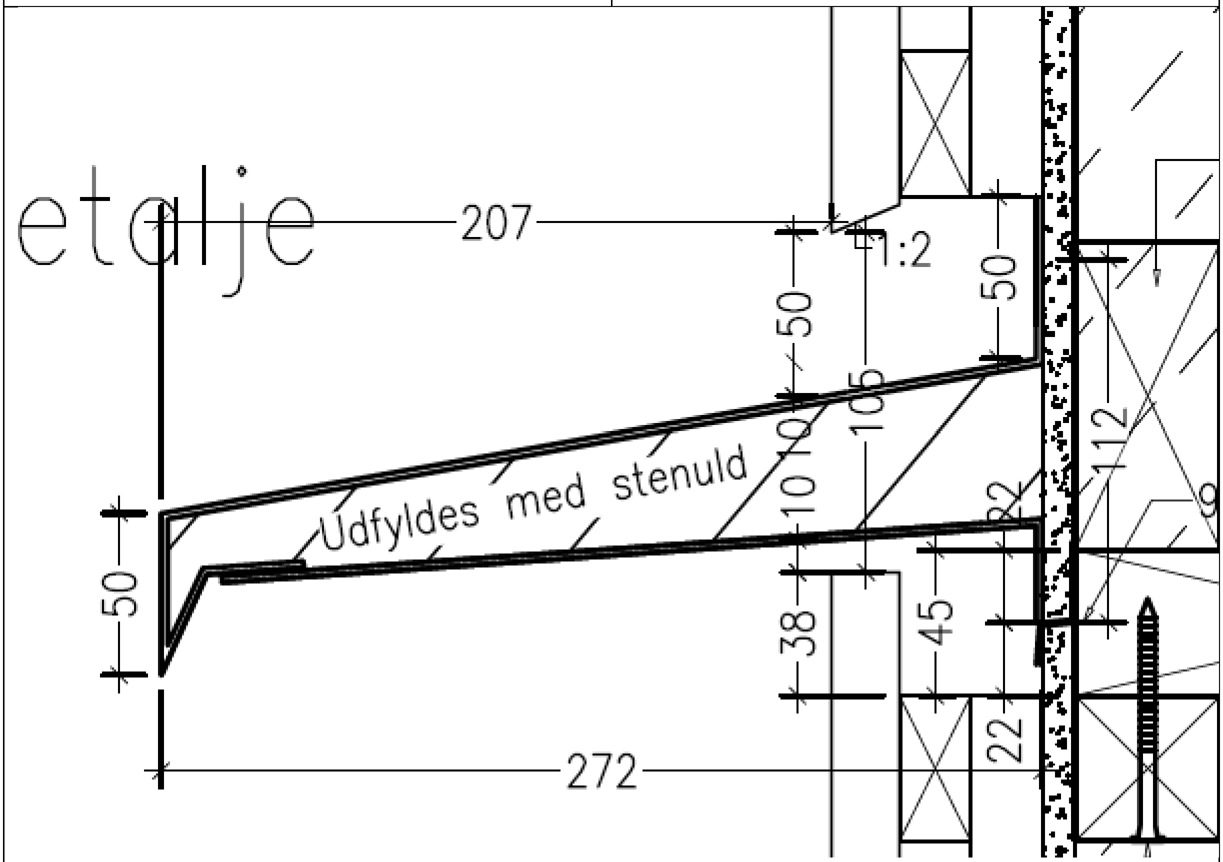
DBI

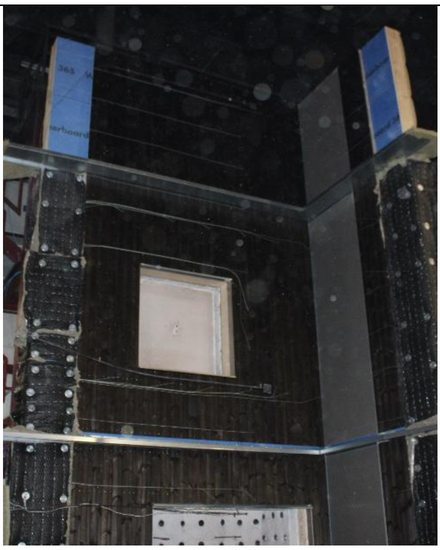
Test 7		
	detalje 305 370 1:2 21 10 76 10 38 45 20 22 22 112 9mm	

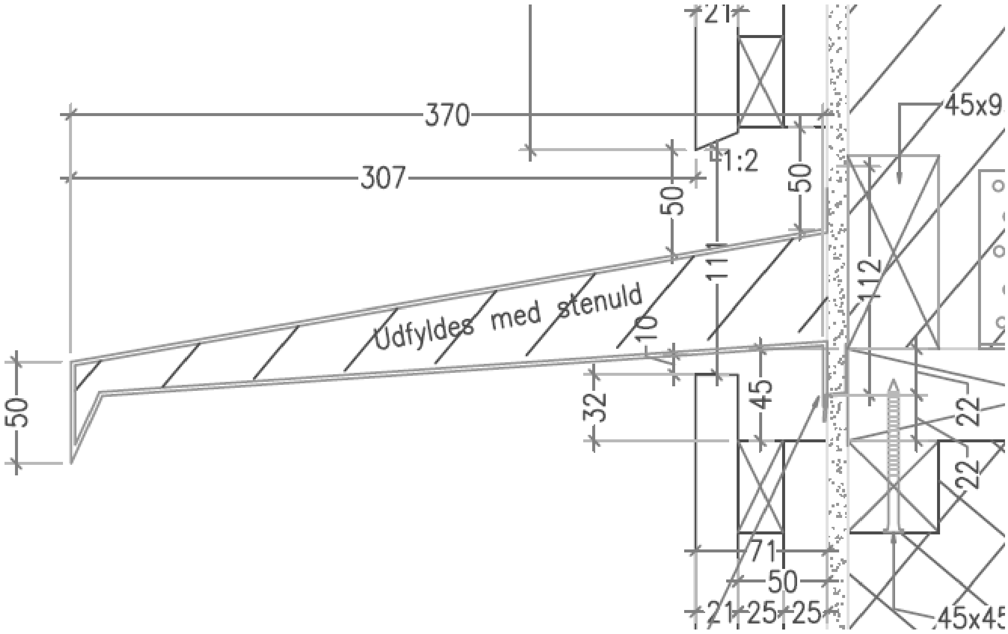
Test 8		
		

Test 9


etalje
207
1:2
50
50
105
Udfyldes med stenuld
50
38
45
22
112
272

Test 10




370
307
21
45x9
1:2
50
50
11
112
Udfyldes med stenuld
10
50
32
45
22
22
71
50
21
25
25
45x45

APPENDIX B – NON-EXTENSIVE LIST OF FAÇADE FIRE TESTS USED IN VARIOUS COUNTRIES

Method	Test specimen	Fuel source and exposure	General comments
SBI	Corner configuration h=1.500 m. W = 1.000 (large wing), W=0.495 (small wing)	Triangular gas burner, with heat output of 30kW placed directly next to the specimen. The heat flux to the surface reach up to 40 kW/m^2 **[43]**	Relatively small physical size, making SBI commercially and technically feasible. Relatively low heat exposure, representing first item ignited, but not a fully developed compartment fire. The test specimen does not include façade detailing, e.g. window frame, fire stops.
European approach (large scale)	Corner configuration. Minimum height from top of the combustion chamber opening 5.5 m. Vertical thermocouple columns (2.75 m from corner on the main face) and 1.45 m from corner on the side wing. One secondary opening.	350 ± 20 kg spruce wood crib, placed inside a combustion chamber with opening dimensions of 1.9 × 2.0 m	
European approach (medium scale)	Corner configuration. Minimum height from top of the combustion chamber opening 4.0 m. And thermocouple columns (2.75 m from corner on the main face) and 1.45 m from corner on the side wing. One secondary opening.	30 ± 1.5 kg spruce wood crib, placed inside a combustion chamber with opening dimensions of 1 × 1 m	
LEPIR II[44]	Single surface configuration consisting of two full levels and part of the lower part of the third level. Two window openings per level on the ground level and first level.	Two cribs of 300 kg softwood per crib. The peak HRR reach almost 5MW.	
BS8414		300 – 488 kg pine wood crib (mostly depends on the density at the time of the test)	
DIN 4102-20	Corner configuration with a minimum height of 5.5 m. Minimum width is 2,5 m for the long wing and 1,5 m for the short wing.	Gas burner or 30 ± 1.5 kg spruce wood crib placed inside a combustion chamber with opening dimensions of 1 × 1 m	Test scenario represents flame peaks in a room fire
DIN 4102-24	Corner configuration Height: 9.8 m Long wing width: 4 m Short wing width: 2 m	200 kg wood crib	Test scenario represents a fire outside the building
SP Fire 105**[2]**	Single wall, 4 × 6 m, with two artificial window openings	60 l of heptane in tray with dimensions 2 × 0.5 m. The opening dimensions of 3.000 × 0.710 m. The air intake to the combustion chamber is ensured at the floor level behind the fuel tray.	Does not allow evaluating corner fire dynamics. Due to the geometry the flames impinge close to the façade. The duration of the test is relatively short (approx. 15-20 minutes). Heat fluxes at the artificial opening levels are measured.
ISO 13785 – 1 **[45]**	Corner configuration with a height of 2.4 m. The width of the long wing is 1.2 m, and the short wing is 0.6 m.	Gas burner with the opening dimensions of 0.1 × 1.2 and the HRR output of 100 ± 5 kW. **[45]** The maximum heat exposure to the specimen surface is around 40 kW/m^2 **[46]**	
ÖNORM B 3800-5	Corner configuration with a height of 6.0 m. The width of the long wing is 3.0 m, and the short wing 1.5 m	25 kg wood crib	
VKF Prüfbestimmung für Aussenwand-bekleidungssysteme 2016	Single surface façade configuration with a minimum height of 8.3 m and a minimum width of 3.0 m	50 ± 1.5 kg spruce wood crib placed inside a combustion chamber with opening dimensions of 1 × 1.5 m	