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INFLUENCE OF SERVICE INSTALLATIONS FOR THE SEPARATION AND STRUCTURAL PERFORMANCE OF TIMBER ASSEMBLIES EXPOSED TO FIRE

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Abstract. *In recent years residential buildings have been increasingly equipped by technological devices and service supplies to gain an appropriate standard of comfort. Despite these service installations and associated penetrations the fire resistance of fire separating elements must not be negatively influenced. There are currently no approved systems or recommendations for fire safe penetration sealing products in separating timber elements available. However, new measures and recommendations for fire safe service installations in timber structures can be derived from numerical simulations and fire tests conducted in a European research project and further work of the authors.*

1 INTRODUCTION

The separating function for wall and floor elements represents one of the most essential capacities in the case of fire, besides the structural stability. The building occupants and fire service must have confidence in the correct function of these elements. The evaluation of the fire resistance for such building elements occurs normally on basis of standardised fire tests, such as listed in EN 13501-2 [1], as well as approved calculation methods, such as those presented in EC 5-1-2 [2]. These methods don't normally take into account any junctions to neighbouring elements, mounting parts such as wall sockets and switches or penetrations of service installations for the likes of electrical wirings, heating systems, water and sewage pipes. However, these service installations are necessary and essential for the use of a building. Simultaneously the guarantee of fire prevention requires that for all building materials and construction methods certified sealing compounds and penetration sealing systems are used, which have the same fire resistance time as the separating building elements, to avoid the spread of fire as well as early ignition of wooden panels or combustible materials inside the elements.

However inspections and surveys of new and existing buildings repeatedly report that for all building materials and construction methods the risk for an early fire spread from one fire cell to the next is mainly caused by blocked doors and especially by inappropriately designed and sealed service installations in walls and floors. At the same time a survey found that 50% of the service installations were not installed properly and would not be able to perform well in the case of fire, resulting in significant limitations of usability for egress ways and the structural elements.

Several fire tests and technical approvals show that every type of service installation passing through fire separating elements has its own specific characteristic, level of performance and therefore range of application. Hence there is no single solution or product that will be used for all services and protect all elements in the same manner to avoid early fire spread.

For the selection and arrangement of an adequate penetration sealing system the services must be classified under consideration of number, size, material of the supply lines and transported substances.

2 ARRANGEMENT CONCEPTS AND STANDARDS

2.1 Arrangement of service installations

Penetrations of building services through separating assemblies are unavoidable, and must be planned and allowed for from the beginning of a project. This helps to avoid unnecessary penetrations and complex and expensive solutions in the latter stages of the construction. Therefore it should be aimed to include all service installations to previously defined fire compartments. This can be done by the application of following design concepts (depicted in Figure 1):

a) central distribution in fire rated service shafts and ducts with appropriate sealing of the penetrated areas
b) penetration sealing in each separating element (wall, floor) with approved sealing compounds and systems
c) continuous encasing of each service line throughout its entire length

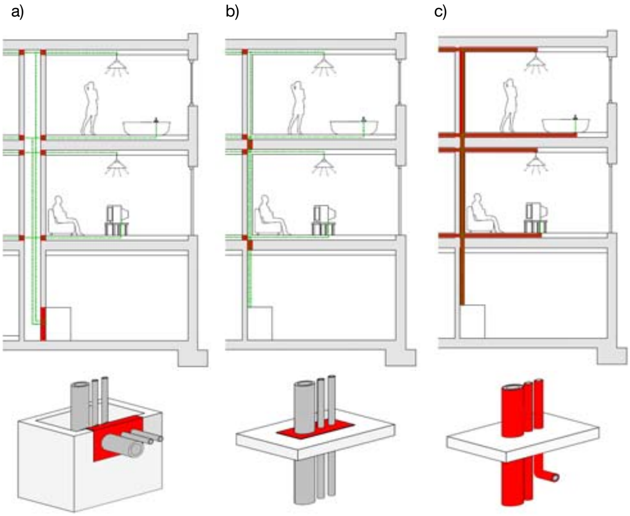


Figure 1. Arrangement concepts of service installations

All of these solutions must not only satisfy the requirements for fire safety but also the requirements for acoustic, moisture and thermal performance. Furthermore, the accessibility for revision, maintenance and additional installations should be allowed for. Based on these considerations and taking into account further aspects, such as practical execution on site and durability the solution of a service shaft in combination with timber structures shows some disadvantages. Most notably the problems of airborne sound transmission between compartments through service shafts, cracks caused by different settlement and moisture movement, and the necessity to seal each penetration through the shaft or duct and finally the high costs can be mentioned. Therefore designs of sealing the penetration of service installations in each separating element may be recommended for timber structures.

2.2 State of the art

Until now, fire tests of penetration sealing systems and sealing compounds for penetrations in timber frame and solid timber constructions are missing and acceptable solutions are rare. Approved sealing systems are typically only available for concrete or drywall construction at the moment. Further recommendations and acceptable solutions for these structures are made in the literature all over the world [4], [5], [6]. For penetrations of service installations in timber assemblies the following weak points can be identified:

- Service installations made from combustible materials and materials that melt at fairly low temperatures, such as wirings or plastic pipes, may lead in combination with wood based panels to a quick formation of gaps or holes in the penetration area during a fire.
- Metal pipe work can increase the heat flow through the assembly, thus an early flame spread to the unexposed side or inside the assembly may be possible.
- The application of penetration sealing systems, such as coated mineral wool boards, usually reduces the cross section of the timber structures (see Figure 13). Gaps and the unprotected reveal area may lead to an early fire spread to the inside cavity of the timber assembly and a sideways passing of the penetration sealing system.

To check the applicability of existing penetration sealing systems and sealing compounds for timber frame and solid timber structures, as well as develop further design rules, numerous fire tests for penetrations of electrical wiring, pipes as well as for the fire save installation of switches and sockets have been carried out.

3 EXPERIMENTAL INVESTIGATION

The series of experiments in these investigations have been split in to three parts. In the first part, different types of penetration sealing compounds for electrical wiring, in combination with wood based panels and solid timber elements were assessed. As timber framed and lined assemblies and non-combustible drywall constructions have similar failure mechanisms when exposed to fire (attrition and the collapse of the lining) the main focus in this study was laid on the modification of existing and already approved penetration sealing systems for drywall constructions, to achieve fire safety in combination with timber structures too. Special attention was paid to the development of measures to line and frame, the reveal area (see Figure 13) to get similar boundary and installation conditions for all sealing systems. The third step in this investigation considered the fire safe design of wall sockets / switches in separating timber elements.

3.1 Test setup for sealing of electrical cables

For the assessment of a fire safe sealing of electrical wirings in combination with wood based panels five small scale fire tests were conducted. The assemblies were made of OSB with dimensions of W x H = 540 mm x 540 mm and thickness of 15 mm and 25 mm respectively. One 15 mm thick panel was additionally lined with 9.5 mm thick gypsum plasterboard. The bulk density of the panels was ~ 580 kg/m³ and moisture content ~ 7 %. All panels were screwed to a wooden frame to ensure more stability in the fire tests and the mounting at the furnace. The single electrical cables or cable bundles applied in these tests are specific for electrical wiring in building structures. These consist of 3 respectively 5 PVC insulated copper conductors with a further outer PVC sheathing and can be classified according to DIN VDE 0250. All electrical cables were supported on the unexposed side, to ensure practical conditions. In these investigations gypsum putty, mineral fibre insulation plugs, fire retardant foams and mastics as well as intumescent wraps and sealing compounds were used to seal the penetration area. The tests were carried out under variation of panel thickness, type of sealing, size of annular gap (0 - 10 mm) and number of electrical wiring per penetration. In each test four different sealing setups were assessed (depicted in Figure 2). The temperature formation on unexposed side was measured at each cable and 25 mm beside the penetration area as well as in the centre of the OSB panel, to compare the failure times at penetrations and the plane undisturbed panels to each other.

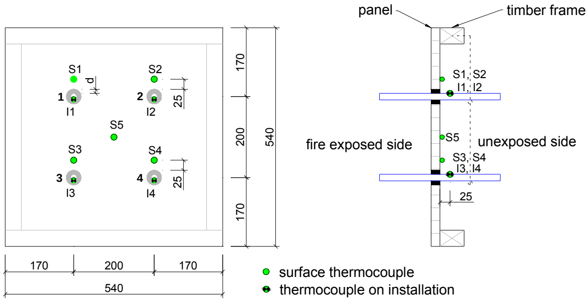


Figure 2. Setup of fire tests for sealing compounds

Figure 3. Failure at penetration sealing with non fire retardant PU foam

3.2 Test setup with penetration sealing systems

To assess the applicability of in drywall constructions approved sealing systems four small scale tests for timber frame and solid timber assemblies were conducted by TU Munich and two full scale tests for timber frame assemblies by the German Society for Wood Research (DGfH e.V.). The tests included sealing systems for plastic pipes, copper and steel pipes, various cables and cable bundles as well as measures for multiple penetrations of cables and pipes. In the small scale tests assembly dimensions of W x H = 1180mm x 1180 mm were used. The first timber frame wall was designed for a fire resistance of 30 minutes, the second and the solid timber assemblies for a fire resistance of 90 minutes each. The design and cross section of the timber frame assemblies can be taken from Figure 4. For the fire tests of solid timber elements, 120 mm thick cross laminated timber panels (CLT) were used, consisting of 5 single layers each and bonded together with melamine resin. These panels had no additional lining. In contrast to the timber frame elements an additional multi penetration sealing system was investigated in the two CLT panels. The used system was made up of an 80 mm thick mineral wool board and coated with an intumescent painting. The board was fitted tightly in the previous with fire rated gypsum plasterboards lined opening in each test. Gaps between the mineral wool board and plasterboard lining were filled by an intumescent painting according to the technical approval of the system.

To ensure appropriate fire safety in the reveal area the required thickness of the attached lining has been determined approximately by numerical simulation in advance. Lining thicknesses from 2 x 10 mm to 2 x 18 mm in combination with a 100 mm wide framed lining around the exposed surface were investigated with respect to heat flow and protection capacity for the timber members located behind. Under consideration of a critical temperature of 300°C (in accordance with EC 5-1-2) the protection capacity of the cladding was determined for point “A” - directly in the corner and “I” - 35 mm above the corne (see Figure 8).

The additional influence of joints in the gypsum plasterboards were not investigated in this manner. In the FE simulations, the lined corners of the reveal areas were exposed to the ISO 834 [7] fire curve over 30, 60 and 90 minutes respectively. The applied thermal force considered a conductive and a radiative fraction at the exposed surface. Therefore emissivity ε and convection coefficient h were assumed equal to 0.8 and 25 W/m^{2}K, respectively, as suggested by Eurocode 1-1-2 [3]. For the unexposed side a convective coefficient of 9 W/m^{2}K (considering of radiation losses too) and ambient temperature of 20°C were used. The thermal dependent material properties for conductivity (k), specific heat (c) and density (ρ) of timber and gypsum plasterboard were taken from Eurocode 5-1-2 [2] and from a research report [8] respectively. In addition, the influence of fasteners normally used to fix the gypsum plasterboards to each other and to the supporting timber structure such as screws and staples were investigated with respect to thermal degradation of the supporting timber members in the reveal area.

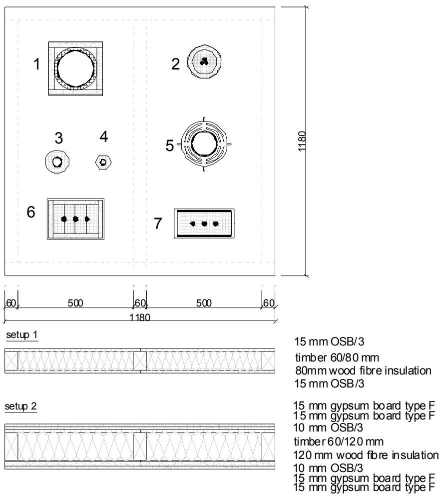


Figure 4. Setup of timber frame assemblies with installed penetration sealing systems

Figure 5. Small scale fire tests assembly (setup 2 - EI90)

Furthermore, two full scale fire tests with a timber frame wall and floor assembly in combination with a mineral wool board multi penetration sealing system and installed services were conducted [9], [10]. Before lining the reveal areas a support infill frame was attached in the opening of the timber frame wall and floor, to stabilise and support the gypsum plasterboard cladding. For these fire tests two layers of 18 mm gypsum plasterboards were used to line the reveal area. The wall and floor assembly were also lined in the entire exposed surface with the same plasterboards.

Each penetration sealing in the small and full scale fire tests was equipped with several type K thermocouples to measure the temperature formation and compare these results to the standard benchmarks. The tests were carried out in accordance with EN 1366-3 and under ISO 834 fire curve exposure. The failure criteria in all tests were measured in terms of:

- integrity (E) considering ignition of cotton pad and flame ejection on unexposed surface and
- insulation (I) with temperature increase less than 180°C above the initial ambient temperature.

Stability or structural adequacy was not recorded for these tests and so no additional load was applied.

4 EXPERIMENTAL RESULTS

4.1 Sealing for electrical wirings

Due to the large number of examined setups [12] only general results will be presented in this paragraph. Several of the examined approved sealing compounds showed excellent results in combination with cable penetrations in OSB panels and solid timber elements, in respect of equal failure times in the penetrated and un-penetrated areas. All conducted tests showed larger heat transfer through the cables itself in comparison to the plane panels and sealing compounds. As expected, an increase in the number and conductor diameter led to an increase of heat transfer throughout the cables and faster temperature formation in the penetration area. For one cable bundle and for inappropriate sealings an early ignition at unexposed side of the OSB lining occurred (see Figure 3).

All test results showed an influence of the annular gap size and the used sealing compounds for the temperature formation at OSB lining in the penetration areas. The tight executed cable penetration, without annular gap, showed a self sealing effect in the penetration, due to the thermal expansion of the outer PVC sheathing. However this execution caused slightly higher temperatures in the penetration area compared to penetrations with a regular sealed annular gap. For the examined penetration sealings of electrical wirings with an annular gap sizes between 5 and 10 mm a formation of joints was obvious between the lining and the sealing material in all fire tests. Those gaps increased by time of exposure and were more distinctive for “passive” sealing compounds, such as uncompressed mineral wool plugs. Therefore a pre compression of flexible mineral wool plugs is needed for durable fire safe sealings. However better results were reached by the use of flexible sealing compounds or by the use of gypsum putty.

4.2 Penetration sealing systems

4.2.1 Single systems

As for the sealing compounds excellent results have also been reached for approved penetration sealing systems in timber structures [11], [13]. Therefore equal failure times for the plane timber elements and penetration areas have been reached (see Figure 6). As the most critical area for an early failure, the junction of penetration sealing system and timber element was found in all tests. This has been caused by problems to fill the joints properly in the entire depth of the lining (see Figure 7). This problem was more significant for multilayer and thick linings in combination with gypsum putty or viscous mastics when compared with intumescent sealing compounds. Here gaps and small voids in the sealed joints were subsequently closed by thermal expansion of the intumescent material.

Figure 6. Failure of small scale timber frame assembly

Figure 7. Failure in sealed penetration junction

4.2.2 Lining of reveal area for multi penetration systems

For designing the setup of fire tests numerical simulations were conducted to determine approximately the required thickness of gypsum plasterboard cladding in the reveal area for various fire resistance. The temperature formation between the reveal lining and the timber element can be taken from Figure 9. In the numerical simulations the 2D heat transfer influence became apparent for the corner, as expected, and resulting in a faster temperature rise as for measurement point “I”. For this point, with less thermal exposure no exceed of critical temperatures were detected in those setups with linings of at least:

- 2 x 10 mm for 30 minutes,
- 12.5 mm x 15 mm for 60 minutes and
- 2 x 18 mm for 90 minutes.

The thermal degradation of the timber members was accepted in the area of exposed corner. In this manner designed and conducted reveal areas showed excellent performance under fire exposure in combination with the 100 mm wide framed lining [13], [9], [10].

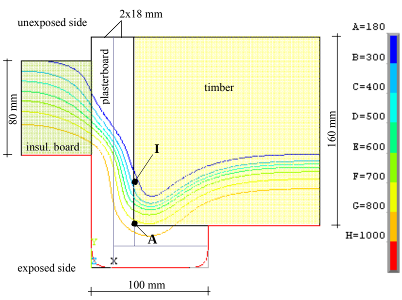


Figure 8. Assembly setup for num. simulation with isotherms for 2 x 18 mm gypsum plasterboard lining after 90 min.

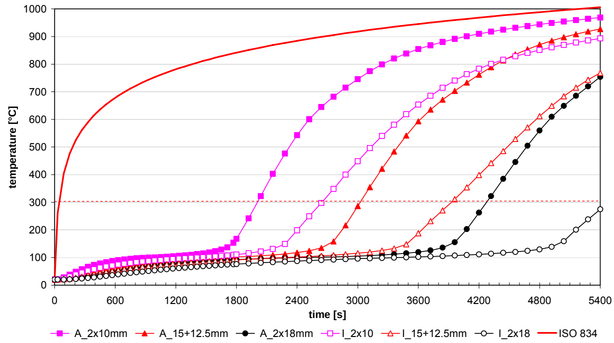


Figure 9. Temperature formation for different of reveal linings

In the pre-examinations as well as in the fire tests the influence of fasteners for the gypsum board lining was examined also. Fasteners penetrating the plasterboard lining caused higher temperatures in the timber compared to the undisturbed area of plasterboards. Screws with a larger penetration length in timber led to lower temperatures compared to shorter ones and slowed down the degradation process alongside the fasteners (see Figure 10). Furthermore skinny fastener caused less colouring and degradation in timber compared to larger fastener diameters. However no negative influences such as excessive local degradation of timber and no early ignition caused by fasteners were recorded in the tests [14].

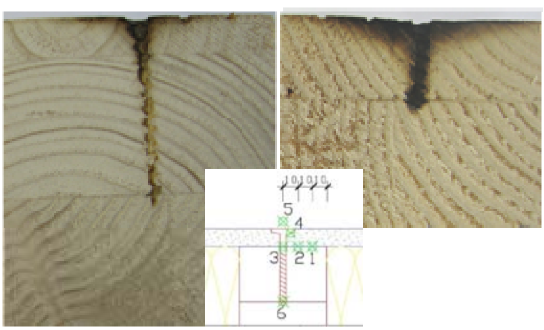


Figure 10. Charring alongside a screw (left 4.3x55mm; right 4.3x35mm) penetrating a 12.5 mm plasterboard

5 RECOMMENDATIONS

5.1 Penetration sealing for electrical wirings in timber structures

The results obtained in this study show the necessity of a proper sealing for electrical wirings in the penetration area to reach fire safety in combination with timber frame- and solid timber structures. As timber frame and drywall structures have similar failure mechanisms and material behaviour of the lining when exposed to fire, many approved sealing measures for drywall structures are appropriate for timber constructions too and should be used as presented in Table 1. Special attention must be paid to the gapless and void free sealing of the 5 – 10 mm wide annular gap in complete thickness in the penetrated lining on both sides of the elements. For solid timber elements a sealing depth of at least 40 mm on both sides is recommended to reach a fire resistance time up to 90 minutes. In the case of an annular gap less than 0.5 mm no additional sealing is needed for skinny cables. For thicker cables and cable bundles the conducted heat through the penetration increases and only highly efficient and durable measures or special penetration sealing systems shall be used.

In addition the following conditions must be observed:

- distance d between adjacent cable penetrations ≥ largest penetration diameter (see Figure 11)
- density of penetrated wooden panel ≥ 400 kg/m³ reaction to fire class at least D s2 d0 (EN 13501-1)
- for smoke proof connections use of permanent flexible sealing compounds or mastics

Table 1. Recommended sealing measures

Sealing measure	Annular gap size	Type of electrical cable		
		Single cable	Cable bundle **	
		NYM* ≤ 5x16mm²	≤ 3 cables 1 x NYM ≤ (5x16mm²) + 2 x NYM ≤ (3x2,5mm²)	≤ 5 cables 5 x NYM ≤ (3x2,5mm²)
no further sealing	≤ 0,5 mm	■		
gypsum putty	5 to 10 mm	■	■	■
intumescent wrappings sealing compounds fire retard. polyurethane foam (with technical approval)		■	■	■
flexible stone wool plugs, density ≥ 70 kg/m³)		■	■	

*) cable NYM Y x Z mm²: Y PVC insulated copper conductors with a further outer PVC sheathing, cross section of conductors Z mm² each (in accordance with DIN VDE 0250)

**) for combustible cavity insulation use of non-combustible stone wool pipe linings around the cables

5.2 Application of penetration sealing systems in timber structures

5.2.1 Single systems

The assessed systems contained combustible and non-combustible service pipes in addition to penetrations of cable bundles. It is found that systems with intumescent materials (“active systems”), which expand when exposed to high temperatures, efficiently seal the gap between the sealing system and lining of the timber frame or solid timber elements. For systems with “passive” sealing materials, such as gypsum putty, the fully gapless filling throughout the complete depth of the lining is needed too. For thick linings of separating timber frame elements the application of a consistent sealing becomes difficult. To optimize these joints for fire conditions an additional 100 mm wide and minimum 12.5 mm thick non-combustible framed lining with gypsum plasterboards is strongly recommended (see Figure 12).

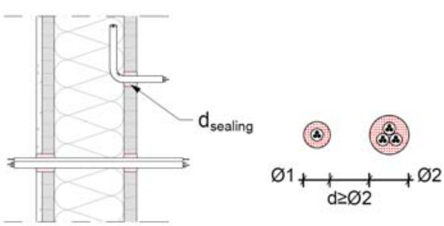


Figure 11. Penetration sealing for electrical wirings

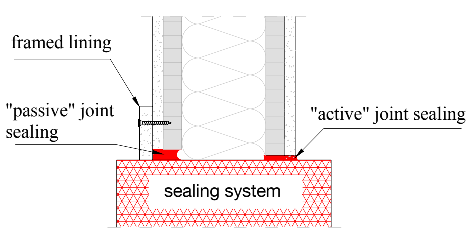
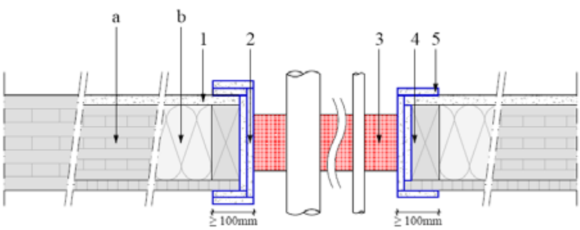


Figure 12. Joint sealing for penetration sealing systems

5.2.1 Multi systems

For the installation of multi penetration sealing systems in compartment timber structures comparable conditions to those used in concrete or drywall constructions must exist. Through this the fire spread inside the timber structure and sidewise passing of the sealing system can be excluded. The main concept is to line the reveal area of the penetrations / openings with a non-combustible encasing cladding, such as gypsum plaster - or gypsum fibre boards over the entire thickness of the separating element, including the attachment of an additional framed lining of at least 100 mm wide around both sides of the surface. This is to create joint steps and avoid continuous joints for convective heat flow through the structure and between reveal lining and structural timber element. For the setup of reveal linings two layers are preferable. In addition for timber frame constructions a support infill frame with at least 40 mm in the opening area is necessary to stabilise and support the reveal lining and the framed lining (see Figure 13).



1	combustible or non-combustible lining
2	non-combustible encasing cladding in reveal area
3	penetration sealing system
4	framed timber structure
5	framed lining of encasing cladding minimal 100 mn
a / b	solid timber structure / timber frame structure

Figure 13. Fire safe lining of reveal area

6 CONCLUSION

The investigations show that the selected approved penetration sealings and systems for separating timber elements are applicable in accordance with the specified design restrictions and no early failure of the penetration will occur in the case of fire. The lining of the reveal area represents an efficient fire safety concept that provides for multiplicity of existing penetration sealing systems similar and fire safe installation conditions. National and international knowledge as well the executed fire tests show that existing penetration sealing systems can be used in combination with timber structures to assure fire safety.

7 ACKNOWLEDGEMENT

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