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Mitigation of fire damages in multi-storey timber buildings – statistical analysis and guidelines for design

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Brandforsk

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Key words: Tall timber buildings, Fire, Fire stop, Fire spread, Water damage

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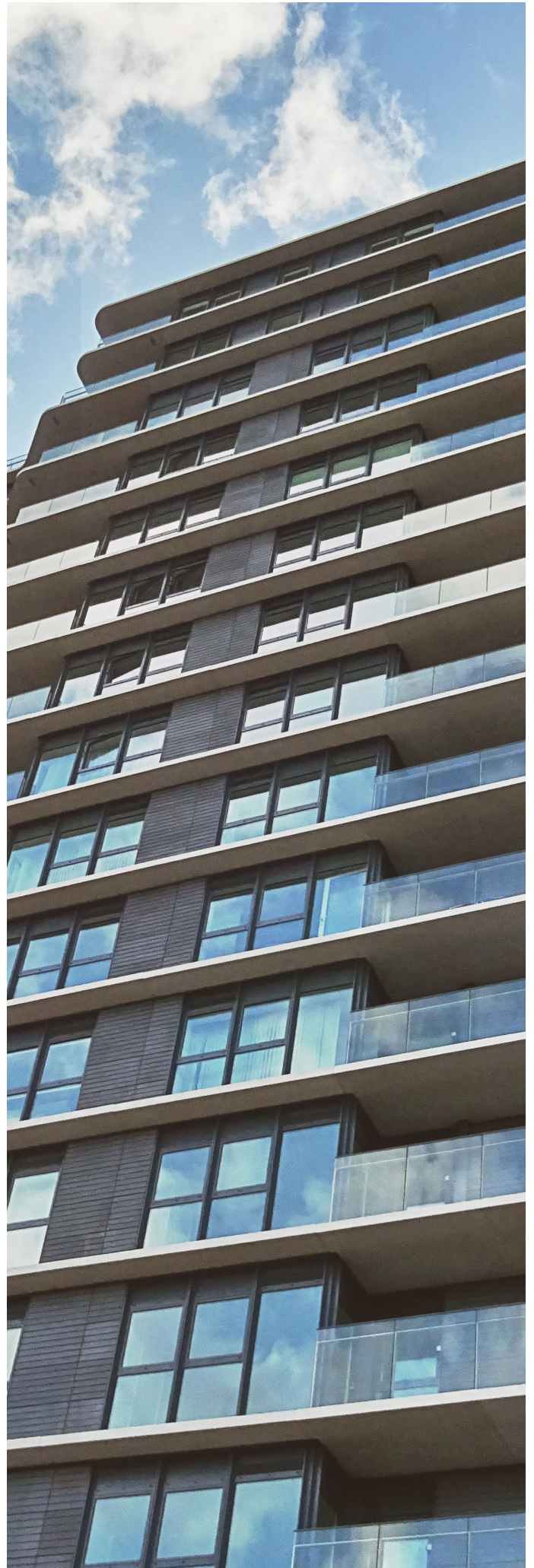
This report constitutes a final working manuscript for the headlined project.

The official project report, to which reference should be made, can be found on the RISE's website.

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Abstract

Mitigation of fire damages in multi-storey timber buildings – statistical analysis and guidelines for design

The number of multi-storey timber buildings has increased during the last twenty years. Recent well-known fires in London, Dubai and Brazil, although not in timber buildings, have increased concerns regarding large fire spread and high damage fires. As timber is a combustible material, concerns have been expressed regarding property safety and it has been questioned whether fire damage is more significant in buildings with timber as the main structural material than in other types of buildings. This report includes a statistical study of data of fires in multi-storey timber buildings in New Zealand and an analysis of high damage fires that occurred in multi-storey timber buildings in the USA. The data from New Zealand showed no significant difference between share of fires that had flame damage out of the compartment of origin in (a) multi-storey timber buildings that were constructed in or later than 1992 and (b) other types of multi-storey buildings that were constructed in or later than 1992. Fires in multi-storey timber buildings that were constructed before 1992 spread more frequently to neighbouring compartments than fires in other multi-storey timber buildings constructed before 1992. Data of high damage fires occurring in multi-storey timber buildings in the USA indicated that outdoor fire spread is the most common cause for large fire spread. Additionally, the data indicates that high water damage is most often caused by fire service interference and is significantly less often related to sprinkler activation.

Based on the analysis of fire spread of high damage fires in the USA, guidelines are given in the report to limit (1) outdoor fire spread, (2) fire spread through cavities, and (3) fire spread directly from a fire compartment to a neighbouring fire compartment. A number of these guidelines were evaluated using a fire test of a two-storey timber structure.

Key words: Tall timber buildings, Fire, Fire stop, Fire spread, Water damage

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Preface

This report is a result of a research project funded by Brandforsk as the main funder and Swedish Wood: *Fire Safety of Multi-Storey Timber Buildings*.

Statistical analysis was performed of data received from the NFPA (National Fire Protection Agency) in USA and the New Zealand fire service.

Guidelines are based on research performed specifically for the present project and on recent projects and a full-scale compartment fire test performed by RISE (Research Institutes of Sweden), TTU (Tallinn University of Technology), and SKA (Estonian Academy of Defence).

The Research Team of this project consisted of:

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1 Introduction

Fire safety regulations have, traditionally, mainly focused on life safety. However, especially for tall buildings, property protection becomes increasingly important. Recent developments have led to an increased amount of multi-storey timber buildings. As timber is a combustible material, concerns have been expressed regarding property safety and it has been questioned whether fire damage is more significant in buildings with timber as the main structural material than in other types of buildings (Björk, 2016). Whether this is correct could be studied statistically. As most countries do not have a long history with multi-storey timber buildings, statistics of fire damages that are relevant for multi-storey timber buildings are difficult to find. Still, a relevant statistical database was provided by the New Zealand Fire Service.

Modern multi-storey buildings are designed to limit fire spread to a single fire compartment. Despite this, there is a probability that fires spread beyond the fire compartment of origin, which has occasionally led to high damage of property in e.g. Sweden and USA. A master thesis by Al-Breidi and Löfström (2017) was performed to study high damage and deadly fires. They obtained access to a database of the NFPA (National Fire Protection Agency) in the USA, which includes data of high damage and deadly fires. Of this database, Al-Breidi and Löfström collected data of all fires in structures with three stories or more with timber as the main structural material, which occurred from 2007 to 2015. They described these fires in their thesis and performed some statistical analysis. The information is further analysed to identify the main modes of fire spread of the high-damage fires that have occurred in the USA in buildings with timber as the main structural material. Based on this, strategies to limit fire spread in tall timber buildings are proposed and guidelines on how to incorporate these strategies are given. The guidelines are based on research performed specifically for the present project and on recent projects and a full-scale compartment fire test performed by RISE (Research Institutes of Sweden), TTU (Tallinn University of Technology), and SKA (Estonian Academy of Defence).

High damage as a consequence of slowly spreading cavity fires has been seen in several occasions. Brandon *et al.* (2016) discussed 3 cavity fires (of which one occurred in a building with a masonry structure). The three fires had the following in common:

- The fire spread through cavities which were enclosed.
- The cavities contained combustible materials.
- The cavity fires outlasted the compartment fires by at least several hours.
- The cavity fires led to re-ignition of compartment fires after several hours.
- The fires were difficult to locate and extinguish and led to high damages.

In the three cases, analysed by Brandon *et al.*, the fire brigade was present at an early stage, but did not have effective methods to extinguish the fire. The state-of-the-art of fire extinguishment methodologies regarding this is summarised by Vylund and Palmkvist (2018). Another aspect of extinguishing fires in timber buildings is the risk for water damage. Water damage is analysed using the statistics from New Zealand and the USA. Efficient extinguishment is key, both, to limit fire damages but also to limit water damage.

The scope of this report is residential buildings with three or more floors that have timber as the main structural material.

2 Statistics from New Zealand

In New Zealand all fire incidents that involve the fire service are included in their data collection system. From their data, a specific data set for the research of this project was obtained from the New Zealand Fire Service. The data set comprised of all fires that occurred from 2000 to 2016 in apartment buildings of three stories or higher. The dataset excluded fires that occurred during the construction phase. With the data, comparisons were made between damages in buildings of timber frame construction and other types of buildings.

The fire service assessed the main structural material and distinguished the following construction types:

- Masonry, bricks, blocks etc.
- Reinforced concrete exposed slab
- Reinforced concrete with combustible cladding
- Reinforced concrete with non-combustible cladding
- Timber frame protected
- Timber frame unprotected

The analysis discussed herein using these data is, therefore, dependent on the correctness of assessments made by the New Zealand fire service.

Figure 1 shows a distribution of direct flame damage (by flames and radiation). It should be noted that the data of this figure contains buildings of all ages. About half of the timber frame buildings were built before 1991 and about two-third of the other buildings were built before 1991. It can be seen that there is a higher frequency of large fire damages in buildings of timber frame construction than buildings of other types of construction. However, Figure 2, which includes only fire in modern buildings (constructed after 1991) shows that this difference of large fire damages does not exist for modern buildings. Of apartment buildings built after 1991, there was no fire that extended beyond the fire cell of origin, which indicates that the fire safety design objective was reached successfully for these buildings. The percentage of fires that spread beyond the fire cell of origin was lower for modern timber buildings than for other types of modern buildings. However, this difference is not statistically significant according to a 2-tailed two proportion test with a significance level of 0.05.

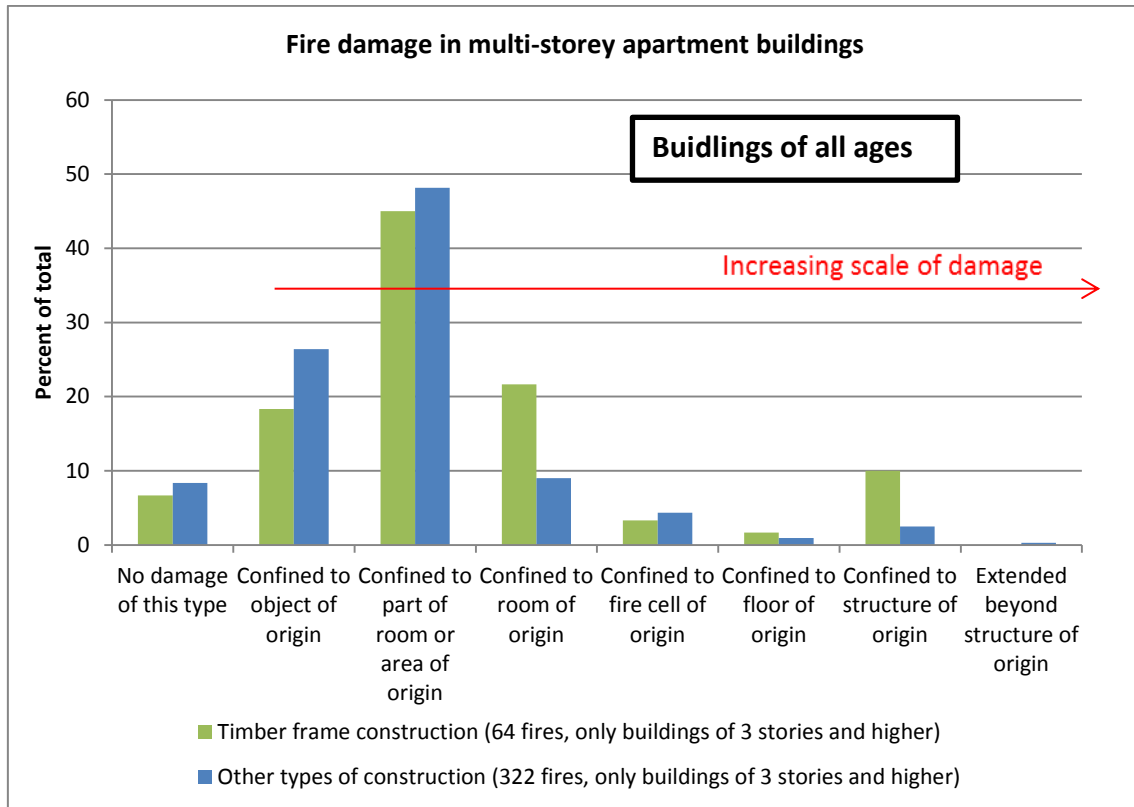


Figure 1: Fire damages after fires in New Zealand from 2000 to 2016, distributed in categories indicating the scale of the damage.

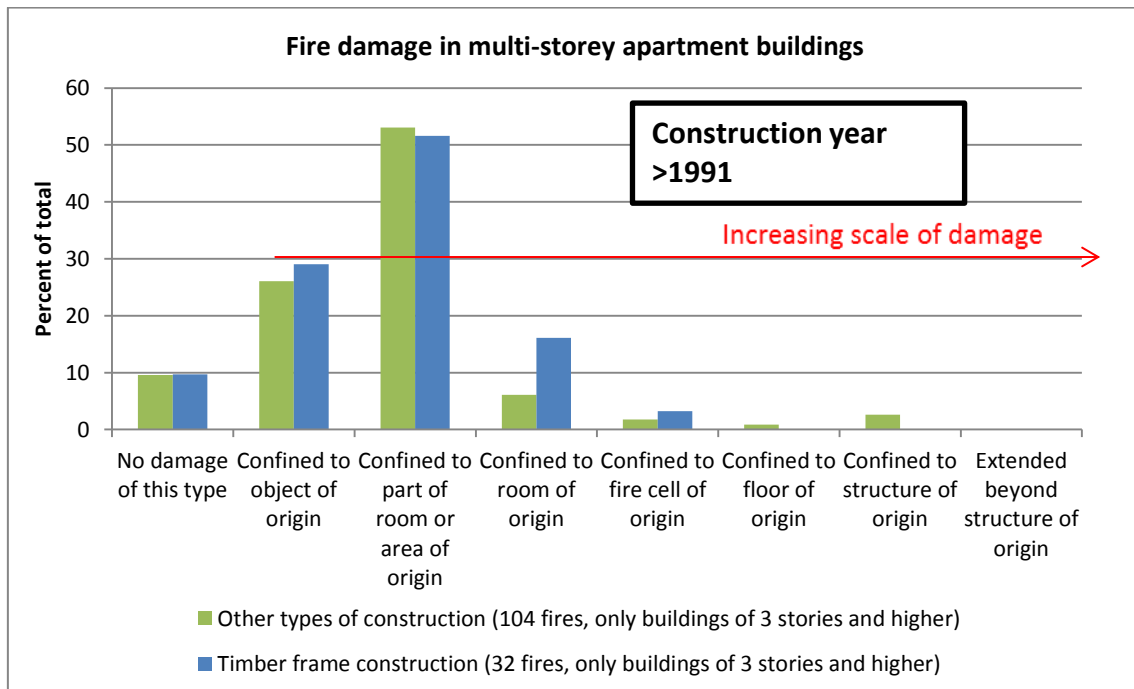


Figure 2: Fire damages after fires in modern buildings in New Zealand from 2000 to 2016, distributed in categories indicating the scale of the damage.

Figure 3 shows the distribution of water damages based on the scale of damage. From the left to the right, the scale of the damage increases, from no water damage at all to damages extended beyond the building of origin. This data includes data of fires in old buildings as well as modern buildings. The distribution of water damages seems to be relatively equal in timber frame construction and other types of buildings.

Figure 4 shows a similar graph, for modern buildings only (built after 1991). It can be noted that the spread of water damage in New Zealand was smaller in modern timber frame buildings than in other modern types of buildings. The frequency of water damages that extended beyond the fire cell of origin is lower in modern timber buildings than in other types of buildings. In buildings of timber frame construction, approximately 12% of the water damages extended beyond the fire cell of origin, while in buildings of other types of construction, 30% of the water damages extended beyond the original fire cell. According to a 2-tailed two proportion test with a significance level of 0.05, this difference is statistically significant. It can also be stated that the frequency of high water damages was lower in modern buildings of timber construction than in traditional buildings of timber construction. These statistics are related to the area of the damage, but do not provide any information about the cost of the corresponding restoration. Unfortunately, reliable data needed to compare costs of restoration of water damages in buildings with different materials has not been found.

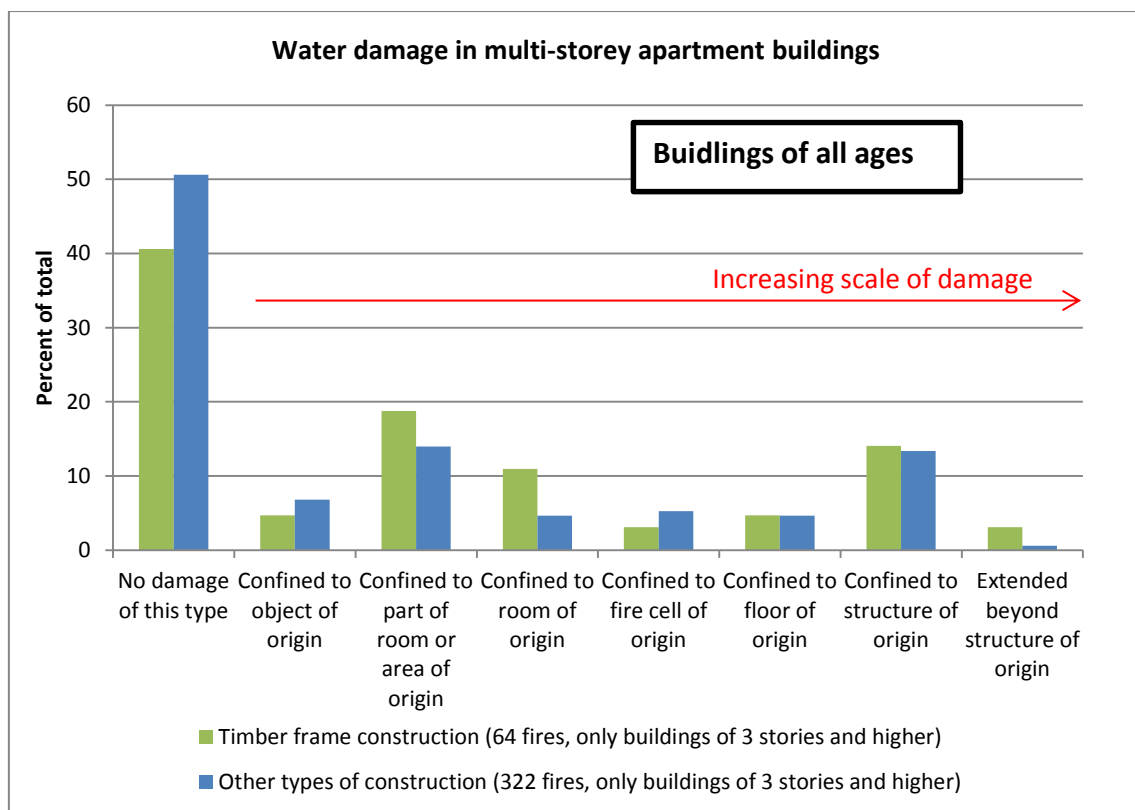


Figure 3: Water damages after fires in New Zealand from 2000 to 2016, distributed in categories indicating the scale of the damage.

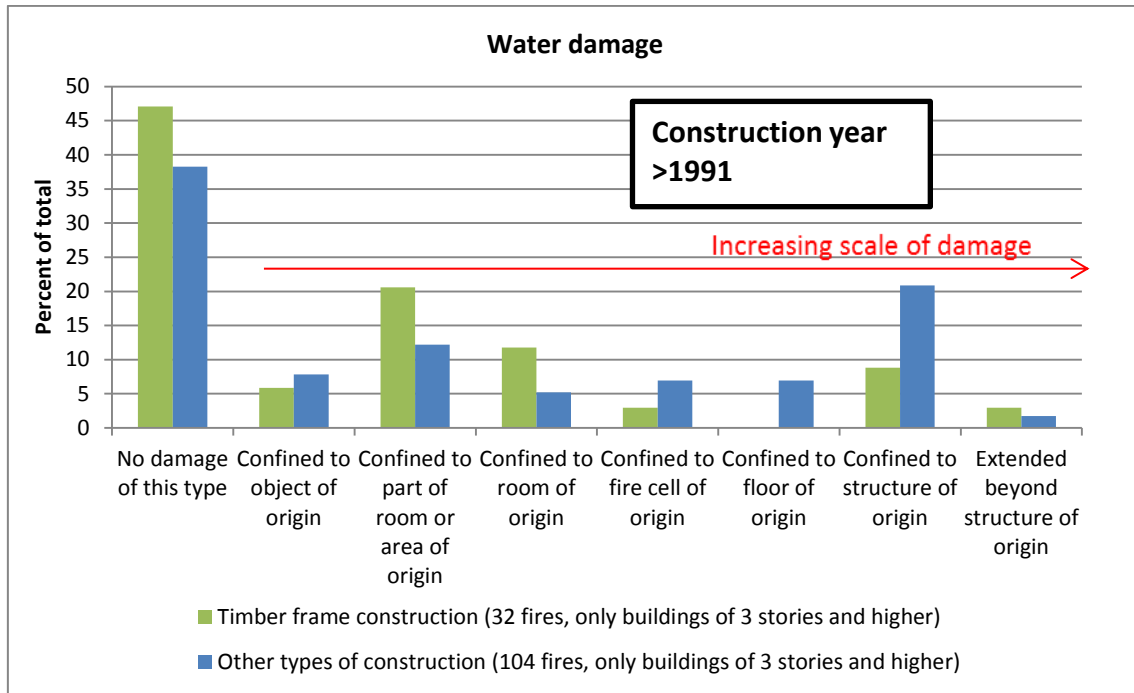


Figure 4: Water damages after fires in modern buildings in New Zealand from 2000 to 2016, distributed in categories indicating the scale of the damage.

To summarise, statistics of fires in apartment buildings of three stories or higher (excluding fires that occurred in the construction phase) from New Zealand have indicated that:

1. Buildings with timber frame structures of three stories or higher with that were constructed after 1991 did not show a higher relative frequency of fire spread beyond the fire cell of origin.
2. If older buildings are included, the relative frequency of fire spread beyond the fire compartment of origin is higher for buildings with timber as the main structural material than for other types of buildings.
3. Fires in modern timber buildings generally resulted in less spread of water damage than fires in other types of buildings.

No fire spread beyond the original fire compartment in any modern residential buildings (constructed after 1991) with timber as the main structural material of 3 stories during the years 2000 to 2016 in New Zealand. However, such high damage fires have occurred in other countries including the USA and Sweden.

3 Analysis of high-damage fires in the USA

For the study presented in this report, a selection of high damage fires is made from the database, the high damage fires includes:

- Fires that led to damages higher than 20% of the property value;

- Fires that spread to more than 2 fire compartments.

This selection of high damage fires includes 14 fires. Figure 5 indicates the main cause of financial losses according to the description of the fires. It should be noted that this data is dependent on the accuracy and completeness of the original reports owned by the NFPA and the interpretation of the researchers. One of the 14 high damage fires actually remained within one fire compartment. However, in that particular case, sprinkler activation led to extinguishment of the fire, but resulted in high water damages (38% property value loss). The fact that 13 out of the 14 identified high damage fires involve large fire spread, gives a strong indication that limiting the fire spread should be a main strategy to reduce property loss in fires. Of the 6 fires that led to high water damage, 1 was extinguished by sprinklers and 5 were extinguished by the fire brigade (Figure 6). 1 of these 5 fires led to complete loss of property value.

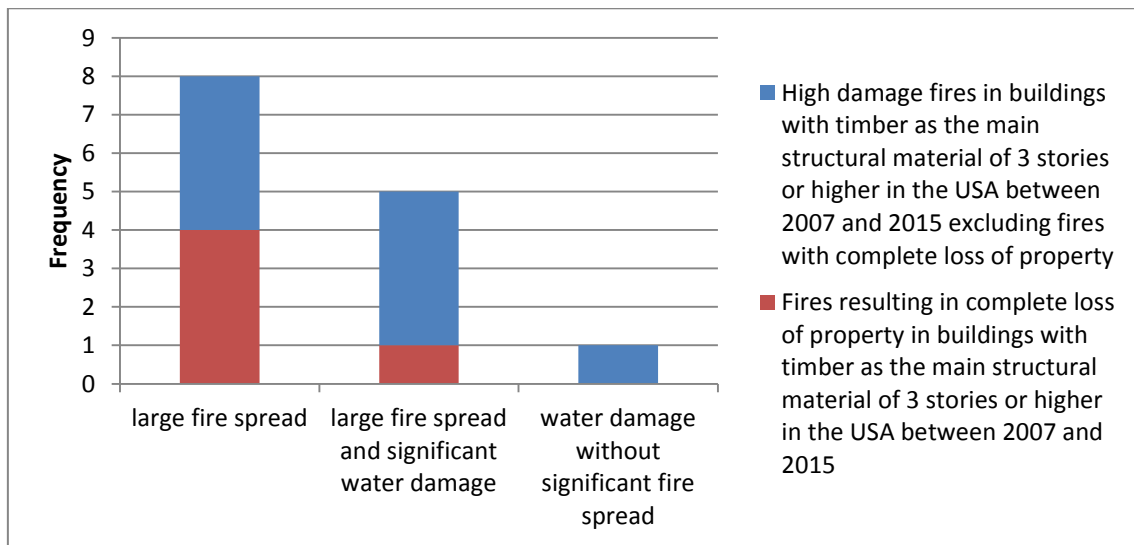


Figure 5: Main causes of high fire damages in the US and their corresponding frequency.

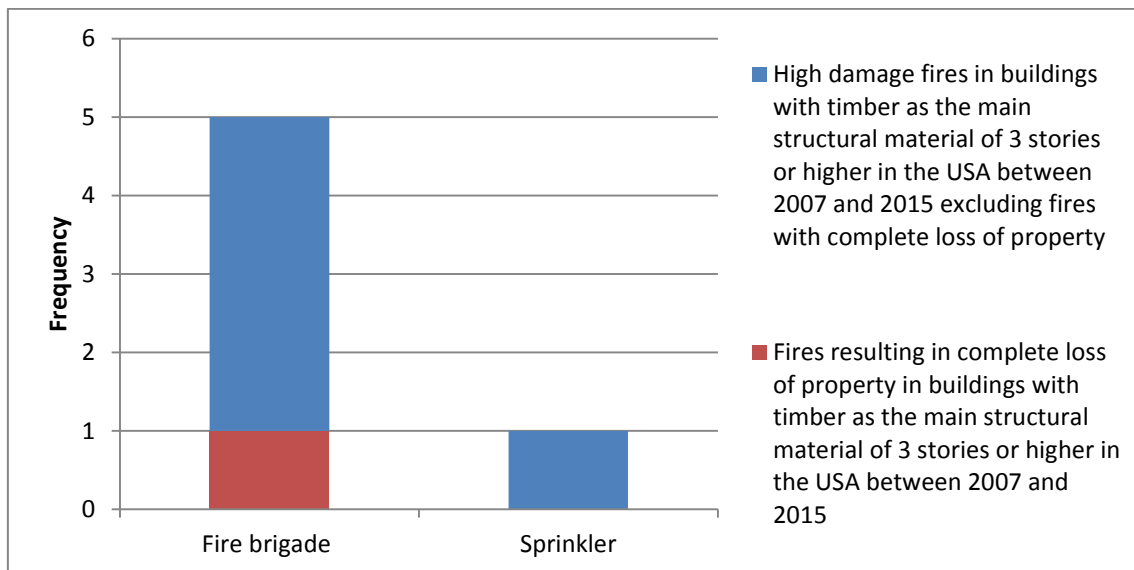


Figure 6: The method of extinguishment of fires that led to high water damages in the US

From the 13 fires that involved significant fire spread, the main modes of fire spread are categorized into:

1. Fire spread via the outside of the building involving the façade and spreading into the building;
2. Fire spread through cavities within walls and floors of the building;
3. Fire spread directly from compartment to compartment.

Figure 7 shows that the most frequent mode of significant fire spread is via the façade. In three of eight cases, the fire entered into the attic according to the reports. Additionally, it can be seen that two of the three cavity fires of this high-damage selection led to complete loss of property.

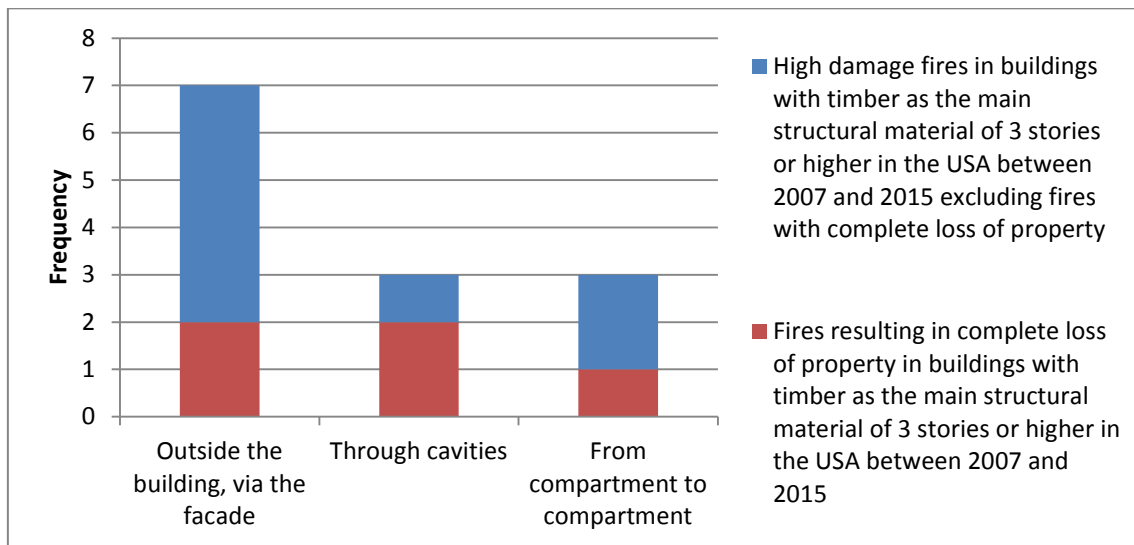


Figure 7: Main modes of fire spread and their corresponding frequency in large damage fires in the US.

As statistics from the USA indicate that large fire spread is more frequently the cause of high property loss, the following sections present strategies to limit fire spread. Strategies to limit water damage should mainly involve a change of approach to extinguish fires by the fire brigade, as the most frequent cause of high water damage is extinguishment by the fire brigade.

4 Strategy to limit fire spread

Potential fire spread routes in timber buildings (categorised in the previous section) as shown in Figure 8 are important to limit. Aspects that should be assessed during the design of buildings with timber as the main structural material are:

1. Limitation of fire spread directly from compartment to compartment:
 - a. Limitation of spread through walls, floors or ceilings;
 - b. Limitation of fire and smoke spread through connections between two wall slabs or a ceiling/floor and wall slab;
 - c. Limitation of fire and smoke spread through wall and ceiling penetrations.
2. Limitation of fire spread through cavities of the building:
 - a. Limitation of fire spread via the cavities between compartments;
 - b. Limitation of fire spread via the cavity of the façade.
3. Limitation of fire spread outside of the building:
 - a. Limitation of fire spread via the façade surface;
 - b. Limitation of fire spread through windows;
 - c. Limitation of fire spread through ventilation openings (such as ventilation openings of attics).

Guidelines on how to address these aspects are provided in Chapter 5, 6 and 7. Additionally, continuous fully developed fires should be avoided as an extended duration of the fire increases the risk of fire spread. A method to achieve this is discussed by Brandon (2018) and not elaborated further here.

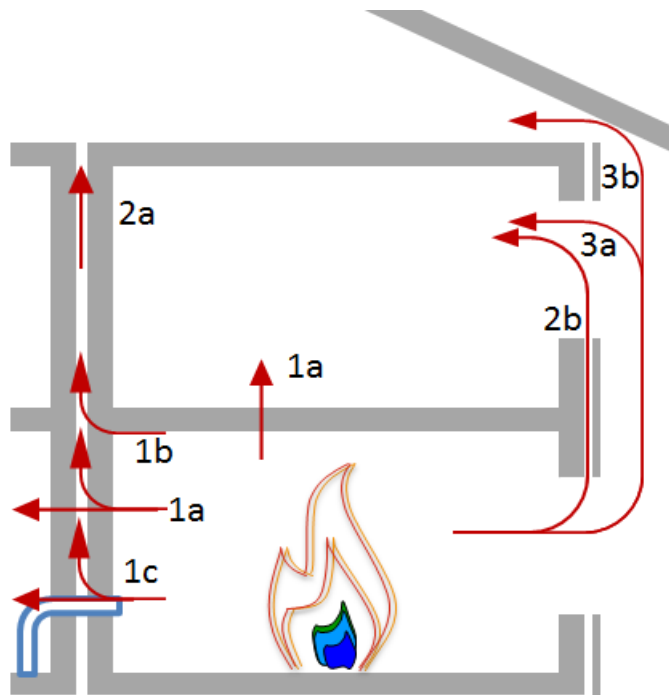


Figure 8: *Potential paths of fire and smoke spread out of the compartment considered for the building design*

5 Guidelines to limit fire spread from compartment to compartment

Fire spread directly from compartment to compartment should be avoided using compartment separating elements (such as walls, doors and ceilings) with standard fire resistance ratings required according to national regulations. In Sweden these regulations are given by Boverket.

Boverket has requirements regarding the integrity (I) and the insulation (E) of compartment separating assemblies, which is expressed in minutes of fire resistance. In addition to that there are requirements for the structural performance (R), which is also expressed in minutes of fire resistance. To indicate whether the fire resistance requirements concern integrity, insulation or structural performance of the member, fire resistance requirements are denoted by the letters R and/or E and I followed by the number of minutes of required fire resistance. A column could, for example, have a structural fire resistance requirement of R90 (90 minutes) and a compartment separating wall could have a fire resistance requirement of EI90 if the wall is not load bearing or REI90 if the wall is load bearing.

In order to demonstrate compliance with the fire resistance requirements fire resistance tests or fire resistance calculations are needed. In addition, the use of the following is recommended:

- fire resistance tested connection details between two walls and between floors and walls or other connections in compartment boundaries.
- penetrating elements that have been fire resistance tested and approved ;

In Sweden, the fire resistance of wall and floor assemblies can be either shown by fire resistance tests or be calculated using Eurocode 5 (EN1995-1-2, 2004), EKS 10 (BFS 2015:6) or the European guidelines for fire safety in timber buildings (Östman *et al.*, 2010), if the calculation rules apply. If the fire resistance of a member is obtained by calculations, the integrity of each element or layer (if required by the assumptions in the calculations) should be performed using fire resistance tested solutions. For example, if fire insulation is assumed to remain in place during the whole fire test for the calculation, the method of fastening of this insulation material must be shown to be effective using fire resistance test results. In walls that separate 2 compartments it is important that the insulation remains in place, independent of which side of the wall is exposed.

5.1 Fire insulation

Fire insulation aims to delay fire spread to adjacent compartments and often also to protect load bearing elements. Different insulation materials can have vastly different protective properties in fire. If fire resistance of floors and walls are demonstrated using fire resistance calculations according to Eurocode 5 or the European guidelines for fire safety in timber buildings, the calculated fire resistance should be conservative. If it is important that the fire insulation remains in place for a certain period (e.g. because the calculated assembly relies on this), the insulation material should be

fastened using fire-resistance-tested fastening methods that resulted in no insulation fall-off for at least that period.

If the fire resistance is demonstrated with a fire resistance test, it is important that the exact same insulation material, product and fastening method are used in the designed building, as were implemented in the fire resistance test. This fastening method could involve fasteners, but also methods to clamp the insulation in place to preventing fall-off (Figure 9).

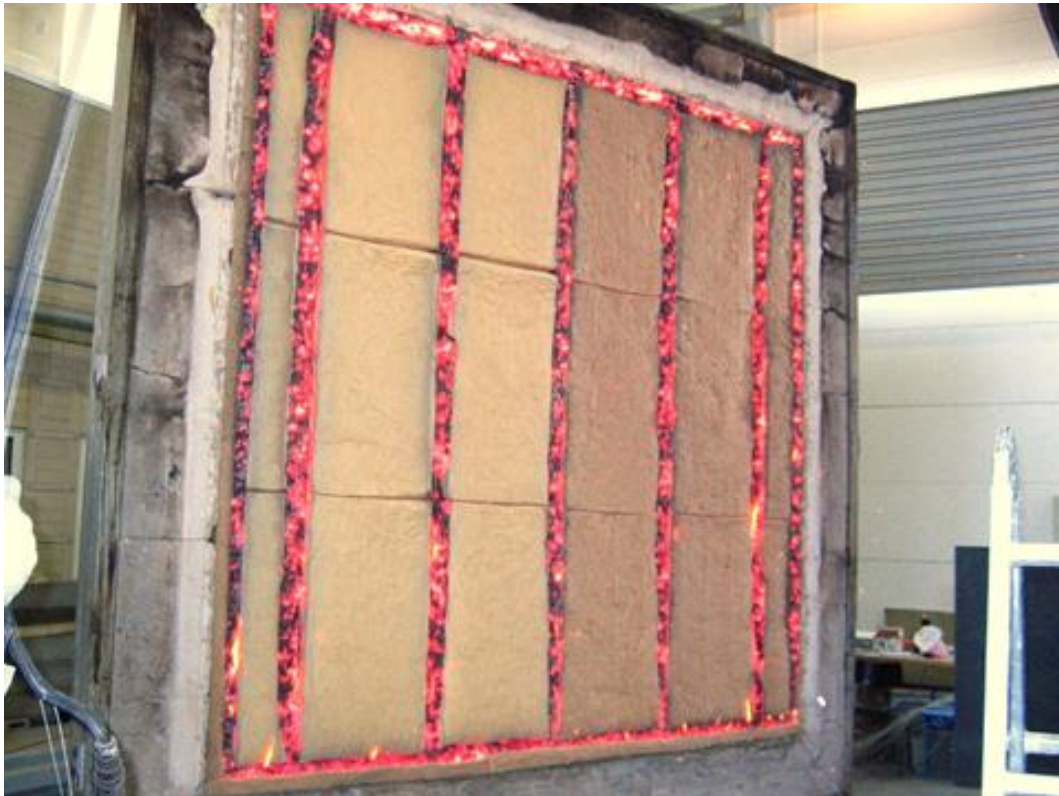


Figure 9: Stone wool fixed using over-dimensioning after 60 minutes fire test.

5.2 Gypsum board protection

Correct application of gypsum plaster boards should avoid premature involvement of protected timber in a fire. Additionally, gypsum plaster boards can be used to increase the fire performance of sensitive points, such as a connection between a wall and ceiling.

Fastening of gypsum plaster boards should be done using fasteners as described by the product manufacturer, using the same or smaller fastener distances and the same or larger penetration depth of the fasteners into the timber. In case performance based design is needed and the involvement of the protected timber would need to be prevented during the whole natural fire, the method discussed by Brandon (2018) can be implemented. If that method would be applied, the minimum fastener distance should be the smallest of: (1) 400 mm and (2) the minimum fastener distance provided

by the gypsum board manufacturer. The penetration depth of the fastener into the wood should be the largest of: (1) 15 mm and (2) the penetration depth provided by the manufacturer.

Chapter 8 gives examples in which gypsum boards are used to increase the robustness of connections between wall and floor assemblies.

5.3 Penetrations in fire rated assemblies

Fire resistance tests are generally performed on ceiling or wall assemblies without penetrations. However, in practice, many of these assemblies have full or partial penetrations for, for example: electrical switches; lamps, wires; water pipes and ventilation shafts. The fire resistance requirements should be met also with these penetrations in place.

If the following requirements are met, additional fire tests are not required:

- The protection time (EI-rating) of the penetrating element including its fasteners and sealing material should be at least similar to the protection time and the fall-off time (if relevant) of the penetrated elements (see examples A, B and C). Hereby, the protection and fall-off time of the penetrated elements should be determined directly from temperature measurements in fire resistance tests. If the protection time of the penetrated elements is not known, a conservative approach is to have the protection time of the penetrating element including its fasteners and sealing material at least equal to the total required time of fire resistance.
- If the penetrating element is attached to elements that fall-off during the required fire resistance tests, there should not be a hole left in any remaining part of the assembly after fall-off that was not present during fire resistance testing of the specific assembly (see examples D and E).
- Penetrating elements that go from one side to the other side of separating elements should be fixed on both sides of the separating element to avoid falling during fires. If the penetrating element is hollow, either entrance of flames into the hollow element should be avoided, or gas flow through the hollow element across the fire compartment's boundary should be avoided during a fire (see example F). If flames can enter the hollow penetrating elements, the use of fire resistant grids is recommended. These penetrating elements should not be in direct contact with combustible elements of the separating member and require a suitable amount of fire insulation between them. The fire insulation used for this should have the same protection time as the required time of fire resistance of the separating element (e.g. wall or floor).

In all other cases, fire resistance tests according to EN 1364 of the exact wall, floor or ceiling assembly including the penetration are required.

5.3.1 Example A, B and C:

The protection time (EI-rating) of the penetrating element including its fasteners and sealing material should be at least similar to the protection time and the fall-off time (if

relevant) of the penetrated elements. Example A: A fire tested timber frame ceiling, with a fire resistance rating of REI60 (Figure 10, left) has one layer of fire protective cladding at the bottom (exposed) side. The ceiling is applied with fire rated and fire sealed downlights. The fall-off time and the protection time of the fire protective cladding are determined directly from tests in accordance with EN 1364 and are exceeded by the fire resistance rating of the downlights and sealant (see Figure 10, right). In this situation the fire resistance is not compromised with the implemented downlights. If the protection time and fall-off time of are not known, a fire resistance of the downlight that is equal to the required fire resistance of the whole assembly is a conservative solution (see Figure 11, Example B). Alternatively, a non-fire-rated downlight can be implemented if fire protective boards with at least the same fire resistive properties as the penetrated parts, protect the internal parts of the assembly. The integrity of the added protective boards should be warranted for at least the fall-off time of the boards, or, when this is unknown, for the duration of required fire resistance of the assembly (see Figure 12, Example C).

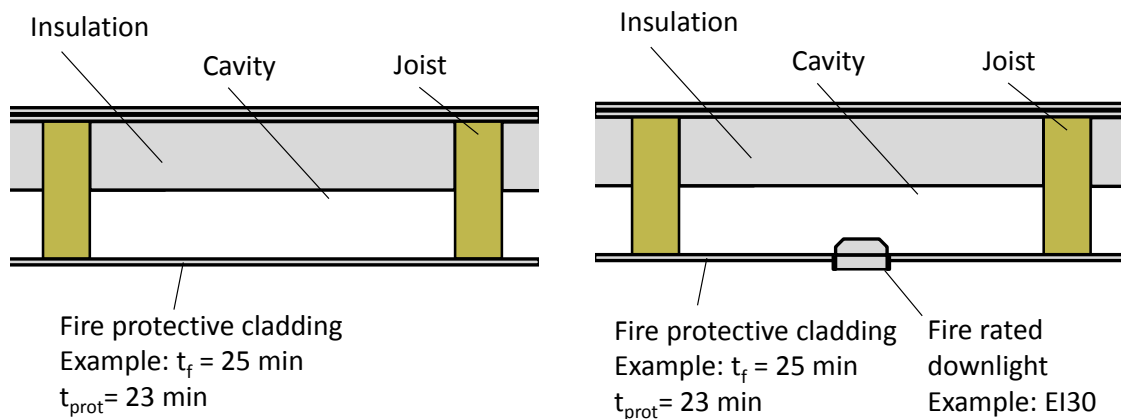


Figure 10: Example A - cross section of a 60minutes fire resistant ceiling (left) and a suitable application of a fire resistant lamp in this ceiling (right)

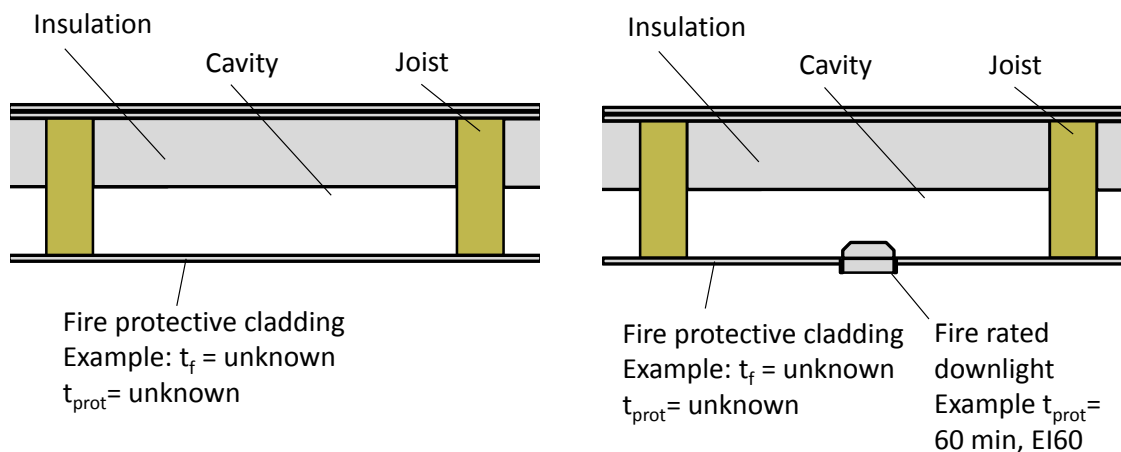


Figure 11: Example B - cross section of a 60minutes fire resistant ceiling (left) and a suitable application of a fire resistant lamp in this ceiling (right)

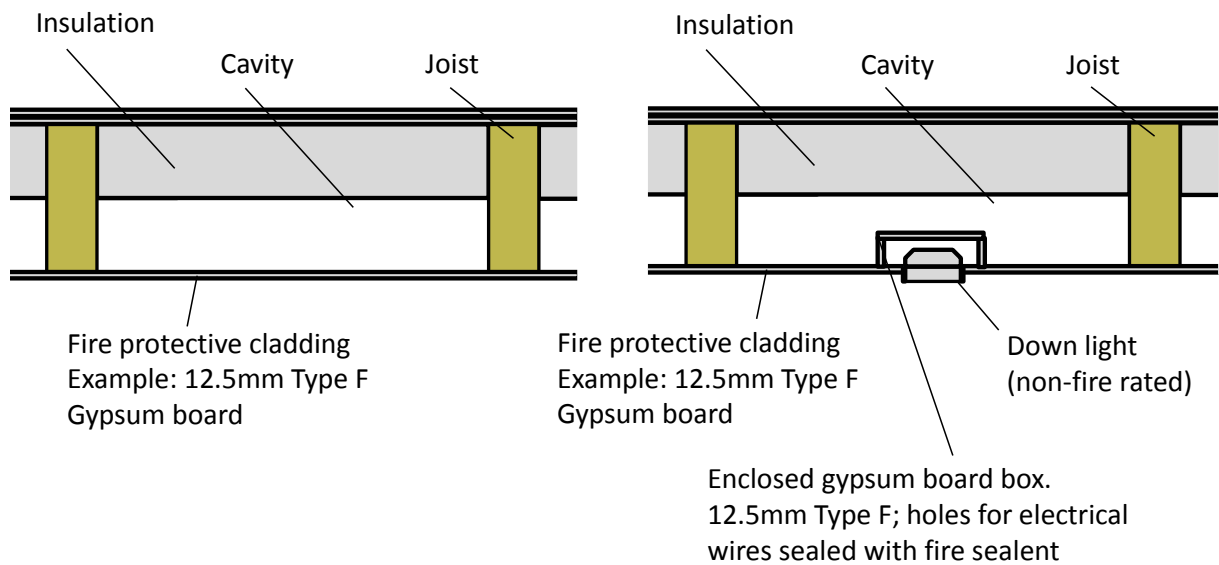


Figure 12: Example C - cross section of a 60minutes fire resistant ceiling (left) and a suitable application of a non-fire-resistant lamp in this ceiling (right)

5.3.2 Example D and E:

Within fire compartments there may be partitioning walls, which do not have fire resistance requirements. It is, however, important that the fire resistance of adjacent assemblies is not compromised by the failure of the non-fire-rated partitioning wall. Therefore, it is important that the fire protective cladding and insulation of fire resistive assemblies are not penetrated by non-fire rated partitioning walls, such as shown in Figure 13 and Figure 14. The assemblies on the left side of these figures are implemented correctly. The fire resistance of the assemblies on the right side is compromised if the wall fails earlier in a fire, than the base layer of fire protective board.

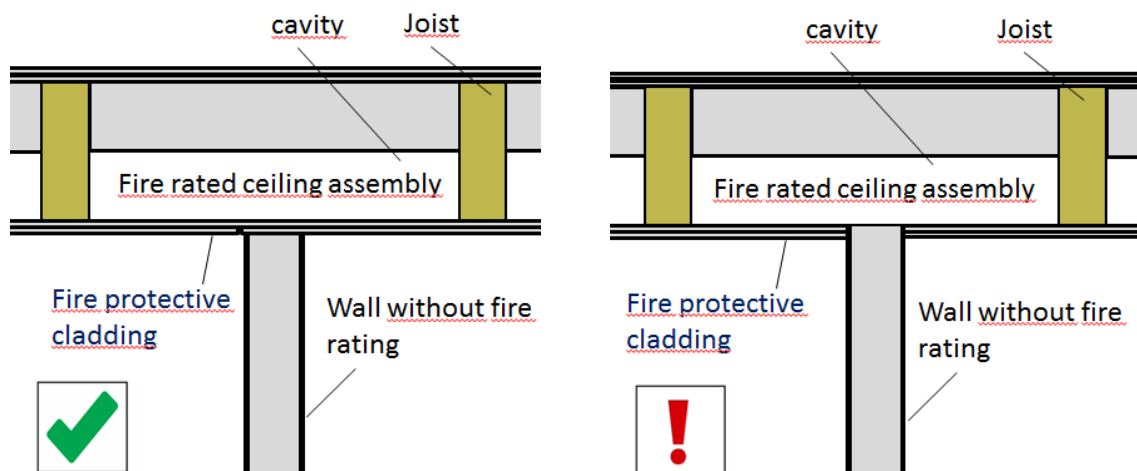


Figure 13: Example D - cross section of a 60minutes fire resistant ceiling (left) and a suitable application of a fire resistant lamp in this ceiling (right)

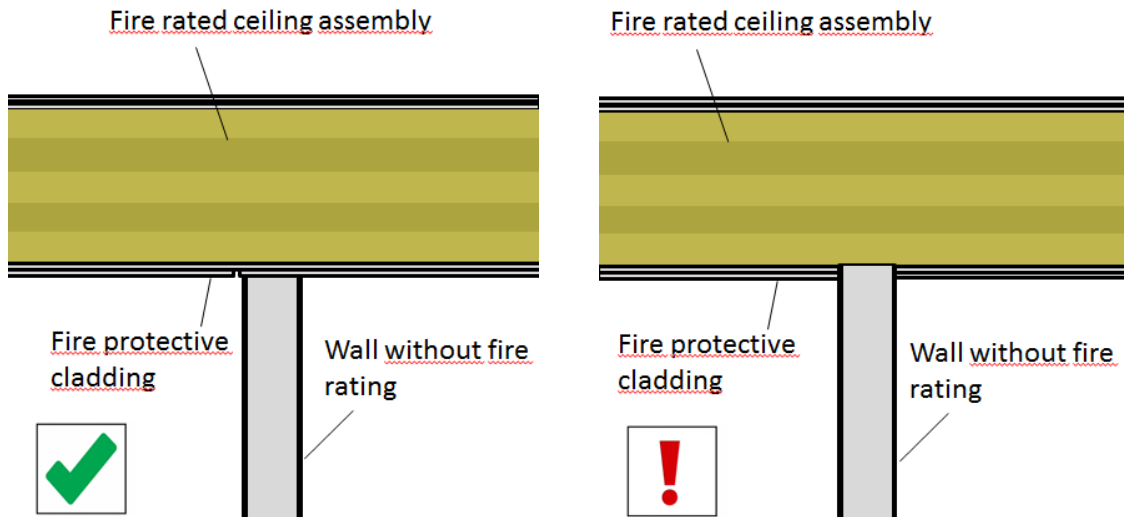


Figure 14: Example E - cross section of a 60minutes fire resistant ceiling (left) and a suitable application of a fire resistant lamp in this ceiling (right)

5.3.3 Example F

Ventilation ducts generally cross from fire compartment to fire compartment and have been the cause of fire spread out of the compartment in multiple building fires. If the fire can enter the ventilation duct, it is important to block the flames from spreading through the duct. This can be done directly at the ventilation openings, or at the compartment boundaries. Additionally, the duct should be insulated to prevent possible ignition of combustibles near the duct in a neighbouring compartment (Figure 15). A tight fit of the ventilation ducts into the wall opening is required.

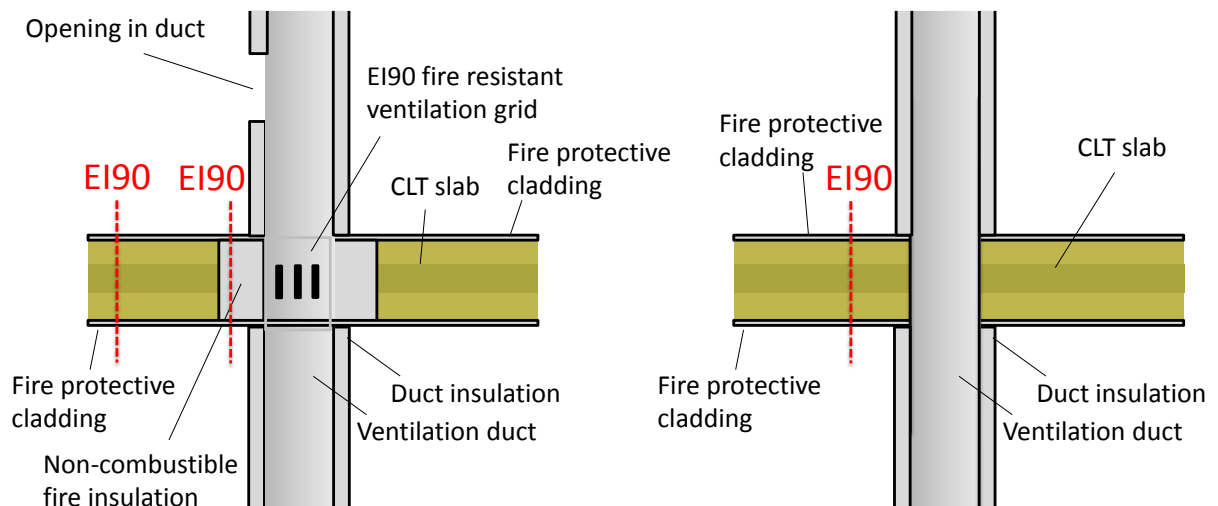


Figure 15: Example F - cross section of a 90minutes fire resistant wall with a ventilation duct with possibilities for flames to enter the duct (left) and without possibilities for flames to enter the ducts (right).

5.4 Connections between fire rated wall or floor assemblies.

Previous compartment fire tests (Medina Hevia, 2014; McGregor 2014; Kampmeier; 2009) have shown that connections between CLT slabs can be sensitive to fire and smoke spread, as can be seen in Figure 15. Connections are recommended to be sealed using methods, with for example intumescent strips or fire retardant sealant, that have been proven to be effective in fire resistance tests according to EN 1364. There are not enough fire resistance tests available to make conservative general guidelines regarding these connections at this stage.



Figure 16: Fire spread through a CLT splice connection, taken from McGregor (2014).

The fire resistance of connections between fire resistive wall or floor slabs can be improved using robust arrangements of gypsum boards or other fire protective boards as done in the case study of Chapter 8.

6 Guidelines for fire stops

In this project fire stops are divided into two different categories with different functions:

- a) Fire stops in cavities with combustible materials between compartment and between buildings, aiming to stop slowly spreading and long lasting smouldering fires (see Figure 17, type a).
- b) Fire stops in cavities in the façade, aiming to stop fire plumes from traveling through the cavities (see Figure 17, type b).

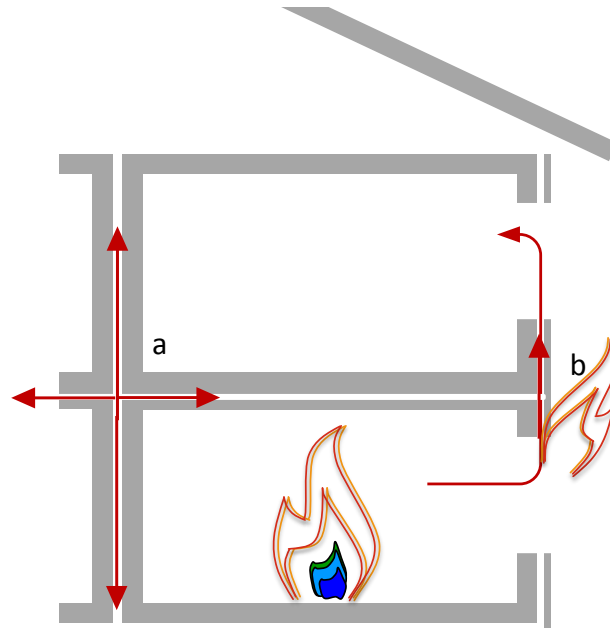


Figure 17: Potential paths of fire spread through cavities

Cavity fires of *type a* can occur in cavities with combustible materials and can involve slow fire spread. The smouldering combustion in these cavities needs significantly less oxygen than flaming combustion and may not extinguish without interference of the fire service. Roughly a fourth of the large damage fires in USA analysed in chapter 3, involved cavity fires of *type a* as the main mode of fire spread. There was also one fire in Sweden in Luleå in 2013, in which a cavity fire of *type a* was the main mode of fire spread (Östman and Stehn, 2014; Figure 18). In a recent project funded by Brandforsk, a new testing method was developed (Just and Brandon, 2016; Brandon *et al.*, 2016) to assess the suitability of fire stops to limit fire spread in cavity fires of *type a*. Guidelines that resulted from that study are discussed further here.



Figure 18: Infrared camera picture indicating a downwards fire spread through cavities²

Cavities fires of *type b* can occur regardless of the material in the cavity. A fire plume coming out of a window or a door opening could cause a fast spreading cavity fire, that travels up to 8 m/min and has fire plumes that are 5 to 10 times higher than fire plumes outside of the building (Jensen, 2013). At the same time, most façade cavities are required to be ventilated in order to prevent moisture damage. Fire stops in cavities of the façade should be used to prevent fast fire spread. Tests according to EN 1364-6 (2016), can be performed to determine the fire resistance of fire stops within the cavity.

6.1 Materials

Fire stops limiting fire spread of type a, should be materials that can be tightly placed within a cavity. The material is preferably non-combustible and made of a soft, compressible, low density insulation material. A compressed density of 50 kg/m³ after installation is recommended for mineral wools, such as glass wool, stone wool and high temperature extruded mineral wool. The materials should have no plastic covering as it can cause small air channels, which increase the amount of hot air flowing into the cavity. Furthermore, it may melt and form droplets.

6.2 Dimensions

There are several installation methods recommended for fire stops. As shown in Figure 19, potential placement of the fire stops could be single, double, or U-shaped. In case mineral wools are used as fire stops, the minimum dimension is recommended to be chosen, so that its compressed density after installation is 50kg/m³ or higher. Additionally, its height after installation, h , should be at least equal or larger than the maximum of 75mm and $1.5t$, where t is the cavity width. For a U-shape placement of the fire stop, the cross-section should be at least $t \times 3t$. Additionally, the minimum density of the uncompressed material should be 25 kg/m³.

In case wood is used as a fire stop, the minimum height of a fire stop should be calculated using a one-dimensional charring rate in accordance with EN1995-1-2:2004. The remaining uncharred height should be 25mm after the required insulation time (for example 60 minutes). It should also be ensured that the fasteners maintain their function for the required insulation time in a standard fire. The wooden fire stop should be placed tight against both opposing surfaces of the cavity and air channels across or along the wood should be avoided.

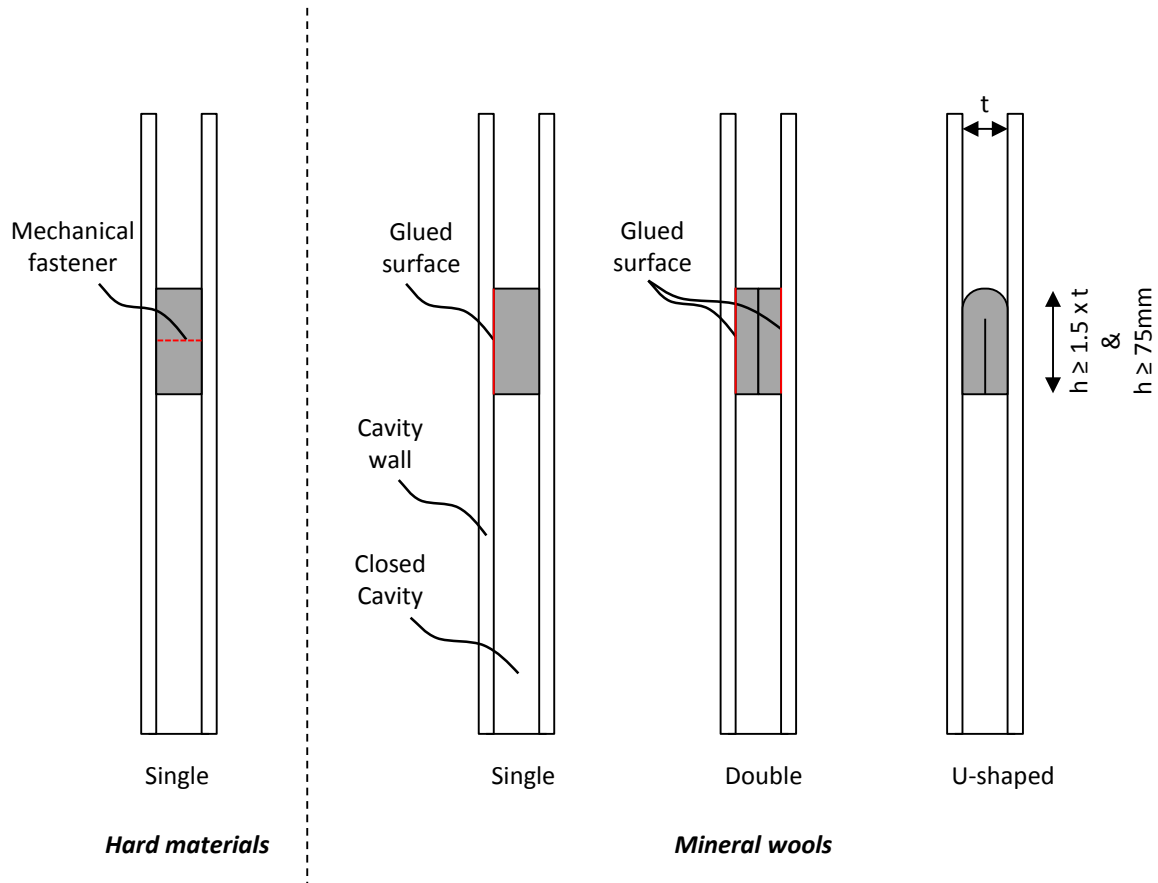


Figure 19: Cross-sections of single double and U-shaped fire stops

6.3 Design

The design of fire stops should aim to (1) avoid falling of the cavity and (2) avoid air channels across and along the fire stops. Falling of the specimens can be avoided by appropriate fixation methods and, if possible, by robust design. Using robust design, falling of the barrier can be avoided, even if the primary fixation method (using glue, fasteners or by clamping) fails. An example of a robust solution that prevents falling of highly exposed fire stops is shown in Figure 20.

Example of robust design of fire stops around a wall opening

A fire leaving a compartment through an opening will expose the upper side of the opening significantly more severely, than the lower side of the opening. Therefore, there is an increased risk that the fire stop above the opening falls, which would allow the fire to easily access the cavity. By letting highly exposed, horizontally positioned, fire stops within walls rest on the vertically positioned elements (Figure 20), the risk of falling becomes small.

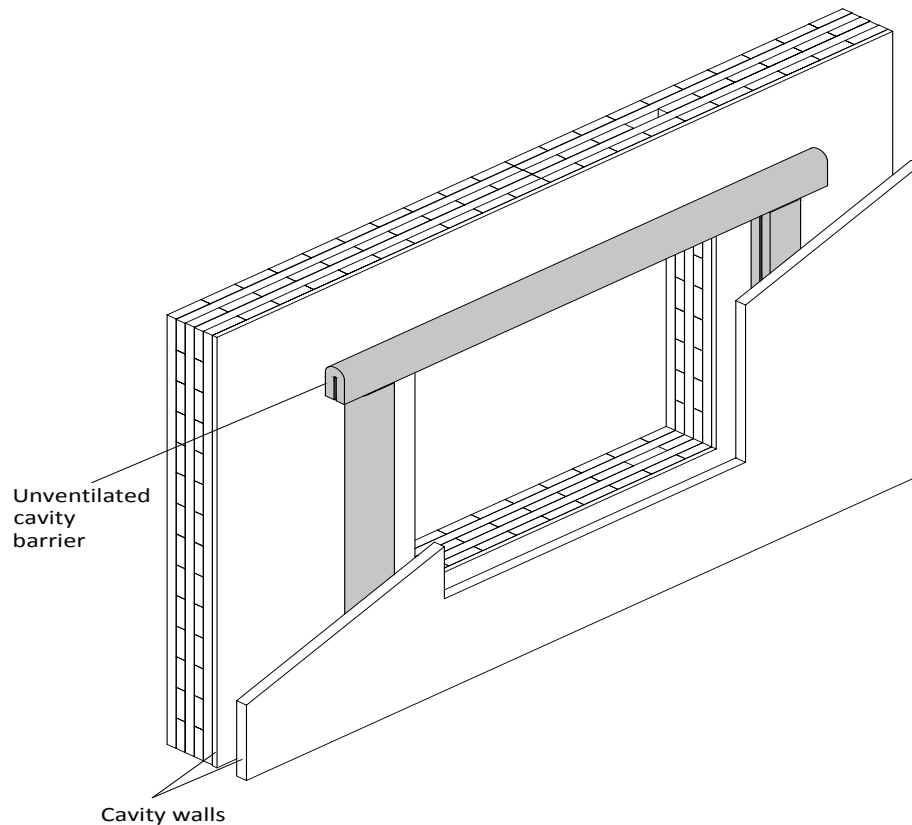


Figure 20: Prevention from falling of fire stop by robust design

Undesired air channels can be avoided by design. Such undesired air channels could occur in corners and bends of the fire stop material, as shown in Figure 21. Solutions can be obtained by designing separate fire stops which are connected, instead of using bended fire stop in corners.

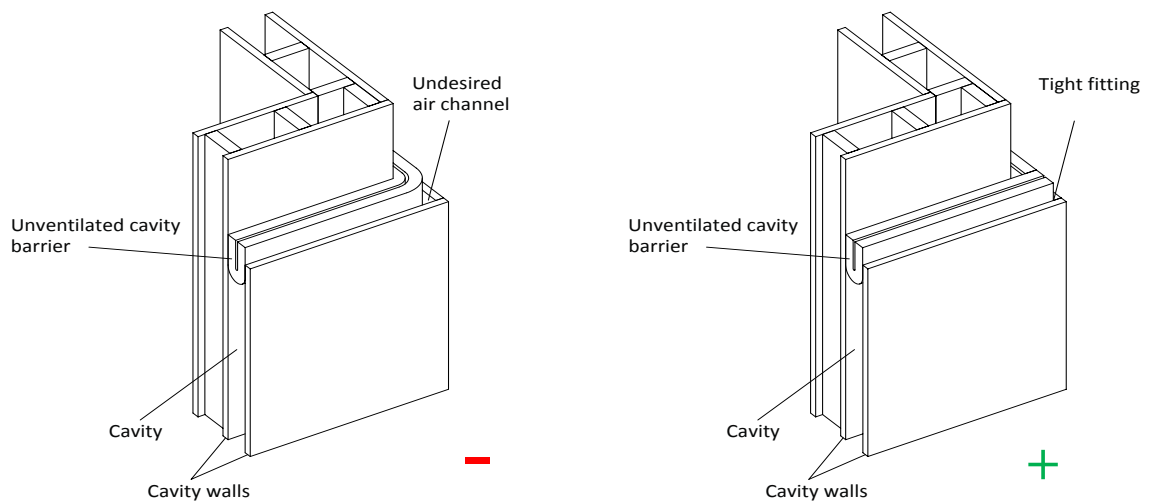


Figure 21: Possible risk for undesired air channel in the outer corner

6.4 Installation

Third party control is recommended for the installation of fire stops in cavities with combustible materials.

A schematic drawing concerning the installation of single, double or U-shaped placed fire stops is shown in Figure 22. The single and double placement of fire stops is especially applicable for cavities between modules of modular buildings. In this case the fire stops should be fixed to the cavity wall before the cavity is closed. Gluing of the cavity with high temperature resistant adhesives is recommended. For fire stops with a double placement, misalignment is allowed as long as the height of the contact area between the fire stops is equal or higher than the maximum of 75mm and $1.5 \times t$ (see Figure 23).

The U-shape placement should be done using an installation board, as shown in Figure 22 and Figure 24. The intended position should be ensured using this installation board, which is especially relevant at the locations of joints. The resistance of the board should be used to indicate whether the fire stop is installed firmly.

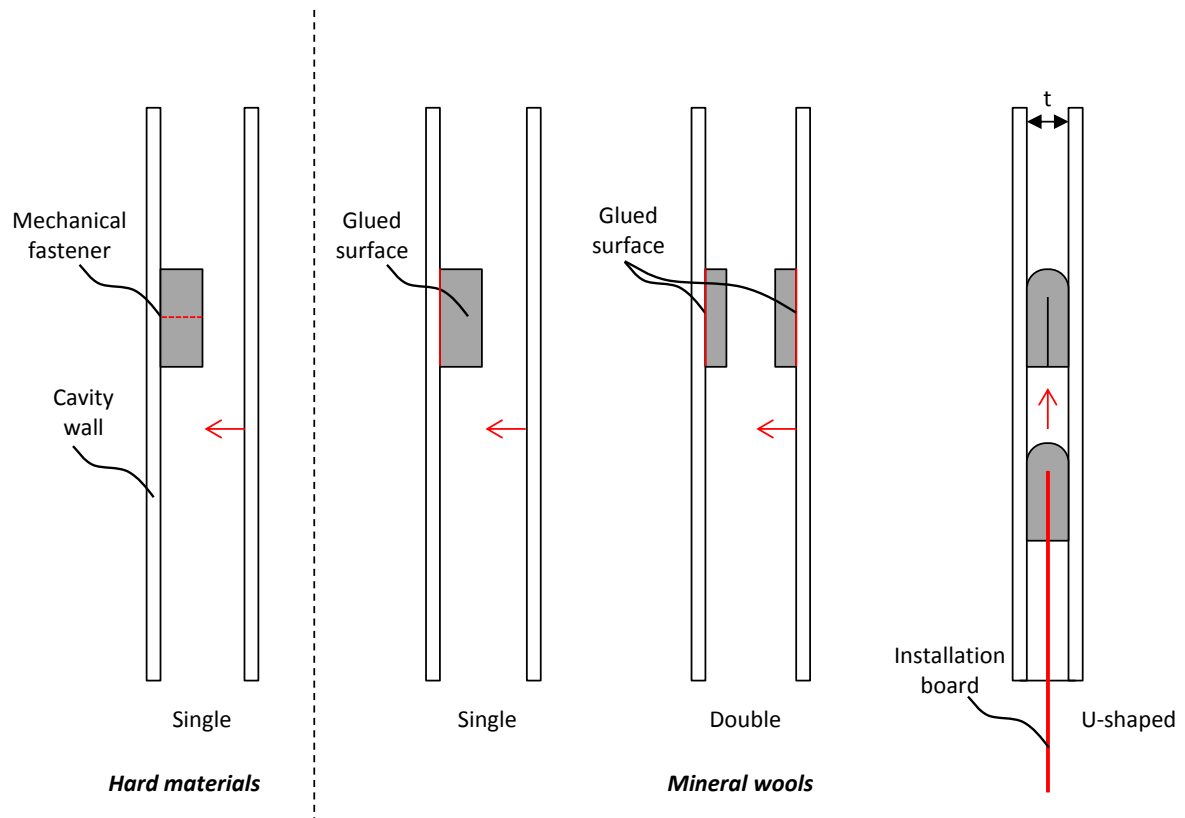


Figure 22: Schematic drawing of installation (red arrows indicate movement of assembly parts)

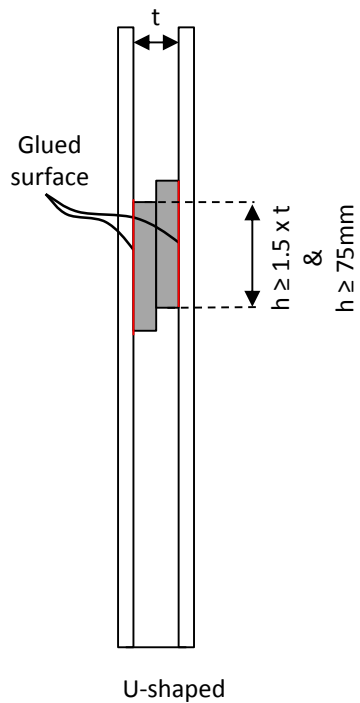


Figure 23: Allowable geometrical misalignment



Figure 24: Sliding fire stop into the cavity for a U-shaped placement

Joints between fire stops should be made, so that air channels in the joint are avoided. Using fire stops with a U-shaped placement could lead to undesired air channels in joints, as shown in Figure 25. Therefore, in-line and butt-joints are recommended for fire stops with a U-shaped placement. However, an overlapped joint, as shown on the left hand side of Figure 25, can be applied if (1) the length of the overlap is at least equal the height, h , of the fire stop and (2) the cavity is made of mineral wool without plastic covering. It must be ensured that both fire stops in one joint are placed tightly against each other.

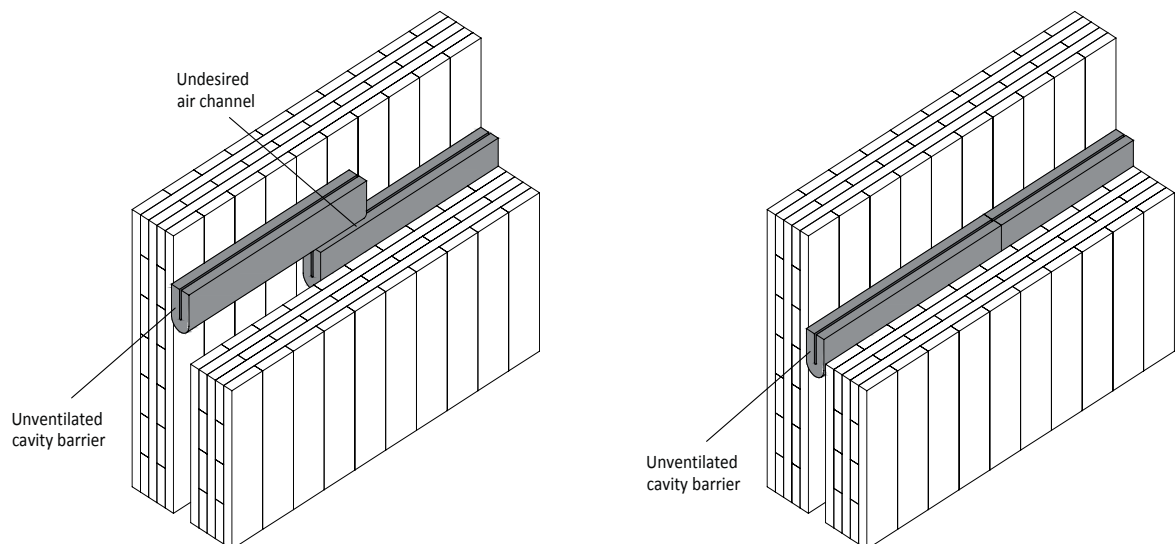


Figure 25: Possible risk for undesired air channel with overlapped joint

7 Guidelines for fire spread along facades and from facades into the building

Seven out of the thirteen large fires in the USA analysed in Chapter 3 involved fire spread outside of the building as the main mode of fire spread. Therefore, it is important to limit the fire spread along facades and from the facades into the building. Important aspects to limit fire spread along the façade and fire spread into the building are discussed below.

It should be noted that facade fires have led to large fire damages in buildings of different structural materials. Therefore, the guidelines are also applicable to buildings with other structural materials.

7.1 Fire rated windows

Frangi and Fontana (2005) showed in a test series that fire can spread relatively quickly during flashover from one compartment to a compartment above it through windows that are not fire rated. In that study the window in the upper floor broke 7,5 minutes after ignition in the worst case. This time is significantly shorter than the time allowed for the fire to spread through most floors. Therefore, the use of fire rated windows is recommended for all tall buildings (class BR1 and BRo buildings in Sweden).

7.2 Location of ventilation openings and the use of fire rated ventilation grids

Approximately one quarter of the large fires in the USA analysed in chapter 3 involved fire spread via the façade or balcony to the attic, through the ventilation openings.

Regarding ventilation openings, two important aspects need to be addressed during the design process of the building:

- The location of ventilation openings
- The fire resistant design of the ventilation openings

Ventilation openings for attics are commonly positioned at the façade at the eave (locations 1 and 2 in Figure 26). Ventilation openings placed above the window (location 1 in Figure 26) have been the access for fire spread to the attic in multiple building fires. A ventilation opening at location 2 instead of location 1 in Figure 26 reduces the risk of fire spread to the attic. However, dependent of the design of the roof, the fire plume may travel horizontally under the eave and potentially reach the ventilation opening at location 2. Therefore, it is recommended to apply fire stopping solutions in attic vents under the eave or to ventilate through other means such as mechanical ventilation using an air supply from other locations.

Ventilation openings for compartments are often positioned under windows (location A in Figure 26). However, in case of a flashover fire in the apartment below this ventilation opening, the fire plume may reach into this ventilation opening, increasing the risk of fire spread to multiple fire compartments. This risk is significantly smaller if the ventilation opening is above the window (location B in Figure 26). The risk is significantly more reduced if the ventilation openings are not positioned above windows or balconies or other potential sources of large fire plumes (location C in Figure 26).

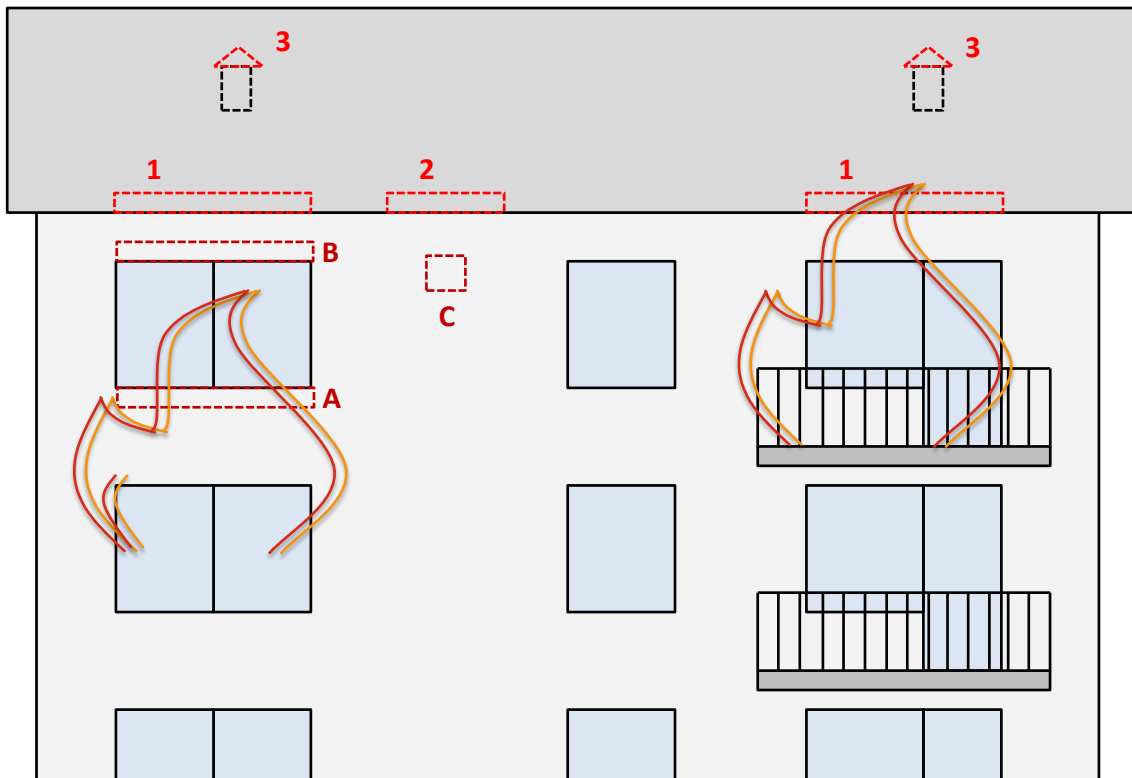


Figure 26: Common locations of ventilation openings for attics and other compartments

Fire resistant ventilation grids are recommended to prevent fire spread into or out from the building. These ventilation grids could for example contain intumescent material that expands, insulates and limits airflow into and out from the building during fires.

7.3 Façade design

In Sweden, façades should be in accordance with Swedish regulations by Boverket (BBR). For multi-storey buildings (BR1), the following is required:

- the separating function of walls between fire compartments is maintained and not compromised by the façade
- the fire spread within the outer wall is restricted
- the risk for fire spread along the facades surface is restricted

- the risk for casualties as a result of falling parts of the façade or outer walls is limited

As mentioned on Boverket's website, in practice this means that facades should be made with non-combustible materials of class A2-s1,d0, or that the façade should be approved using façade fire test *SP-Fire 105*. An example of a strategy to limit fire spread via the façade is discussed in section 8.2.5. A common, approach to limit fire spread on timber facades is the use of impregnated timber. However, it should be noted that the effectiveness of most fire retardant impregnations in wooden facades reduces significantly due to weathering within a few years. Therefore, only the use of fire retardant impregnations that are shown to be effective after years of natural weathering, are recommended.

8 Case study

An ongoing study led by RISE and Tallinn University of Technology is aiming to assess state of the art solutions for limitation of fire spread and for achieving decaying fires. The study comprised a fire test of a two-floor building with CLT as the structural material. The ignited compartment had two exposed CLT walls in order to meet architectural requests and had untreated wooden panels (without impregnation) as façade material.

The fire test was performed at the Estonian Academy of Security Sciences in Estonia and involved the following partners and contributors:

RKAS – Estonian Real estate Development
 Peetri Puit
 Estonian Academy of Defence (SKA)
 Swedish Wood
 Formas
 Brandforsk
 Tignum
 TU Munich
 TU Braunschweig
 Aru Grupp AS
 Paroc
 Enerest OÜ
 Tefire OÜ
 Genoke Raitwood

This report summarizes only results that are relevant for the topic of this report. Analysis of the data is ongoing.

8.1 Aims

The experiment served to evaluate a state-of-the-art design strategy to limit fire spread.

For the design of the building, technical details with the following aims were implemented:

Limitation of fire and smoke spread with the emphasis on:

- a. Limitation of spread through the wall or ceiling
- b. Limitation of fire and smoke spread through connections between CLT slabs
- c. Limitation of fire and smoke spread through wall and ceiling penetrations
- d. Limitation of fire spread via the cavity of the façade
- e. Limitation of fire spread via the façade surface.

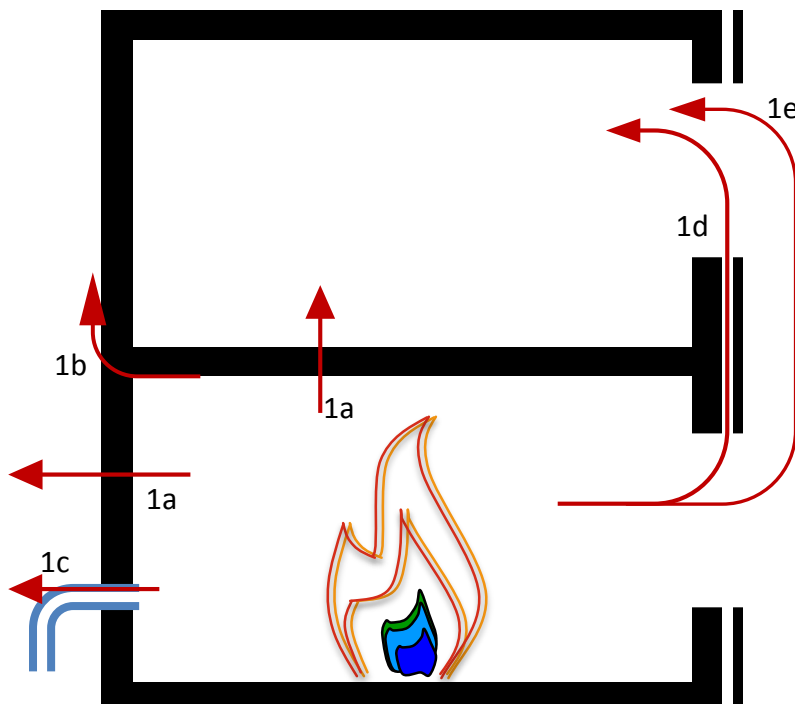


Figure 27: Potential paths of fire and smoke spread out of the compartment considered for the building design

This study assesses fire and smoke spread in a challenging scenario that meets common practical and architectural requirements, such as having combustible façade materials and exposed timber inside the fire compartment.

- 43% of the walls and ceiling comprised of unprotected CLT (2 walls and a fire door)
- Timber façade panels without impregnation
- Combustible PIR insulation in one of the facades (the other façade had stone wool insulation, for comparisons)

A very severe fire scenario is chosen, which involved:

- 600 MJ/m² fuel load density (office furniture, Figure 28)
- No sprinkler activation
- No fire service interference for at least two hours

It should be noted that the absence of fire service interference within two hours is extremely unlikely in most countries of Europe.

The interior dimensions of the compartments on both floors were 4.5m x 3.5m x 2.5m (depth x width x height). Both compartments had two windows of 1.5 x 1.5m. The windows on the lower floor were intentionally broken 20 minutes after ignition, to allow flashover to occur.



Figure 28: Interior of compartment before the fire test

As mentioned by Brandon (2018), in order to achieve decaying fires, the involvement of exposed CLT should be avoided. To avoid the involvement of the protected CLT in the fire, 2 layers of 15mm type-F gypsum board are placed on the two shortest of the four walls. The ceiling had a conservative number of three layers of 15mm type-F gypsum boards. The gypsum boards were positioned so that the joints between gypsum boards of different layers were not aligned (Figure 29). The screw distance was approximately 300 mm in both directions for every board of every layer and the length of the screws were chosen so that the tip of the screw reached at least 20 mm into the CLT.

After the test, an assessment was made of how many gypsum boards were needed to protect the CLT for the entire duration of the fire. *Note: the exposed layer showed only local failure at the top of a wall. The second layer and the base layer were undamaged. No other fall-off of gypsum was observed.*

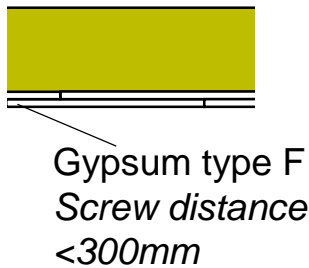


Figure 29: Gypsum board layers positioned so that joints are not aligned

8.2 Strategies to limit fire spread.

Techniques and strategies implemented to limit fire spread are discussed below.

8.2.1 Limiting fire spread through the floors or walls

The fire spread through floors and walls is generally assessed in fire resistance tests. However, this assessment is only done for standardized exposure in accordance with EN 1363-1 (2012) and does not provide information about fire spread in natural compartment fires. Fire spread through CLT for this project is assessed using an estimated char depth according to Brandon (2016).

In many countries, the doors in fire compartment boundaries are allowed to have a fire resistance lower than walls and ceilings. In this experiment a 30 minutes fire resistant door was implemented (EI30).

8.2.2 Limiting fire and smoke spread through connections between CLT slabs

For the test all connections had a 1.5 x 20 mm intumescent tape implemented in the connection to avoid fire and smoke spread (Figure 30). The gypsum boards under the ceiling were positioned tightly against the exposed walls (Figure 30, left). At the gypsum protected walls, the ceiling boards were laid on top of the wall boards, which can delay fall-off of the ceiling board. The following gypsum layers were positioned so that outflowing gases need to change direction multiple times to reach the connection.

Connection configurations in which the ceiling is positioned on top of a wall (see, Figure 30, left) and of connections in which the ceiling is hanging besides a continuous wall (see, Figure 30, right) were, both, tested. The largest gap measured between a CLT wall and the CLT ceiling panel was 14 mm (Figure 31).

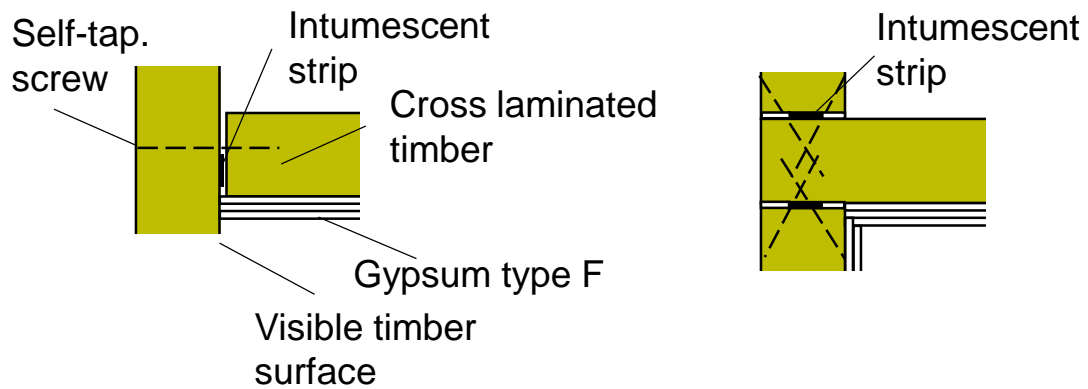


Figure 30: Implemented connections between floors and walls



Figure 31: maximum gap measured (14mm) in between wall and floor slab

1.5 x 20 mm intumescent tape was also applied in connections between two CLT elements in the same plane (see Figure 32). This connection was made in the exposed walls and in the floor and ceiling. All connections used large self-tapping screws.

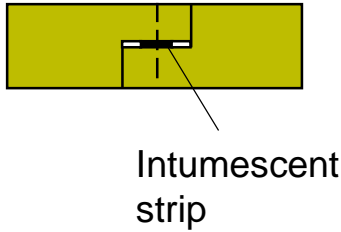


Figure 32: Connection of two slabs within the same plane (cross-section of the exposed wall)

8.2.3 Limiting fire and smoke spread through wall and ceiling penetrations

Several small wall and ceiling penetrations and one larger penetration for a ventilation shaft were implemented. The ventilation shaft had a grid with intumescent strips that expand at elevated temperatures to stop the fire from spreading. The shaft was partially protected by stone wool insulation. The ventilation grid was positioned in a hole through stone wool insulation with the same thickness as the wall (see Figure 33). The other small penetrations were for cables and tubes. These were sealed using fire caulk, rated for 60 minutes fire resistance.

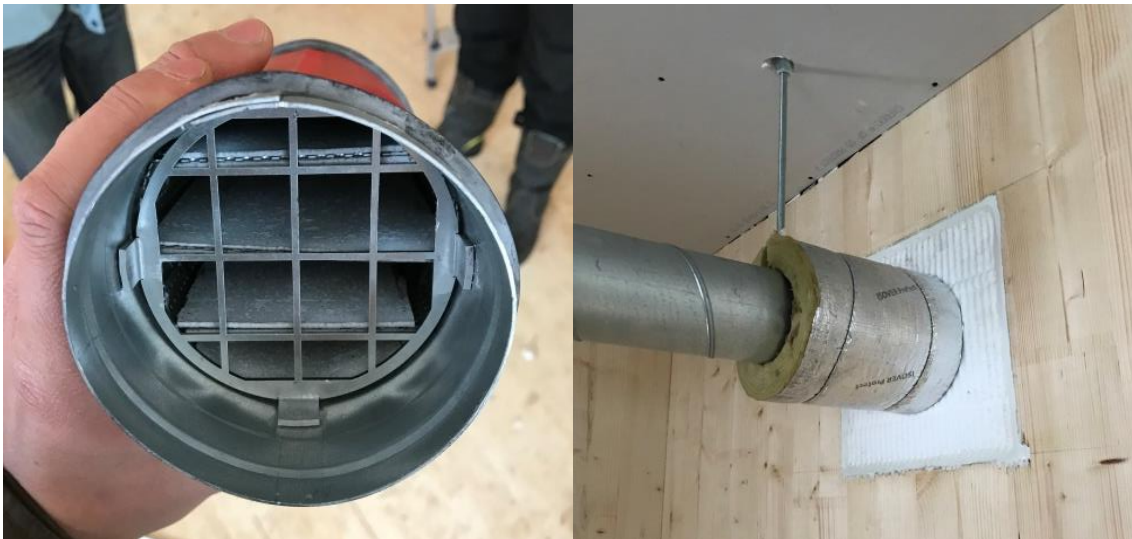


Figure 33: Fire resistive ventilation grid (left) installed in an exposed CLT wall (right).

8.2.4 Limiting fire spread through the cavity in the façade

Fire spread through façades can lead to significant risk of lives and property damage, as seen recently in the fire of the Grenfell tower in London. Fire spread within cavities can be significantly faster than fire spread through the outside of the façade. Additionally, when there is a smouldering fire within a cavity with combustible materials, the fire may spread slowly for a long time period. Both types of fires can be avoided using fire stops. Stone wool fire stops were used following the guidelines given by Just and Brandon (2016). The cross-sectional dimensions of these stone wool strips were 40mm thick by 80mm high. The thickness of the cavity was 20mm after the installation of the façade boards. The strips were glued on the insulation material, before the façade

boards were attached, in horizontal lines just above and just below the windows (Figure 34). Additionally, to assess a method to limit fire spread in ventilated cavities a 500mm high layer of intumescent paint in a façade cavity above the fire plume of the window (a severely exposed location) was implemented. A stone wool fire stop, as described before, was positioned at the upper part of this cavity.

Stone wool fire stop
Intumescent paint for ventilated fire stop



Figure 34: Fire stops installed during the construction phase

8.2.5 Limitation of fire spread via the façade surface

As timber is a combustible material, fire can generally spread on a façade with untreated timber. Treatment or impregnation of timber in a façade is, however, not recommended, as studied impregnations wear off within a few years. Therefore, this study seeks for a solution for implementing untreated timber in facades. Limiting the fire spread within the cavity is the first step of the strategy, as this can avoid heating the façade panels from two opposite sides. The fire spread on the façade is further limited by implementing a 1.2 meter strip of non-combustible cement board (see Figure 35). In order for the fire to spread from the first floor façade to the second floor façade, the fire needs jump over 1.2 meter of non-combustible material. 30 minutes fire resistant windows (EI30) were used in the second floor, in order to prevent fire spread to the upper floor.



Figure 35: Façade of the building with timber panels and non-combustible cement board strips.

8.3 Summary of fire test

A summary of important events is given in Tabell 1. Figures corresponding to the events are referred to in the table.

Tabell 1: Overview of events during the test.

Event	Testing time (h:mm)	Short description
Ignition	0:00	A couch against the long wall under the window was ignited using a highly flammable oil and a propane burner.
Breaking of window	0:20	In accordance with the test protocol, the windows of the ignited compartment were broken, because the gas temperatures decreased for at least 10 minutes. The lack of oxygen inside did not allow the fire to develop (see Figure 36, left)
Flashover	0:47	Flashover occurred and fire plumes were exiting both windows (see Figure 36, right)
Start of decay	1:05	The fire plumes on the outside disappeared and the temperatures inside the compartment started to drop.

Event	Testing time (h:mm)	Short description
Delamination of the outer lamella	1:50	<p>The exposed layer of the exposed CLT walls delaminated due to weakening of the adhesive. Leading to a second flashover within minutes.</p> <p><i>Note: this event can be avoided using methods discussed by Brandon and Dagenais (2018)</i></p>
Start of second decay	2:05	<p>The fire plumes on the outside disappeared and the temperatures inside the compartment started to drop. Figure 37 shows the fire at about 1:40 into the test.</p>
Extinguishment	2:15	<p>Firstly, the fire inside was extinguished using a firehose from the outside of each window. Secondly the visible flames of the façade were extinguished.</p> <p>Thirdly, two fire men entered the compartment. One of them had a thermal camera to locate the fire. He gave instructions to the other fire man who extinguished the smouldering fires with a fire hose. Lastly, the same two men extinguished smouldering fires in the façade using the same equipment.</p> <p>The fire was successfully extinguished within a few minutes.</p>



Figure 36: Breaking of the window at 0:20h (left) flashover at 0:47h (right)



Figure 37: 35 minutes into the first decay phase at 1:17h (left) start of the second decay phase at 1:40h (right)

8.4 Evaluation of fire spread

Fire spread via the façade was larger for the façade with stone wool insulation than for the façade with combustible PIR insulation. In the PIR façade, the timber façade panels on the second floor did not ignite. The façade with stone wool insulation had fire spread to the timber panels on the second floor. Both facades had similar cavities and similar fire stops in these cavities. Both of the 30 minute fire resistant windows withstood the fire without failure of the inner glass. It should be stated that there are numerous PIR insulation materials. The performance of this PIR insulation does, therefore, not guarantee similar performance for other PIR insulation materials.



Figure 38: Façade with stone wool insulation (left) and PIR insulation (right, some panels removed)

The interior of the upper floor was practically undamaged (Figure 39 and Figure 40). Besides some minor colouring of an area of approximately 30 cm², no fire damage could be seen. The intumescent strips in corner connections of the CLT elements expanded and the temperatures measured on the unexposed side did not indicate any fire spread.



Figure 39: 2nd floor after the test



Figure 40: 2nd floor after the test (some minor colouring seen in the bottom of a wall)

Temperatures measured on the none-exposed sides of penetrations did not indicate fire spread and remained close to ambient temperature. Thermal cameras indicated that, the temperatures on the unexposed side of connections and penetrations did not increase significantly. Also visually, none of the penetrations showed any sign of fire spread (Figure 41). The 30 minutes fire resistant door withstood the fire without complete integrity failure. However, during the decay phase a significant amount of material fell from the door, which made a loud noise and was observed visually through the window.



Figure 41: Unexposed side of the ventilation duct (left) and the 30 minutes fire resistant door (right).

9 Summary and conclusions

A statistical study of fires in New Zealand between 2000 and 2016 showed an increased fire spread and an increased spread of water damage in multi-storey (3 stories or higher) timber apartment buildings constructed in 1991 or before, in comparison with other buildings of the same age. In multi-storey apartment buildings built after 1991, both the spread of water damage was statistically smaller in buildings of timber construction than other types of construction. None of the 63 fires between 2000 and 2016 in modern multi-storey timber buildings led to fire damage beyond the fire compartment of origin. However, as such large fires have occurred in other countries, analysis of large damage fires was performed.

Analysis of large damage fires in multi-storey timber buildings in the USA showed the following:

- More than half of the large fires in the available data base involved façade fires as the main mode of fire spread.
- Approximately a quarter of the fires involved cavities fires as the main mode of fire spread.
- Approximately a quarter of the fires involved fire spread from compartment directly to neighbouring compartments as the main mode of fire spread.
- Only one high damage fire had no large fire spread, but involved water damage causing high property damage.

Extensive water damage was reported for six fires. Of these six fires, five were extinguished by the fire brigade and one was extinguished by sprinklers.

Based on analysis of large damage fires important aspects for the prevention of high fire spread should include:

1. Limitation of fire spread directly from compartment to compartment:
 - a. Limitation of spread through walls, floors or ceilings
 - b. Limitation of fire and smoke spread through connections between CLT slabs
 - c. Limitation of fire and smoke spread through wall and ceiling penetrations
2. Limitation of fire spread through cavities of the building.
 - a. Limitation of fire spread via the cavities between compartments
 - b. Limitation of fire spread via the cavity of the façade.
3. Limitation of fire spread outside of the building.
 - a. Limitation of fire spread via the façade surface.
 - b. Limitation of fire spread through windows
 - c. Limitation of fire spread through ventilation openings (such as ventilation openings of attics)

Strategies to limit water damage should mainly involve a change of approach to extinguish fires by the fire brigade, as the most frequent cause of high water damage is extinguishment by the fire brigade.

10 Recommendations for further studies

The case study mentioned in this report involved a mass timber two floor structure. An additional case study for light timber frame structures will be useful to test the state-of-the-art knowledge of limiting fire spread, further. Therefore, a full scale compartment test as a case study to limit fire spread in light timber frame structures is recommended.

A previous statistical study from the UK showed that fires in timber buildings under construction have led to higher damages than fires in other types of buildings under construction. A study of methodologies to prevent large fire spread during the construction phase is recommended.

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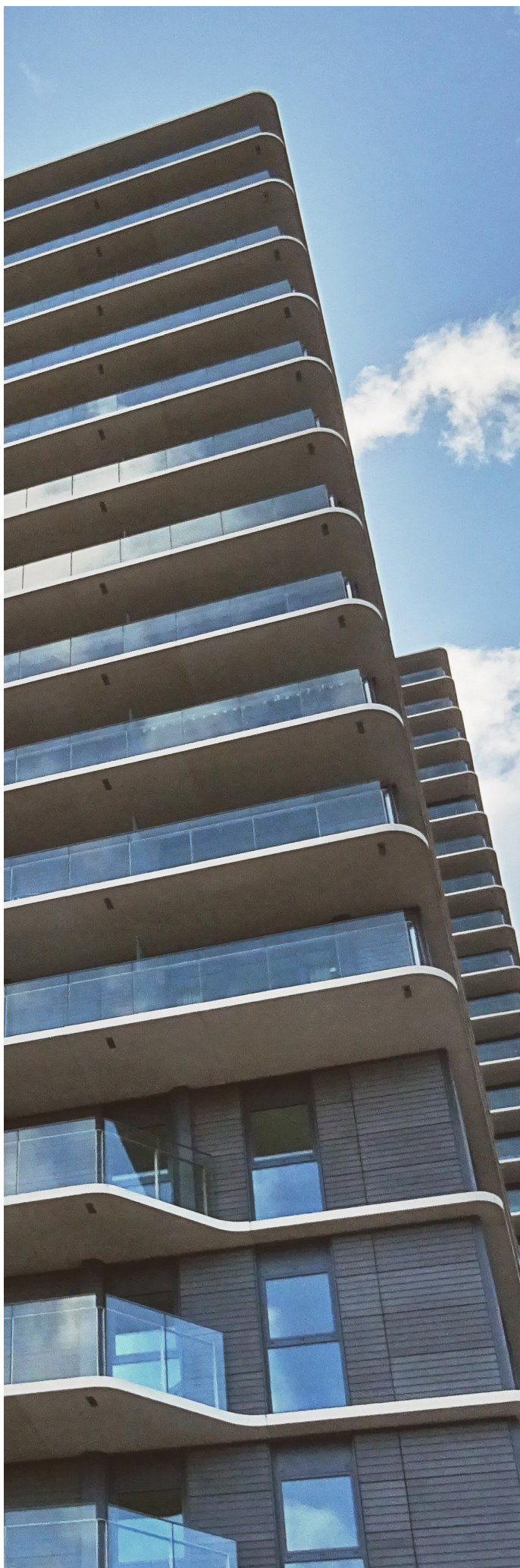
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