Passive House Institute

Integrating wood beams into the airtight layer

Prepared within the framework of the EU Research Project 3EnCult

3encult
EFFICIENT ENERGY FOR EU CULTURAL HERITAGE

SEVENTH FRAMEWORK PROGRAMME

3ENCULT is co-funded by the EU Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 260162. The European Union is not liable for any use that may be made of the information contained in this publication which is merely representing the authors view.

January 2014

Integrating wood beams into the airtight layer

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Contents

1 Introduction and summary

As a rule, the use of interior insulation is the only option possible in refurbishment projects involving historical building facades. In refurbishments which demand a high level of energy efficiency, old and cracked wood beams represent a difficult challenge for designers and craftsmen. Accepted standards do not provide a solution for this problem. Even among experts there is no consensus on dealing with penetrations of the airtight layer by wood beams. Inadequate integration of beam heads into the airtight layer of the building poses a risk. This will greatly increase the likelihood of structural damage due to convective moisture transport into the cold exterior wall area (see also: [AkkP 32]). Other penetrations of the airtight layer frequently occur in the roof area, particularly at the roof/wall connection to the eaves, the collar beam connection to rafters and where supporting beams rest on an insulated top floor ceiling.

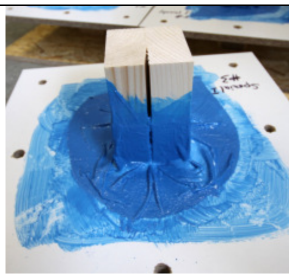
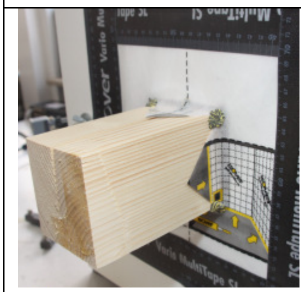
The level of airtightness of the building envelope plays a decisive role in energy efficient buildings in particular. Details such as the integration of beams heads with cracks are especially crucial for the level of airtightness achieved in a refurbished building. Defective planning or execution can lead to an increased heating energy demand and structural damage. Frequently, in order to check the building substance (statics) and determine the work necessary, old beams have to be examined at the point where they are integrated into the wall. Subject to the prerequisite that the wood beam can be exposed completely (all around), the important issue is execution of the airtight connection of the beam to the airtight layer of the wall with interior insulation.

For this purpose, a series of experiments for airtight integration of wood beams were carried out at the Passive House Institute. The methods and materials which were suitable for this purpose and the amount of residual leakage of the tested methods were also studied in the process. Seven different commercially available variants and four so-called "alternative solutions" for sealing wood beams in refurbished existing buildings were examined for this. These involved additional measures or materials and methods which are not commonly used for this specific application. Numerous specialist manufacturers were contacted for a selection of products and methods to be tested and asked about approaches for solving this specific problem. Of those contacted, ten German and foreign companies made product samples available to the Passive House Institute and some also provided advice regarding the use of these products.

In order to allow comparison of the different solutions with each other, standardised "**sample beams**" (8 x 8 cm) were prepared with a defined gap which tapered off to zero. The triangle-shaped gap was intended to depict the problem arising with actual cracks: sealing right up to the end of the gap is very difficult. The study focused on joining of the wood beam and sealing of the gap. Laminated wood boards ("wood panel") were used as the wall layer.

A total of twelve different combinations of the following product groups and methods for airtight joining of wood beams were possible from the product samples of the manufacturers and the "alternative solutions": adhesive tape, sealant/adhesive, adhesive primer, elastic butyl rubber tape, pure acrylic dispersion ("special solution"), plaster sealing tape, sealing membrane collar, thick bituminous coating, drilled hole for injecting sealant, and poured gypsum plaster. The combinations of materials consisted of up to three materials. Products by different manufacturers were not combined in the case of the commercially available solutions; this was intended to rule out any incompatibility of the products used with one another. A comparison of two similar products by different manufacturers was carried out for one combination.

Table 1: Overview of different sealing methods carried out with sample beams

			
Adhesive tape	Butyl rubber tape	Special solution (pure acrylic dispersion)	Plaster sealing tape
			
Sealing membrane collar	Drilled hole for sealant	Thick bituminous coating	Poured gypsum plaster

The experiments were carried out using a test stand based on [DIN EN 12114]. The individual samples which were measured consisted of a wood panel, the wood beam penetration through the panel and the tested sealing method. A series of different differential pressures between the surrounding and the test box were created for each test. The volumetric flow passing through the residual leaks of the sealed wood beam was measured. The leaks in the test box itself were taken into account as an offset value using a closed airtightly coated wood panel (without an opening for a beam). Evaluation took place similarly to an airtightness measurement in a building (blower-door measurement) with a pressure difference of 50 Pa. The series of experiments carried out here provides information for successful sealing of exposed wood beams in the area of the beam head in refurbishments of existing buildings and the size of the leakage flows that would occur at a pressure difference of 50 Pa.

On account of the measuring devices used, the measurement errors in this study are between 3 and 7% with reference to the respective measured value (calculated in accordance with [DIN EN 12114]).

Measurement results

The results obtained from the tested methods were presented as arithmetic average values of the excess and negative pressure measurement obtained from each of the three individual samples tested. The respective minimum and maximum measured values (lines depicted as I) are shown next to the average values (columns). The measured values had to be corrected slightly compared with the previously published results ([PHT 2012] and [Buildair 2013]) on account of a fault in the measuring device.

On the whole, it is apparent that the successful methods always involve sealing of the cross-section of the crack in the beam. As soon as this crack was filled in with a suitable material, the leakage volume flow could be reduced significantly compared with simple sealing using adhesive tape. The best measured value - that is the smallest leakage flow rate - results with the solution with the drilled hole for sealant, with just 0.03 m^3/h (corresponds with a reduction by 98%). This type of sealing of cracks can be combined with all other methods. However, the beam statics must be clarified prior to using this method since it involves drilling.

Whether the gap can be sealed with the chosen method or not is decisive for the success of the method. Special products were used for creating airtight connections in all experiments. All in all, it is clear that rather than the type of material of the special products chosen for sealing, what matters is that the cross-section of the crack is sealed as extensively as possible. It is obvious that airtightness will increase noticeably as soon as the cross-section of the crack is reduced. Within the framework of this study, no statements could be made regarding the permanence of the tested connections, which may vary. All tested samples were put into storage protected against UV light and could be examined again at a later point in time.

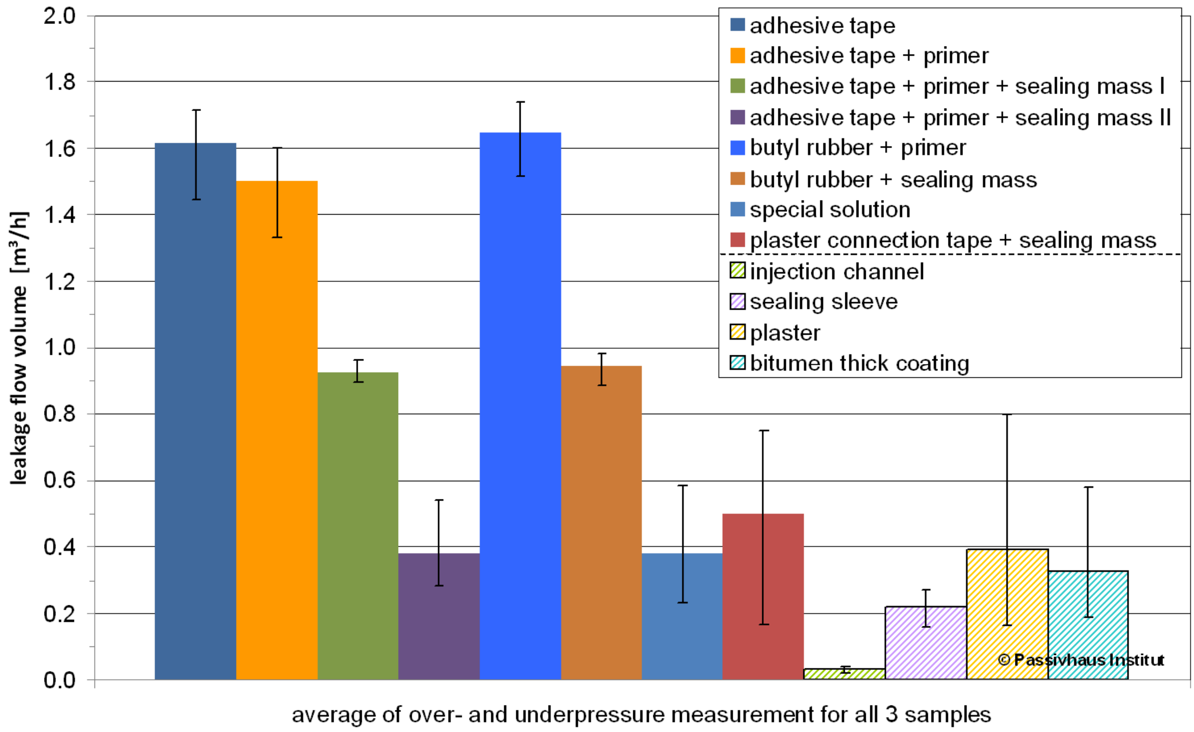


Figure 1: **Comparison of the leakage flows during the measurements, standardised for a pressure difference of 50 Pa (average value of the excess and negative pressure measurement of the three samples respectively). The thin black line depicts the measured minimum and maximum average values.**

The different methods for sealing wood beams differ considerably with regard to **ease of use**, this was also taken into account for this study. Joining a beam to the airtight layer (vapour retardant membrane, wood panels etc.) is relatively quick if specific sealing of the crack does not take place. In contrast, a qualitatively high standard of sealing - for which accessibility of the beam and thorough cleaning are prerequisites - requires more time and diligence. The choice of method in each individual case must be decided in accordance with the respective boundary conditions.

Transfer of the results

The investigation using the small sample beams with just one leak was carried out in order to allow a clear comparison of the different methods. In this way, influences other than those due to sealing could be ruled out or minimised. Thus the situation was purposely simplified compared with the situation with historical old beams. Some measurements were carried out using larger beams for transfer of the results to actual situations which are encountered typically.

For this purpose, the most successful sealing methods were additionally tested using an old sample wood beam (ca. 16 x 12 cm) (designated as old or "actual" beam here) and another "large" sample beam (16 x 15 cm). This larger sample beam exhibits numerous differently shaped cracks; there are various small cracks and a few large ones which all taper off to zero in order to approximate the actual naturally occurring shape of cracks. The total leakage area with this larger sample beam was ca. 11.5 cm^2, while that of the small sample beam in the more extensive investigation was just over ca. 0.9 cm^2.

In this case, sealing using only airtight adhesive tape again serves as a reference measurement, without any other measures relating to sealing of cracks. With the large sample beam, an 89% reduction in the leakage volume flow was achieved after the cracks had been filled in by injecting with sealant and joining with adhesive tape, with a residual leakage volume flow of just under 1.2 m^3/h. With the old beam, the residual leakage is just 0.4 m^3/h with the same method, which represents a 95 % reduction. With the method using pure acrylic dispersion (paste-like compound), the residual leakage is just 0.5 m^3/h for the large sample beam, which represents a reduction of 96 %. Thus, as anticipated, the success of the sealing measure can be translated onto this larger beam with differently shaped cracks.

Estimation of the scale of the leakage flows which actually occur is possible through this transfer of the sealing methods. However, in doing so, it must be considered that the test stand measurements were carried out on completely exposed beams; there was no masonry or the like which could have hindered or reduced air flow to the sealing area; therefore completely different leakage volume flows occur in reality. For example, pressure differences of 3 to 8 Pa can be expected in reality on account of wind flow and thermals around the building; the values are higher only during strong gusts of wind or with very high buildings. For applying the measured values for actual buildings with such pressure differences, these must be calculated down accordingly.

The procedure for successful sealing of beams can be reduced to the following work steps:

- expose the beam
- clean the beam area which is to be integrated
- fill cracks
- carry out sealing of the beam to the wall level

A prerequisite here is the use of suitable materials (special products) all throughout. The decision in favour of or against a particular method or combination of methods for sealing wood beam connections must always remain subject to a case-by-case review.

Airtightness of OSB boards

Construction of the test box for the sealed beam measurements took place using oriented strand boards. With the first measurements it was discovered that non-airtightness of the test box could not be disregarded. The specific cause was that the OSBs used were not airtight. For this reason, the test box was subsequently sealed all over the surface using airtight adhesive tape.

Airtightness of the OSBs may also be of interest in the case of refurbished old buildings. In order to be able to estimate the airtightness of OSBs more accurately and to assess the effects on their application in construction, it was decided that more extensive examination of the airtightness of these boards should be carried out during the course of this project; the existing test box could be used for this purpose.

Type 3 and 4 OSBs with a thickness of 16, 18 and 22 cm belonging to four major manufacturers were purchased from bulk suppliers in Germany. Three or four samples were cut out from each board. The board to be tested was airtightly installed in the test stand and the 200 x 200 mm area was tested for airtightness.

In [Zeller 2012], a maximum q_{50}-value of 0.1 $m^3/(m^2h)$ is required for areic tightness; for Passive Houses this is 0.06 $m^3/(m^2h)$, while the value stated in [Langmans 2010] is 0.09 $m^3/(m^2h)$. In Canada the requirement for areic tightness of building materials is just q_{50} = 0.048 $m^3/(m^2h)$. The present examination focused on a moderate target value of 0.1 $m^3/(m^2h)$.

An overview of the measurement results for all tested OSBs is shown in Figure 37. The q_{50} measurement results demonstrate – analogous to the study by [Langmans 2010] – very large scatter of the three individual values of each board. The reason for this is probably the non-homogeneous material with the typically coarse chips. The scale of the results is also comparable with the results obtained in [Langmans 2010]. The average measured values (bar) for each board are between 0.08 and 0.78 $m^3/(m^2h)$ for the **Type 3 OSB**, and those of the individual measurements (line depicted as I) are between 0.03 and 1.27 $m^3/(m^2h)$. The average values and the smallest and largest measured value for q_{50} are shown respectively. The four manufacturers are represented with letters from A to D. The four series of measurements for the **Type 4** OSBs have average values (red bars) between 0.07 and 0.34 $m^3/(m^2h)$, the respective individual measurements (line depicted as I) are between 0.06 and 0.4 $m^3/(m^2h)$. In addition, a board which was obtained from a DIY store was also measured and represented (beige bar).

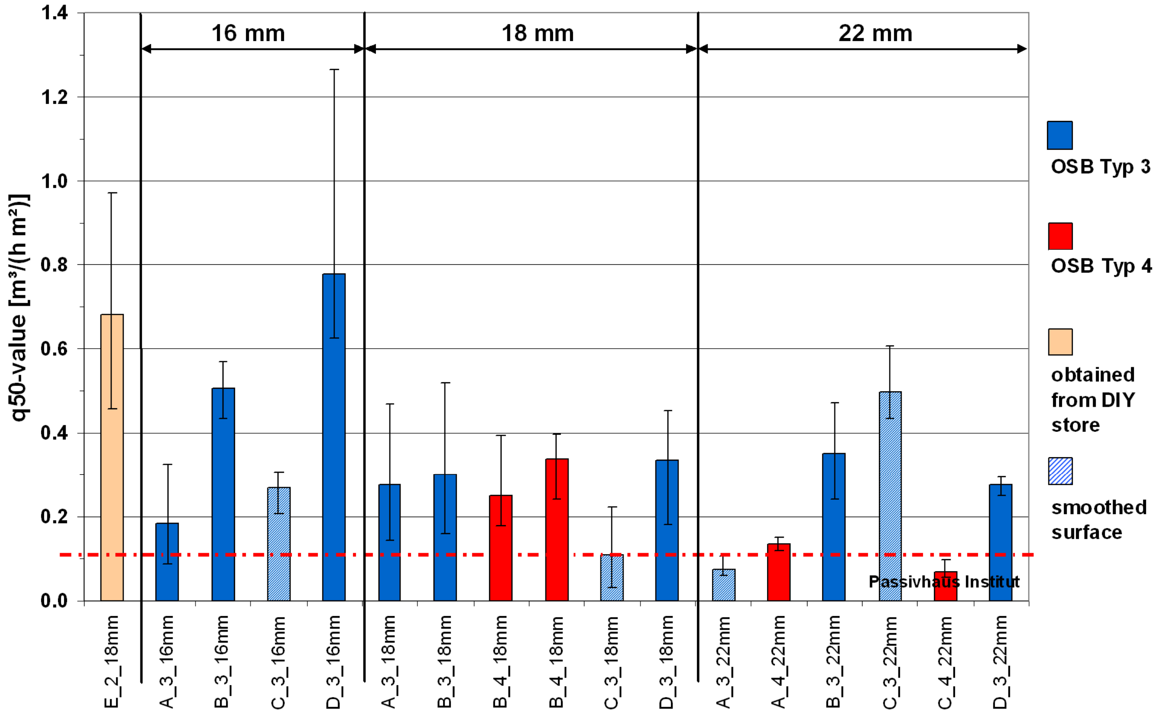


Figure 2: **Measurement results for airtightness (q_{50}-value) of "OSB Type 3" and "OSB Type 4" from four different manufacturers (A...D) sorted according to board thicknesses of 16, 18 and 22 mm. In addition, the result for a board obtained from a DIY store is also shown. The average value from three measurements (bar) and the smallest and largest measured value (line depicted as I) are shown. The target value is 0.1 m³/(m²h) (dotted red line).**

Only three of the seventeen average values of the boards are below or equal to the target value of q_{50} = 0.1 m³/(m²h). These are two 22 mm boards (Type 3 and 4) and an 18 mm board (Type 3). All other measured values are significantly higher than the target value. The board obtained from a DIY store (18 mm) additionally shows a considerably poorer value than the other 18 mm boards, but is better than the least airtight 16 mm board.

If the OSBs are used as an airtight layer in a building, the insufficiently airtight boards will lead to a higher leakage volume flow in the building. With a target value of $n_{50} = 0.6\ h^{-1}$, the share of the total leakage from OSBs is between 20 and 40 % for a calculated sample building, depending on the quality of the board (average value of the measurements for all tested 18 mm boards or all boards belonging to the manufacturer with the highest q_{50}-values).

Achieving a high level of airtightness of the building envelope, as is necessary in Passive Houses and EnerPHit refurbishments, is still possible using the tested OSBs as the airtight layer. However, the safety margin for the stipulated values for airtightness decreases with the quality and must possibly be compensated elsewhere with much effort and hard work for greater precision etc.

The designer and supplier as well as the contracted craftsman usually do not have any knowledge about quality of airtightness of the OSBs used. In the interest of a high level of airtightness of the building envelope for ensuring structural integrity, and planning reliability, mandatory provision of information relating to airtightness must be made compulsory on the part of manufacturers; imprints on the boards themselves would be most practical for this purpose. Alternatively, it is also conceivable for manufacturers to work out other solutions in order to provide the necessary quality and certainty for designers, building contractors and investors.

The present documentation was created within the framework of the EU research project "3EnCult" (Efficient ENergy for EU Cultural Heritage). The authors would like to thank the manufacturers involved for providing product samples for testing wood beam sealing.

2 Basics

2.1 Airtight buildings

Airtightness of the building envelope provides a significant contribution to the energy efficiency of buildings. The standard of insulation during the mid-1970s was so inadequate that heat losses due to infiltration and exfiltration resulting from leaks were not particularly significant and received scant attention. It was only due to the gradual improvement of building insulation that the importance of airtightness also increased. In 1995, the first attempt was made in Germany to implement a standard for air permeability of the building envelope. For the very first time, the [WSVO1995] (German building efficiency ordinance of 1995) explicitly stipulated in Paragraph 4 (1) the installation of "an airtight layer across the entire surface"; before this, the focus was only on leaks e.g. at window joints (thermal insulation ordinance of 24.02.1982). With the publication of the [DIN4108-T7] in 1996 (Pre-Standard of May 1996), professionals and designers were provided with guidelines for different detail solutions.

Why is an airtight construction necessary?

According to the latest research findings, implementation of an airtight building envelope is absolutely essential. The reason for this is improved protection against heat, moisture, fire and noise which are associated with airtightness of the building. Moreover, the airtight layer provides effective protection against harmful substances (such as nitrous gases near roads with heavy traffic or radon gas from the ground) and also forms the basis for cost-effective operation of a highly efficient ventilation system with heat recovery [BW2008]. The position of the airtight layer depends on the wall structure and the materials used. Figure 3 shows a schematic diagram of the airtight layer using the so-called "pencil rule": in each sectional drawing it must be possible to outline the airtight layer without taking the pencil off the paper [Peper/Feist/Sariri 1999/2009]. Avoidance of penetrations in the airtight layer (by electrical installations, beams heads, floor levels etc.) should form part of the diligently prepared concept for airtightness by the designer responsible.

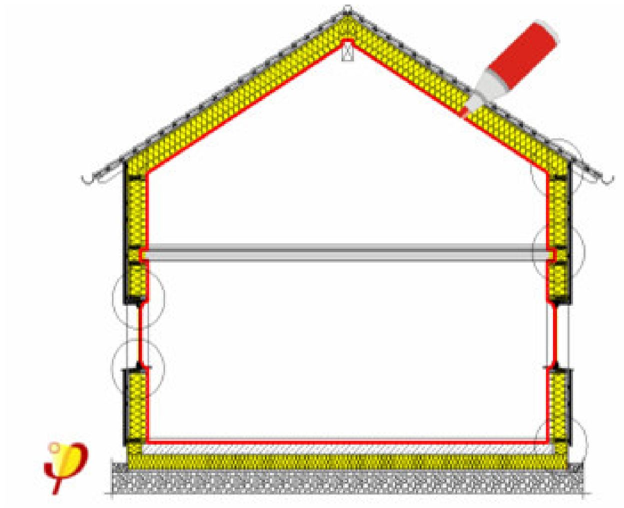


Figure 3: **In the sectional drawing the airtight layer can be outlined without having to take the pencil off the paper ("pencil rule") (Source: PHI)**

Thermal protection

In winter, uncontrolled air exchange between the interior of a building and the outside leads to increased heating consumption. Pressure differences across the building envelope are the driving force for air exchange. These are caused by two different effects.

For one thing, areas with excess and negative pressure between the outside and the inside are created locally due to wind pressure and wind suction, leading to air flows at leaks in the building envelope. The more exposed the location of a house is, the stronger the influence of the wind will be. Distribution of pressure at the building envelope resulting from the influence of wind can be reproduced using the detailed calculation methods described in [DIN_EN15242].

For another thing, temperature-induced pressure differences between the outside and the inside arise as a result of the heating and air conditioning; warmer air layers have a lower density than colder air layers and therefore rise upwards. A poorly implemented airtightness layer leads to a significant increase in heating consumption in winter months for the reasons mentioned above. In order to illustrate this point, reference is made here to an example from [BW2008]: "An entrance door is assumed […] with a gap that has a height of 5-10 mm. […] with a gap length of 1 m and a gap depth of 70 mm; volume flows of ca. 45 to 90 m³/h can flow through this gap. This leads to unnecessary heat losses depending on the temperature difference and the pressure load duration […]". Reference should be made to [DIN EN ISO13790] for detailed calculation of the additional heat losses caused by leakages.

Moisture protection

Convective moisture gain inside the wall structure is responsible for many kinds of structural damage. Warm humid air from the interior passes through leaks in the building envelope from the inside towards the outside. Longer flow paths through the construction with reduced air velocity and decreased air temperature are particularly critical as large amounts of moisture may condense over time and remain inside the construction. Interior insulation which has not been correctly sealed and therefore allows indoor air to enter behind the insulation can also result in damage due to mould and damp (see Figure 4) (compare [Borsch-Laaks et. al 2009] and [Künzel et. al 2010]). In this case, the moisture in the air which is increasingly cooling down condenses, resulting in moisture patches/accumulation which can lead to mould and fungal decay in case of insufficient drying (dehumidification through diffusion and evaporation).

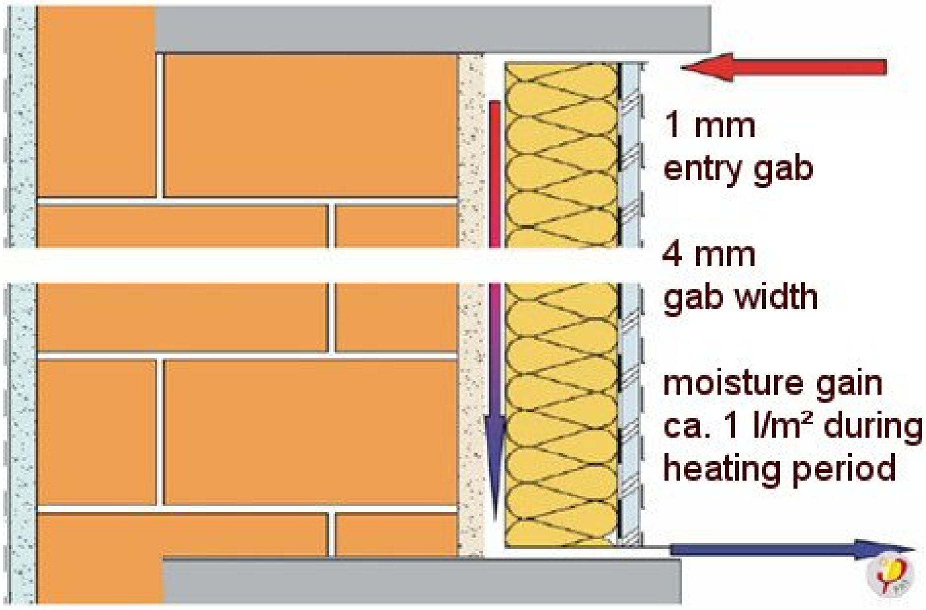


Figure 4: Convective moisture gain with air flow behind interior insulation [Pfluger 2005])

A concept for airtightness which is implemented diligently, especially with regard to detail connections, reduces such damaging air flows through and behind insulation and therefore minimises structural damage as a result of convective moisture gain.

Fire and noise protection

Airtightness of exterior building components is a major requirement for fire resistant constructions. In the event of fire, further transfer of heat and toxic fumes is caused by leakages to a considerable degree. Reference is made to [BW2008] for further information on this topic. There are also sound protection requirements for airtightness; air flow through leaks facilitates sound transmission, thereby affecting acoustic protection.

Controlled ventilation

For reliable and cost-effective operation of a highly efficient ventilation system, a high standard of airtightness of the building envelope is essential. Particularly in the case of heat recovery from extract air it quickly becomes clear why leaks in the building envelope make a ventilation system uneconomical. The warm indoor air which passes through these leaks is not directed through the heat exchanger of the ventilation system which ensures heat recovery and warming of the outdoor air. Less heating energy is therefore recovered than would be the case with a sufficiently airtight building envelope. Compared with a sufficiently airtight building envelope, this leads to higher energy consumption for heating and increased costs.

Airtightness test

During the airtightness test for a building, a series of varying pressure differences against the outside are generated by means of a blower fan which is usually installed temporarily in a door opening. These pressure differences range between ca. 20 and 100 Pa excess or negative pressure. The mass air flows transferred by the fan correspond with the mass flow which passes through the leaks in the building envelope, thus providing a measure of the air permeability of the building envelope [Zeller 2008].

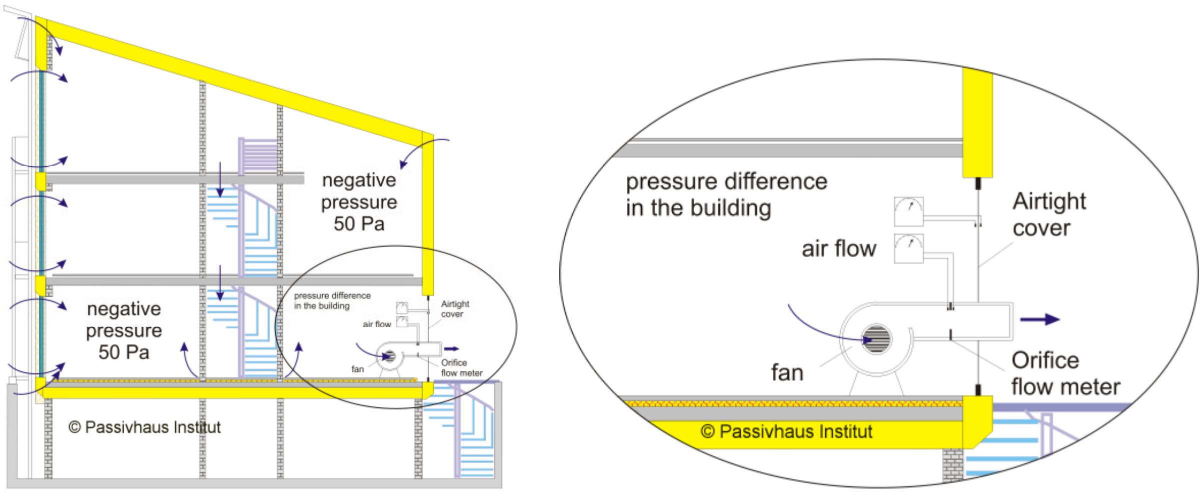


Figure 5: Basic test set-up for an airtightness measurement [Peper/Feist/Sariri 1999/2009])

From the pairs of measured values obtained by means of the airtightness test, logarithmic characteristic lines can be generated which reflect the relevant mass flow transferred at the respective pressure. Through double-logarithmic application, the mentioned characteristic line can be described by a linear equation. From the parameters of the linear equation thus obtained, it is possible to ascertain the flow coefficient C and flow exponent n by using the general flow equation. In this way, it will be possible to determine the volume flow at 50 Pa. This is described in the standards as the **leakage flow**.

Flow equation $\dot{V} = C * \Delta p^n \quad \left[\frac{m^3}{h}\right]$ (Formula 1)

Linear equation $y = a * x + b$ (Formula 2)

Logarithmic flow equation $\log(\dot{V}) = \log(\Delta p) * n + \log(C)$ (Formula 3)

The flow coefficient C describes the intersection point of the y-axis at a building pressure of 1 pascal. Since this is a logarithmic equation, it is not possible to determine the intersection point with the y-axis at 0 pascal. The flow exponent n describes the gradient of the straight line and simultaneously permits qualitative evaluation of the leakages which are present. The flow exponent is usually between 0.5 and 1. Flows are mostly turbulent if it is closer to 0.5; if the value is closer to 1, then laminar flows will predominate.

Calculation of the coefficients C and n is explained in [DIN EN 13829]. Ascertaining the coefficients is considerably facilitated by data spreadsheet programmes or software which has been specially designed for pressure difference measurement.

The air change rate at 50 Pa can be obtained by dividing the leakage flow by the clear building volume. This is the n_{50}-value which is used to calculate the ventilation heat losses due to infiltration and exfiltration.

$$n_{50} = \frac{\dot{V}_{50}}{V_{Gebäude}} \quad \left[\frac{1}{h}\right]$$ (Formula 4)

By dividing the leakage flow by the envelope area of the building, the measure for air permeability of the building envelope area (q_{50}-value) can be ascertained. This describes the quality of the airtightness of the entire building envelope of the construction. This information is recommended in particular for larger buildings (> 1500 m³ air volume).

$$q_{50} = \frac{\dot{V}_{50}}{A_{Gebäudehülle}} \quad \left[\frac{m^3}{m^2 * h}\right]$$ (Formula 5)

In Europe, measurements for airtightness of building envelopes are carried out in accordance with [DIN EN 13829]. This contains comprehensive information on the topic of differential pressure measurement.

Special requirements for interior insulation

When refurbishing historical buildings, improved thermal protection is often only possible with insulation on the inside, e.g. in the case of protected facades and also in densely developed inner city areas. In contrast with exterior insulation, additional requirements apply for interior insulation with reference to building physics.

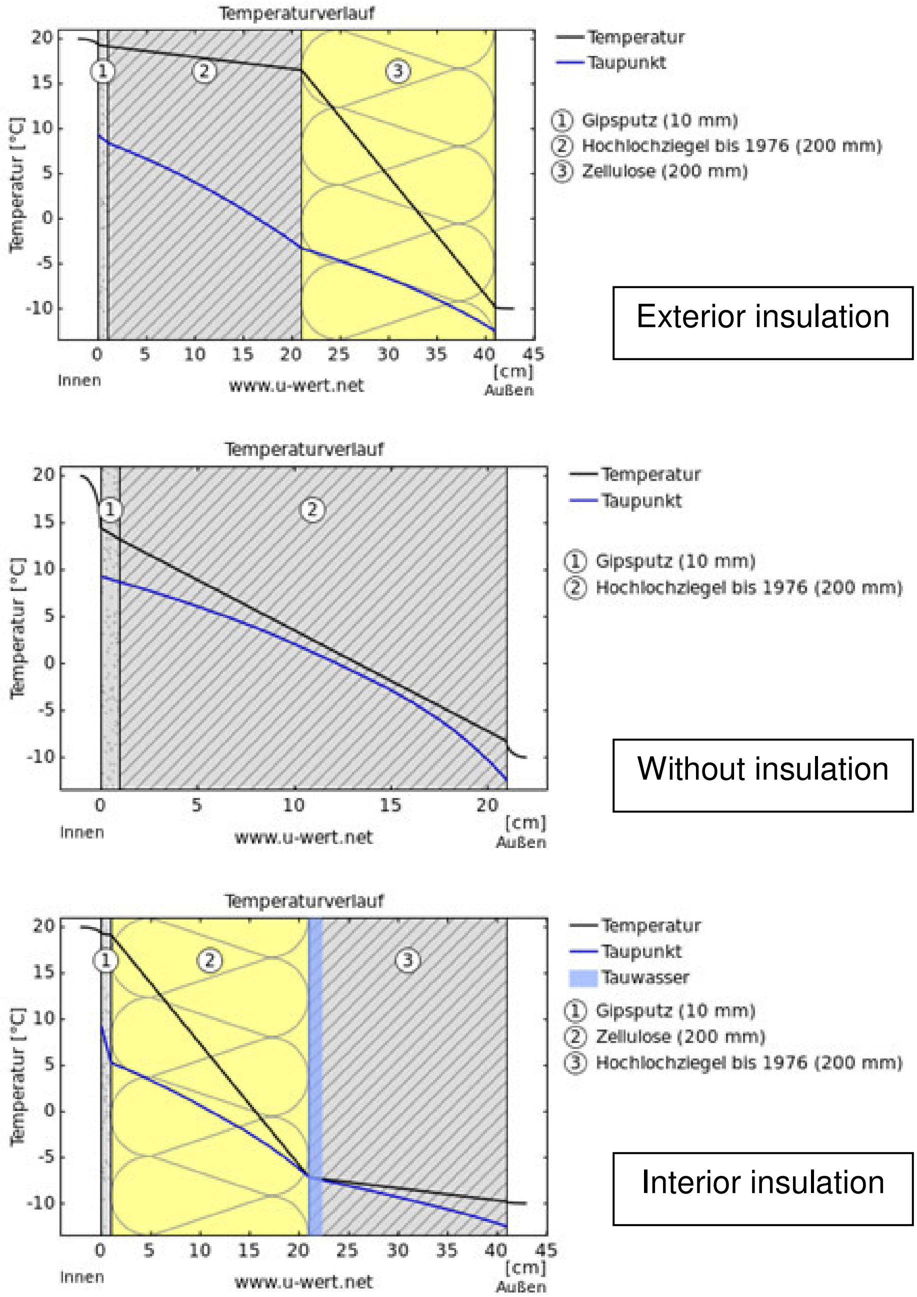


Figure 6: **Temperature and dewpoint profile for masonry walls with exterior insulation (above), without insulation (middle) and with interior insulation (below). The calculations and representations were carried out using the online tool from www.u-wert.net. (Translation: Temperatur = temperature, Taupunkt = dewpoint, Gipsputz = gypsum plaster, Hochlochziegel bis = vertical coring brick up to..., Zellulose =cellulose, Tauwasser = condensate, Temperaturverlauf = temperature profile, Innen = inside, Außen = outside)**

A layer of insulation applied on the inside of the exterior wall results in a change in the building physics related behaviour of the exterior wall: in the cool winter months, the temperature of the wall is significantly lowered because the temperature drop largely takes place inside the interior insulation. The insulating effect of the masonry wall and the temperature drop occurring here is minimal in contrast; this increases the risk of condensation forming inside the wall since the dewpoint is now reached inside the exterior wall structure (Figure 6).

A newly inserted vapour retarder on the room side should reduce moisture gain in the wall structure which is caused by vapour diffusion from the interior space. However, this will also hinder drying out of the moisture in the wall towards the interior space. It is therefore particularly important to ensure careful execution of the airtight layer when using interior insulation in order to minimise moisture entry from the indoor space into the wall structure through leaks.

3 Beams in existing buildings

A lot of wood beams are found in the roof area and in the ceilings of many existing buildings. These often lead to penetrations in the insulation layer and the airtightness layer when implementing interior insulation. In practice, considerable challenges arise at these places in relation to achieving airtightness. Frequently, there are a large number of penetrations which are also difficult to access. This makes it difficult to achieve proper sealing of the airtight layer to the beam heads. The risk of leakage flows is particularly great in the roof area on account of thermals inside the building. Air moisture may condense at the points with missing or defective sealing to the wood beams or beam heads, possibly leading to moisture damage depending on the extent of the boundary conditions. Since wood is an organic substance, it may begin to rot and, at the worst, may lose its stability.

Figure 7: Partly exposed wood beam ceilings with wall supports of the wood beams in two refurbishment projects (Pictures: PHI)

Crack formation and types of cracks

Cracks form in wood when tensile forces exceed the stability of the wood. Apart from mechanical influences, moisture-induced shrinkage and expansion of wood are the main cause of tensile forces. Wood absorbs or releases moisture depending on the air humidity level. This effect is known as hygroscopy. The absorption and emission of moisture takes place up to the equilibrium moisture content which results in ca. 10 mass percent wood moisture with a standard indoor climate (20℃, 50% relative air humidity). Distortion takes place with levels below the fibre saturation point. This is specific to the type of wood, with an average wood moisture of 30 mass percent. The actual formation of cracks is the result of anisotropy (directional dependence) of the wood. Expansion and shrinkage occurs in the longitudinal, radial and tangential directions to the ratio of 1:10:20 (approximately). Figure 8 illustrates the anisotropy of wood.

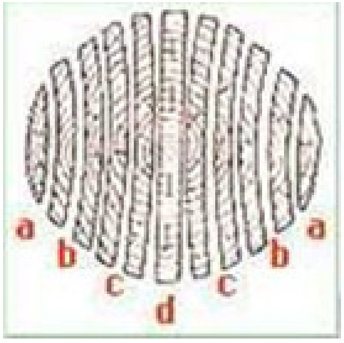


Figure 8: **Anisotropic shrinkage and expansion of wood (Source: [Hol])**

In existing building stock, the most common cracks in wood beams are dry cracks. These form as a result of wood movement which occurs below the already mentioned fibre saturation point. Figure 9 shows the typical course of such cracks. These always expand in the radial direction and dependon the type of cut of the beam. In comparison with quartered beams, the risk of cracks is thus greater when using solid wood beams.

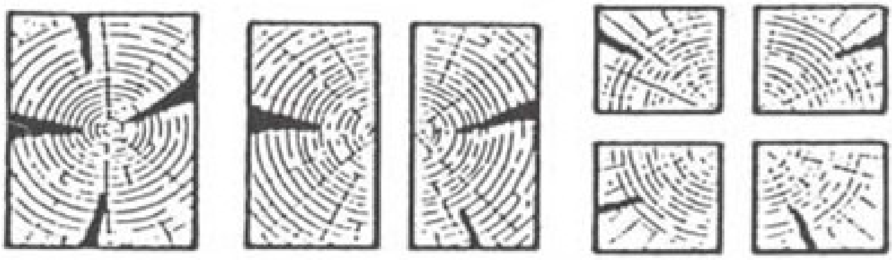


Figure 9: **Course of dry cracks with different types of wood cuts (left: solid wood beam; centre: half beam; right: quartered beam) (Source: [GDHeV])**

Structural damage due to moisture

Fungi account for two-thirds of the damage to wood in constructions; the remaining third is caused by insects [Müller 2011]. The wood is destroyed by the fungus and this sometimes happens in combination with insect infestation. Moisture almost always plays a decisive role in this type of damage. Fungal infestation is only possible if free water is present inside the cells; fibre saturation point must be exceeded over a longer period of time (> 6 months) for this. If this is not the case, the fungus will cease to grow; however, this does not rule out renewed growth if moisture saturation occurs again. As a rule, fungi are not killed off by the temperatures which normally prevail in constructions (between - 20℃ and + 40℃) [Müller 2011], therefore careful appraisal of the wood beams is extremely important in refurbishment measures with interior insulation.

4 Test procedure

4.1 Test set-up and measuring devices

On account of the special challenges of airtight sealing presenting in refurbishments of existing buildings, the aim was to identify methods with a high prospect of success. For this purpose, several methods and products for airtight integration of wood beams were tested in experiments based on [DIN EN 12114]. The test set-up consisted of a test box made of wood panels, two membrane vacuum pumps (diaphragm pumps) and measuring devices for volumetric flow, temperature, air pressure, differential pressure and humidity measurement.

The test stand consisted of a test box made of engineered wood board (OSB) which is covered all over with special adhesive tape in order to increase its airtightness (Figure 10 / "A"). There was a cover at the front of the test box which was penetrated by a wood beam with an artificially created crack. It was possible to exchange the cover with the beam (fixed with screws)); there was a sealing gasket between the test box and the cover.

Inside the test box, varying pressure differences were generated with the aid of two pumps (Figure 10 / "C") and the resulting leakage volume flow was measured using one of the two variable area flowmeters (Figure 10 / "B"). The amount of the measured volumetric flow which escaped from the test stand between the cover and the wood beam penetration was used as a measure of quality of the method for beam sealing being tested.

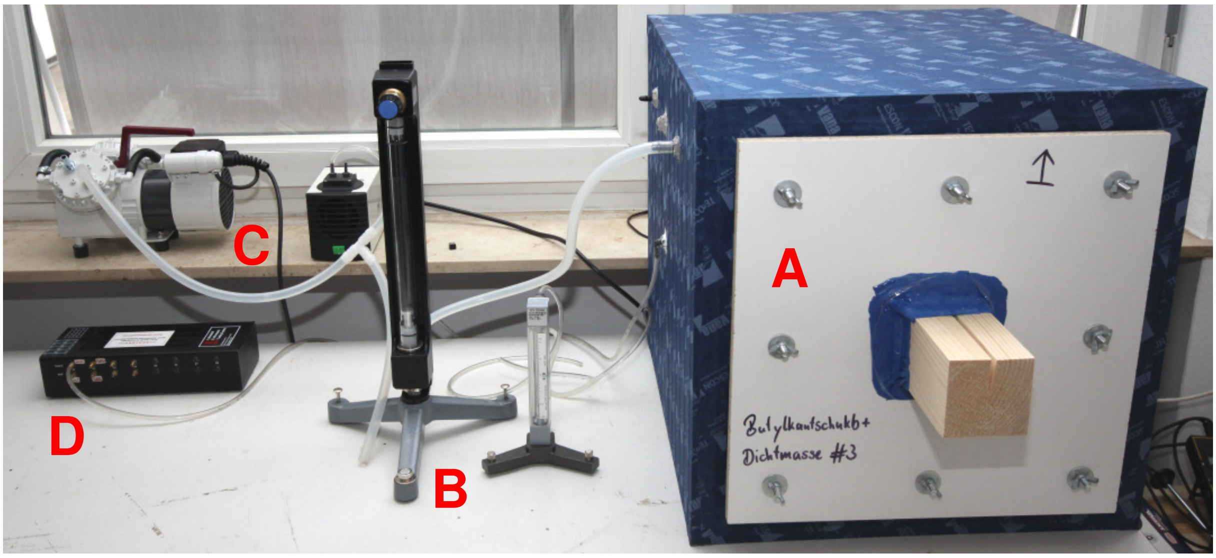


Figure 10: Test set-up at the Passive House Institute for the airtightness measurement for beam heads (A: test box with cover and a sealed sample beam; B: variable area flowmeter; C: membrane vacuum pump; D: differential pressure measurement)

The pressure differences resulting from air transfer between the test box and its surroundings were registered by a pressure load cell (Figure 10 / "D") and recorded by a computer. Using spreadsheet programs, it was possible to calculate the curve functions from the characteristic lines which were thus generated ($\dot{V}_{leakage} = f(p_{difference})$). With this, the value for the leakage volume flow could be calculated e.g. for a pressure difference of 50 Pa (see also Appendix 7.1). The measurements carried out within the framework of this study were always standardised for a pressure difference of 50 Pa.

For the measurements it is imperative to take into account non-airtightness of the test stand without a penetrating beam. In order to be able to ascertain the airtightness of the test stand (residual leakage of the test box without a beam integrated into it), a cover without a penetrating beam was fixed to the test box. With this "zero pressure measurement", it was possible to ascertain through measurements the residual leakage of the box and sealing to the cover, and to deduct this in the measurements. After some tests it was decided that it would be expedient to perform the zero pressure measurements at least once per measurement day. The volumetric flows thus ascertained were subtracted from the daily measurements.

The experiment set-up at the PHI was almost identical with that outlined in the [DIN EN 12114] standard.

Details of the test set-up and measurement technology

The components of the test set-up and the measuring devices used will be explained in detail in this section.

Test box (test stand)

A cube-shaped box with sides measuring 50 cm which was made of 18 mm thick engineered wood boards (OSBs) was prepared as a test box. After some test measurements, the box was completely covered on the outside with airtight adhesive tape in order to increase airtightness even further. OSBs are considered to be suitable components for implementation as an airtight layer. However, studies (e.g. by [Langmans et. al 2010]) have shown that this generally does not apply for all boards. In order to obtain more information regarding this, measurements were also carried out on different types of OSBs following the tests with the beam heads (see Section 6).

On one side of the test box there was an opening where a cover could be connected (by means of screws). The covers used in the test consisted of coated chipboards penetrated by the wood beams which were to be sealed (Figure 11). In this way, it was possible to change the covers quickly for testing different sealing methods without any major alterations.

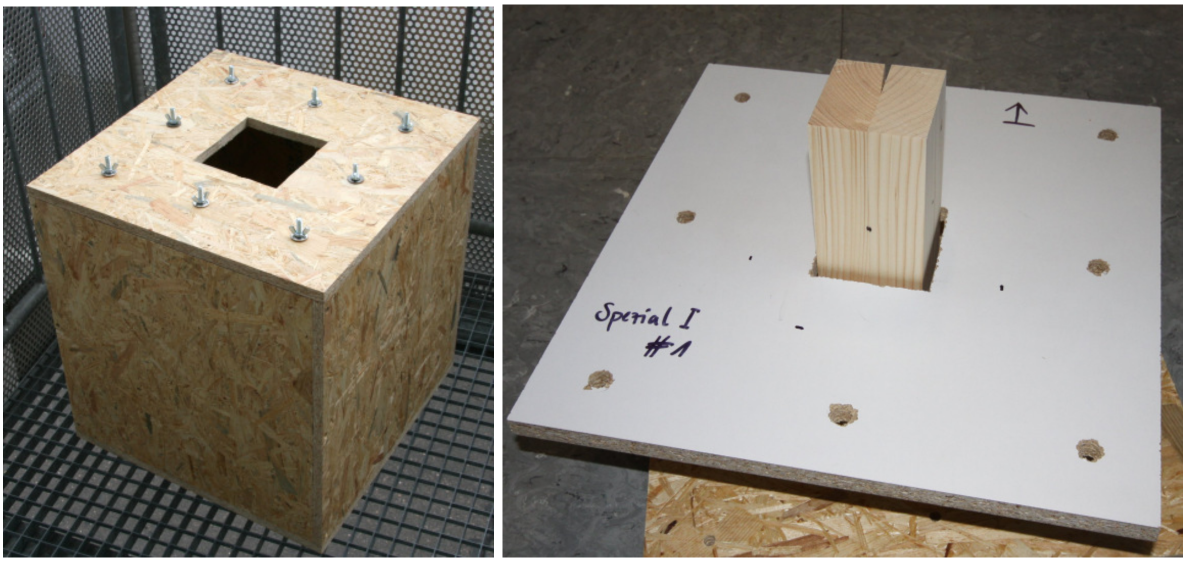


Figure 11: **Test box with opening and screws for fixing the cover, without adhesive tape covering and without sealing of the cover (left). Cover with penetrating beam, here without sealing, with holes for screws (right).**

The airtight connection between the test box and a cover with the penetrating beam was created using a 4 cm wide gasket of closed-cell EPDM-based foam attached to the box. This foam material was resilient enough to cause the material to press evenly and airtightly on each cover when screwed into place. Furthermore, three tube nozzles for connecting the tubes were attached to one side of the box. These were used for measuring the pressure difference and the connection to the membrane vacuum pumps.

Membrane vacuum pumps

Two different membrane vacuum pumps by the manufacturer KNF Neuberger (volume flows up to 4 l/min: model N 86 KT.18; volume flows between 4 and 39 l/min: model N026.1.2 AN.18) were used for generating the pressure difference between the test box and the surroundings which was necessary for the measurement.

Each pump was connected to the volume flow measuring devices by means of a tube. Since these devices do not have a control mechanism, volume flow had to be regulated by means of a T-shaped tube connector and a tube clamp. For changing the air flow rate which flows into the box or out of it, the flow resistance had to be increased by means of the tube clamp in one of the two directions given by the T-connectors.

It turned out that a surge tank was necessary in order to smooth out the intermittent volume flow delivered by the pumps. For this purpose, a steel container with a capacity of ca. 3 litres was integrated into the tube connection between the pump and the volume flow measuring device.

Volume flow measuring device

Two variable area flowmeters were used to measure the volume flow. These consisted of a cone-shaped glass tube with a floating element which moves vertically. Air flows upwards from below through the testing tube and raises the floating element against the force of gravity. A visual reading of the volume flow can be made by means of a measurement scale on the side of the glass cone.

The smaller of the two volume flow measuring devices with a floating element belongsed to the manufacturer Yokogawa (model: RGC1) and was designed for a maximum volume flow of 4 l/min under normal conditions (20 °C, 1013 hPa). The larger of the volume flow measuring devices used belonged to the company Mecon (model: Minix MA 302) and was designed for an air flow rate between 4 and 40 l/min under normal conditions.

Another tube led directly from the output of the flow meter to the test box. [DIN EN 12114] requires that the "measurement of the air flow rate should take place with a measurement accuracy of ± 5%". The manufacturing company Mecon gives the measurement accuracy class of 2.5 (in accordance with [VDI/VDE 3513 Blatt 2]) for the "Minix MA 302" device. This means that with a flow rate of 20 % onwards based on the maximum flow rate, there is a total error of 5 % (based on the measured value). For larger flow rate amounts, this error decreases further until it reaches a maximum flow rate of 2.5 %. For leakage volume flows greater than 8 l/min the measurement accuracy is within the range required by the standard.

The company Yokogawa gives an accuracy class of 4 for the measurement accuracy of the second flow meter "RGC1" that was used. According to [VDI/VDE 3513 Blatt2], this results in a measurement error of 5 % or less with an air flow rate greater than 2 l/min for this device; this complies with the standard. The use of two volume flow measuring devices ensures that volume flows smaller than 4 l/min can also be measured with a high level of accuracy.

Pressure load cells

The APT system (Automated Performance Testing) by the manufacturer TEC (The Energy Conservatory; Minneapolis/USA) was used as a pressure load cell. This is a 4 channel pressure gauge/manometer which is used in combination with the TECTITE Express software for carrying out automatic differential pressure measurements particularly during Blower-Door tests. The pressure is measured with a measurement accuracy of ± 1 %. Hence, the requirement in [DIN EN 12114], which stipulates a measurement accuracy of ± 5 % for the pressure measurement, was clearly met in this case also. The pressure difference based on the test specimen could be tracked and recorded on a computer in real-time using the TECLOG software (see 7.1, Appendix A). In this way, the pressure difference between the ambient air and the test box was measured for each set volume flow in the experiment. This resulted in pairs of measured values consisting of the volume flow and the corresponding pressure difference.

4.2 Test procedure

Sample beams

The aim of these tests was to allow the comparison of different methods of sealing wood beams with each other. Since old wood beams in refurbishment projects consist of very different types of wood and sizes and have different kinds of cracks, these could be used for comparing the different methods. For this reason, various test beams were used to examine the size and types of cracks which were suitable for the comparative tests. A selection of these test beams were prepared by a wood joinery business and tested in the PHI in order to determine the best type of "sample beam".

A sample beam size of 80 mm x 80 mm x 250 mm was set for the comparative measurements. All these sample beams had an identical crack which served as a leak. This was intended to simulate a crack in the wood as typically found in old wood beams, so it was a V shape instead of a simple cut made with a saw. As shown in Figure 12, the "crack width" tapers off to zero at the bottom. This was intended to represent – as required in [DIN EN 12114] – typical leaks which occur as cracks in actual practice. Due to production-related reasons, the sample beams therefore consisted of two parts glued together. It was not possible to completely avoid slight variations due to the material and workmanship. The complexity of more elaborate shapes would have led to production-induced diversification which would have had a negative effect on the accuracy of the measurements.

The reason for having sample beams with a single leak was the maximum possible elimination of influencing factors and thus uncertainties in the comparative measurement. Apart from this, the effort for manufacturing, measuring and evaluation could be kept within a manageable cost and time frame.

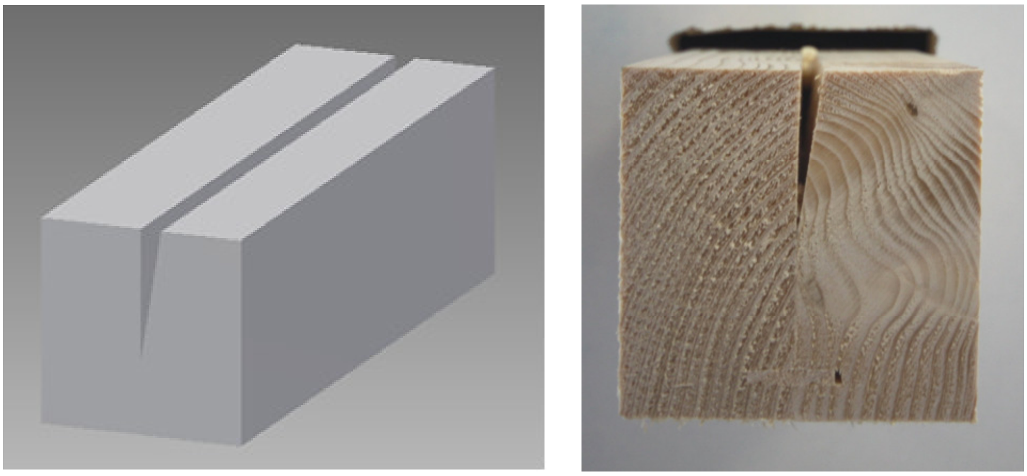


Figure 12: 3D model and photograph of the front end of the sample beam (length: 250 mm, edge length: 80 x 80 mm, area of crack: 0.9 cm²)

In practice, beams usually have numerous cracks of different sizes and shapes. In order to transfer test results to more complex geometries and beams in existing buildings, a series of measurements was subsequently carried out using a large sample beam with differently sized cracks and with sections of an old beam from an existing building. The manually produced large sample beam had an edge length of 160 mm x 150 mm and a leakage area of ca. 11.5 cm²; the old beam had an edge length of ca. 120 mm x 160 mm with different leakage areas (depending on the section). In the picture with the front views (Figure 13), the cracks tapering off to zero are visible in both beams.

Figure 13: Cut surface of the large sample beam (ca. 16 mm x 15 mm) and of the old beam (ca. 120 mm x 145 mm)

Conduction of the tests

In preparation of the measurements with different methods for sealing beams, a sample beam was fixed to each cover by means of an angle bracket. In doing so, the beam was fixed into place in such a way that a uniform (annular) gap resulted all around the opening in the cover. The beams were then sealed with the cover using the respective sealing method. Three identical samples were prepared for each method in order to provide a certain degree of certainty against influences due to workmanship. The samples thus created were screwed airtightly to the test stand one after another and then measured. The entire sealing process was documented through photographs.

A series of increasing volume flows were delivered into the test stand using the large or the smaller membrane vacuum pump depending on the leakage flow of the tested samples. The ensuing excess pressure for the respective volume flow was documented and transferred to the spreadsheet programme together with the test conditions prevailing at the time of the test (temperature, relative humidity and barometric pressure) for preparation of the characteristic lines. The same procedure as described for excess pressure was used for the negative pressure measurement. Data pairs consisting of the pressure difference and the volume flow resulted for excess pressure and negative pressure measurements. The other two samples for the same sealing method were measured in the same way directly after this.

As described before, the air permeability of the test stand itself was determined as the "baseline measurement" at least every day. In order to allow evaluation of the sealing method without any influence by the test box, this offset value was deducted from the measured value.

Evaluation procedure

Evaluation of the measured values was carried out using MS Excel. After entering the measured value pairs in the evaluation tool, the volume flow was transposed to the reference conditions under which the variable area flowmeters were calibrated. Moreover, creation of an average value and specification of the minimum and maximum measured values of the three samples for a method are useful for proper evaluation of the measurement results. It is not expedient to calculate the standard deviation with just three samples.

Correction of the air flow rate

The equation necessary for transposing the measured volume flow to the reference conditions (20 °C, 1013 hPa and 50 % relative air humidity) is found in [DIN EN 12114]:

$$\dot{V}_0 = \dot{V} * \sqrt{\frac{\rho}{\rho_0}} \qquad \left[\frac{m^3}{h}\right] \qquad \text{(Formula 6)}$$

Whereby:

$\dot{V}_0$ is the adjusted air flow rate under reference conditions;

$\dot{V}$ is the measured air flow rate under laboratory conditions;

ρ_0 is the density of air under reference conditions ($\rho_0 = 1{,}198\ kg / m^3$);

ρ is the density of air under laboratory conditions, calculated according to Formula 9

$$\rho = \frac{p_a - 0{,}378802 * p_w}{287{,}055 * T} \quad \left[\frac{kg}{m^3}\right] \qquad \text{(Formula 7)}$$

Whereby:

p_a is the air pressure in Pa;

T is the thermodynamic temperature in K;

p_w is the water vapour pressure in Pa, calculated according to Formula 10

$$p_w = 610{,}5 * \phi \exp\left(\frac{21{,}875 * (T - 273{,}15)}{T - 7{,}65}\right) \quad [Pa] \qquad \text{(Formula 8)}$$

Whereby:

ϕ the relative air humidity

The extremely constant laboratory conditions only lead to marginal adjustment factors for the measured volume flow. These were between -1.002 and +1.005 for the measurements that took place.

Characteristic lines resulted from the measured data pairs (leakage flow volume and pressure difference) for excess pressure and negative pressure conditions. These are shown in a double algorithmic chart (see 7.2: Appendix B). Each flow equation can be depicted with the coefficients C and n using the MS Excel trend line function. The desired leakage flow at a pressure difference of 50 Pa can be obtained for excess and negative pressures by using the corresponding pressure of 50 Pa for the variable Δp. The average of these two values gives the desired leakage volume flow. The offset value of the test stand should be subtracted for final assessment.

5 Examination of the sealing methods

For this examination, a distinction was made between sealing methods which were recommended by manufacturers and other solutions (referred to as "alternative solutions" here).

Numerous manufacturers were contacted for a selection of products and methods to be tested and asked about approaches for solving this specific problem. Of those contacted, ten companies at home and abroad made product samples available to the Passive House Institute, and some also provided advice regarding the use of these products. For selecting the products to be tested for airtight integration of the ends of old wood beams, several specialist manufacturers were contacted and asked about approaches for solving this specific problem. Consequently, of those contacted, ten companies at home and abroad made product samples available to the Passive House Institute, where the experiments were to be carried out. A wide range of solutions - by no means exhaustive - were thus made available.

Eight different methods for sealing the sample beams were chosen from these samples. These methods consisted of a combination of up to three materials from the following product groups: adhesive tape, sealant/adhesive, adhesive primer, elastic butyl rubber tape, a special solution, and plaster sealing tape. For each tested sealing method, "system compliance" was always ensured, i.e. products from different manufacturers were not combined with one another other in the methods in order to rule out incompatibility of the used products. The focus of this examination was on the different methods of sealing and not on the individual products of the manufacturers.

A total of eight series of measurements with solutions provided by manufacturers, and four series of measurements with alternative solutions will be presented and evaluated here. A comparison of manufacturers was carried out for the combination **a**dhesive tape + **a**dhesive primer + **s**ealant (AAS), which is the reason why this method was tested twice.

Table 1 gives an overview of the methods, which are twelve in total. As mentioned before, three sample beams were prepared and measured at the test stand for each test.

Table 2: **Product matrix of the different combinations of materials for the tested methods (method = Product I + Product II + Product III)**

Method	Product I	Product II	Product III
Manufacturers' solutions			
1	Adhesive tape	-	-
2		Adhesive primer	-
3 + 4			Sealant/adhesive
5	Elastic butyl rubber tape with special non-woven backing	Adhesive primer	-
6		Sealant/adhesive	-
7	"Special solution" (pure acrylate dispersion with non-woven material)	-	-
8	Plaster sealing tape	Sealant/adhesive	-
Alternative solutions			
9	Sealing membrane collar	Sealant	Adhesive tape
10	Sealant (drilled hole for sealant)	Adhesive tape	-
11	Thick bituminous coating	-	-
12	Poured gypsum plaster (only usable horizontally)	-	-

5.1 Description of materials

The materials used for the test are described below in brief:

Adhesive tape

Adhesive tapes used for airtightness usually have an acrylate-based adhesive on a carrier material with maximum elasticity and tear resistance, such as polyester fabric.

These adhesive tapes are used for airtight connection of vapour retarders as well as for sealing of penetrations (electrical installations, beam heads, chimneys etc.).

Adhesive primer

Adhesive primer mostly consists of a water-based acrylate-copolymer dispersion.

The primer is used to create optimal conditions on the substrate on which the adhesive tape is to be applied. For example, primer is used for pre-treatment of wood fibreboards etc. Use of a primer always increases the quality of the bond between the substrate and the adhesive tape. According to the manufacturers of one water-based product, after application a drying time of 15 to 30 minutes is necessary before tape can be applied on this.

Sealant/adhesive

A variety of sealant and sealing adhesive products are available, ranging from special-purpose rubbers and single-component special polymers to modified acrylate polymer dispersions and two-component reactive epoxy adhesives. The basic material of the adhesives or sealants of some manufacturers is not immediately apparent.

The purpose of all variants mentioned here is the creation of permanently elastic bonding of the airtight sheeting either at overlaps or for connection of airtight sheeting and penetrations. Sealants and adhesives can also be used to even out irregularities of the substrate in order to avoid leaks. The viscosity of the respective material is of crucial importance for filling in the artificially created leaks in the sample beams and thus also for filling in of the cracks which occur in beams in actual practice.

Butyl rubber tape

Adhesive tapes made of butyl rubber are characterised by a high degree of flexibility and extensibility. Another advantage is the ductility of these tapes in the case of penetrations. In this context one can even speak of sealing collars which can be formed by hand. Due to the thick layer of material, it is possible to even out smaller irregularities in the substrate and thus avoid small leaks. Besides sealing of penetrations, butyl rubber tapes are also used for airtight joining of gaps, components and overlapping airtight sheeting.

"Special solution"

The method referred to as a "special solution" is a paste-like functional coating. This consists of a pseudoplastic pure acrylate dispersion which is applied together with a special-purpose non-woven material to the area to be sealed. First a coating of dispersion is applied, then the non-woven material is placed over the dispersion and formed corresponding to the penetration. Dispersion is again applied over this.

Figure 14: "Special solution" for sealing a penetration through sheeting, using a paste-like functional coating based on pure acrylate dispersion (source: Dörken GmbH & Co. KG)

Plaster sealing tape

For connections involving doors, windows, or even purlins and ceiling beams, among other things plaster sealing tapes are also used in practice. These consist of a non-woven polypropylene or polyethylene layer with a special-purpose membrane. One side of the tape is attached to the penetration similar to an adhesive tape. The other side is plastered over airtightly. The tested products demonstrated slightly vapour retarding characteristics with a sd-value of ca. 2.5 m.

Thick bituminous coating

A thick bituminous coating is normally used for sealing masonry ("black tank"). Industrially produced mixtures of bitumen and synthetic polymers (elastomeric bitumen) are used for this.

5.2 Description of the methods and process

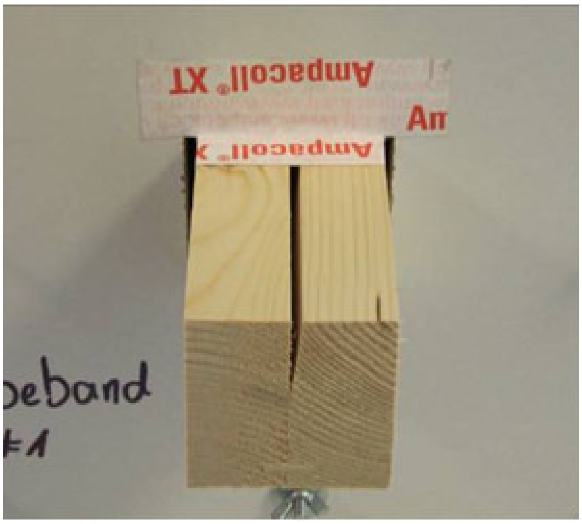
The process for the sealing procedure was examined and described for each of the three samples for a sealing method. These methods are presented here with photographs of the work steps. Any specific characteristics which were noticed during the procedure were also described.

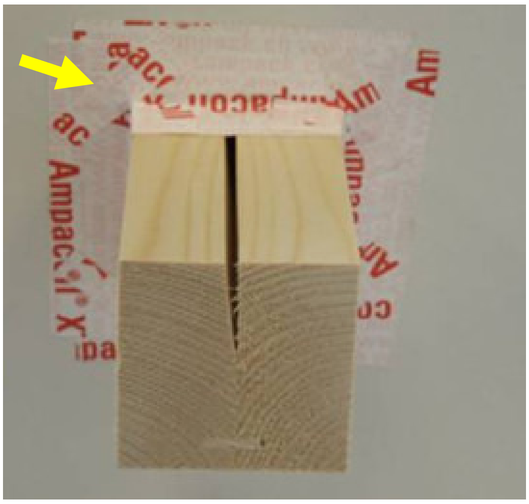
Some of the tests were carried out in the context of the work by [Bangert 2012]. The measured values had to be adjusted slightly compared to other already published results ([PHT 2012] and [Buildair 2013]) on account of an error in the measuring device. The statements and general findings are not affected by these minor corrections.

Method: Adhesive tape

In this method, only tape is applied all around the beam and joined to the cover; no further sealing of the crack in the test beam is carried out. The individual steps of the procedure are explained in Table 3.

Table 3: Steps of the procedure for the adhesive tape method

1.	A strip of adhesive tape extending 3 cm on both sides of the beam is applied at the transition of the sample beam to the cover, this must be done in a strain-free manner so that component movements can be accommodated. There must be sufficient adhesive tape width on the beam and the cover (centre). A cut is made in the adhesive tape at each edge of the beam in order to guarantee absence of tension in the bond.	
2.	The second strip of adhesive tape is applied in the same way as Step 1. Due to overlapping of both strips of adhesive tape, there is a small remaining weak point which is sealed with an additional strip of adhesive tape.	

3.	The remaining sides are joined with more strips of adhesive in an identical manner. The smaller diagonally applied strip of tape which seals the weak points at the corners is visible in the picture, above left (arrow).	

As mentioned before, the excess pressure and negative pressure were measured at the test stand for each sample. As a rule, the results of both these measures varied on account of the layout of the residual leaks and the type of sealing. There are "movable" areas of the bond which are more or less airtightly sealed depending on the type of pressure. This phenomenon is familiar from airtightness measurements in existing buildings. This can be compared with a one-way valve: if air can pass through a leak from one side, then a current of air in the opposite direction closes the leak.

The arithmetic mean for each measurement is obtained from the respective negative and excess pressure. A common average value is then calculated from the three average values. This value is used for the subsequent comparison of the methods. All results are standardised for a differential pressure of 50 Pa.

The result of the three excess pressure measurements with the adhesive tape method is $V_{p,ex}$= 1.80 m³/h at 50 Pa, after deduction of the residual leakage of the box (offset value). The offset-adjusted result of the negative pressure measurement is much better with $V_{p,neg}$= 1.45 m³/h. Hence, the volume flow transferred at negative pressure is only ca. 80 % of that transferred at excess pressure. For the arithmetic mean from the measurement at excess and negative pressure, the result is **V_p= 1.61 m³/h**. Figure 15 below shows the measurement results for all three samples with the adhesive tape method at excess and negative pressure, as well as the arithmetic mean.

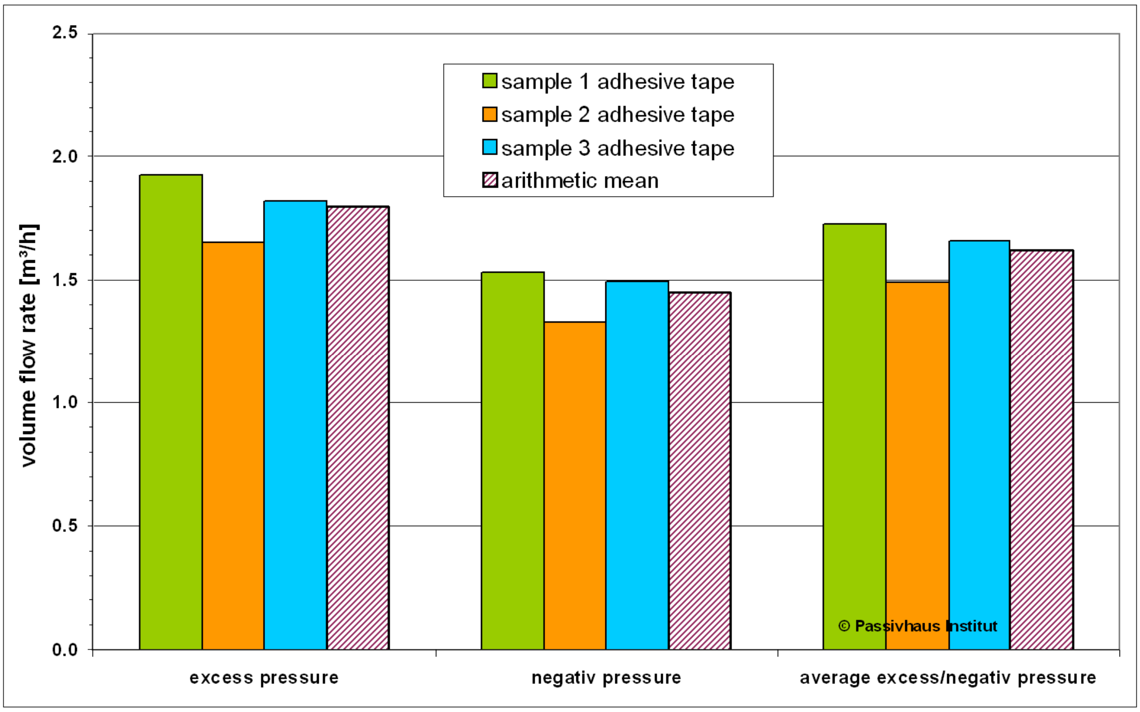


Figure 15: Measurement results for sealing using adhesive tape at excess and negative pressure for each of the 3 samples, and the arithmetic mean values

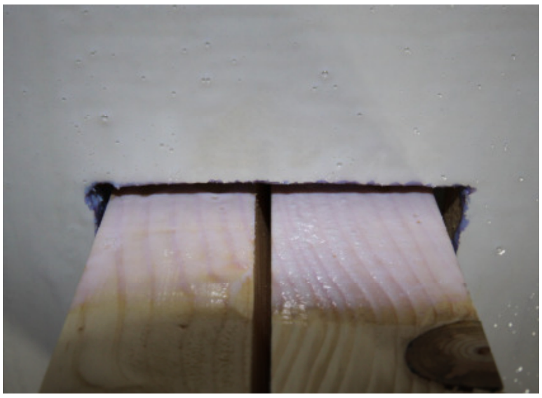
The sealing method using adhesive tape is of particular interest for this study since it provides the leakage flow which would result if the artificially created crack in the beam is not sealed at all although the beam is connected to the cover and thus to the airtight layer. If it is assumed that the adhesive tape and the bond are completely airtight, then this measurement provides the maximum volume flow rate which escapes through the crack. In the present study, the measured value serves as a **reference value** for the different sealing methods. The relevance of this value is also of special interest, since in practice, penetrations by beams are frequently sealed in this way, provided that the beams are completely exposed for this work in the first place.

Method: Adhesive tape + adhesive primer

Adhesive primer is used to prepare porous surfaces, such as masonry, plaster, concrete, untreated wood and soft wood fibreboards, for the application of adhesive tape. Primer was used here in order to improve bonding with the beam even further.

Adhesive primer was applied to the vertically positioned beam using a brush. The vertical position of the beam was intended to rule out to a great extent any possible influences due to the location of the crack. For example, if the crack opening is pointing upwards, the fluid adhesive primer can run into this. However, if the crack is on the underside, the adhesive primer will immediately run out of the crack. The adhesive primer has a milky consistency and therefore flows down the beam quite fast. The drying time stated by the manufacturer depends greatly on the substrate. The adhesive primer will take longer to dry if the absorbency is low.

The procedure for adhesive tape is the same as that for the preceding method with adhesive tape. For comparison purposes, the same product was used. In this way, an attempt could be made to evaluate the influence of the adhesive primer.



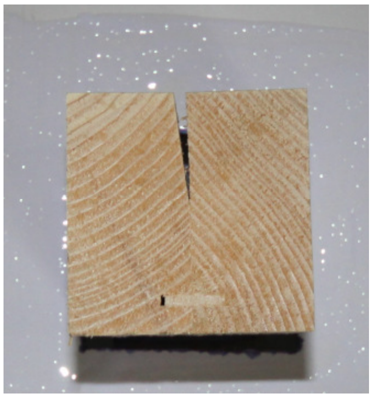


Figure 16: Beam with adhesive primer prior to application of adhesive tape

The differences ascertained with the measurements for excess and negative pressure are not relevant in practice; depending on the kind of conditions, other differences may result. The results of the individual measurements for all tested methods are presented in Appendix 12.5. The average values of all measurements are presented and compared in Section 8.3.

According to expectations, with Vp = 1.50 m³/h the measured result is in the same order of magnitude as the measurement without adhesive primer. As in the previous test, it was ascertained that less volume flow was transferred out of the test stand at negative pressure. In comparison with the first two samples, the third sample has a somewhat reduced volume flow, which can be attributed to the workmanship of the sealing procedure.

It can be stated that the influence of the adhesive primer on the quality of sealing of the beam is small. This is not surprising since - as described above - the primer does not have a noticeable influence on sealing of the crack. These methods can therefore be considered as almost identical. With that said, no general statement can be made regarding the necessity or usefulness of adhesive primers. Adhesive primer is necessary in particular for the substrates mentioned above and provides considerable advantages in relation to the durability of the bond. In general, the manufacturer's instructions should always be observed.

Method: Adhesive tape + adhesive primer + sealant

In the method with adhesive tape + adhesive primer + sealant ("AAS"), adhesive primer and adhesive tape were used as in the preceding method, the only difference being that the crack was filled using sealant out of a cartridge. Unlike the previous tests, this reduced the leakage area of the crack, which can be expected to result in a decreased leakage volume flow.

A comparison of manufacturers was carried out for the method with "AAS". The variants to be compared will be referred to as "AAS I" and "AAS II". For each of the methods "AAS I" and "AAS II", exclusively products belonging to a single manufacturer were used. This is referred to as " system compliance". The objective is to use only products that are compatible with each other.

Before applying the adhesive primer and the adhesive tape, an applicator gun was first used to inject the sealant into the artificial crack of the beam in the horizontal position. The attempt was made to inject the sealant as deep into the crack of the sample beam as allowed by the tip of the cartridge. It was found that in both cases the sealant could not be pressed completely down to the tip of the crack. After a visual inspection, it was apparent that the sealant penetrated more deeply in the variant "AAS II" (see Figure 17). This difference is also apparent in the measurement results. The reasons for better penetration were a lower viscosity and the narrower cartridge nozzle.

It is therefore recommended that a narrower cartridge nozzle is used in case of thinner cracks. In this way the crack can be filled a greater depth, which is equivalent to a reduction of the residual leakage.

After filling the crack with the sealant and applying primer to the beam, the adhesive tape was applied all around the beam as described previously.

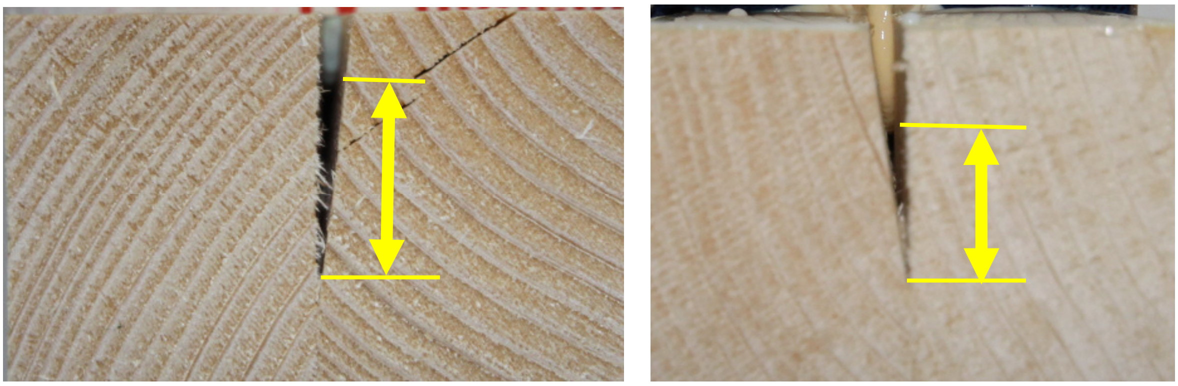


Figure 17: **Penetration depth of the sealant in the crack with the methods AAS I and AAS II. The arrows show the remaining gap.**

A better level of crack sealing could be achieved in both cases if the crack opening was covered. This can be achieved, for example, by applying a collar around the beam before injecting the sealant. Without this collar, the material will simply spill out at the top of the crack when injecting the sealant. This is not helpful for sealing cracks.

After injecting the sealant, the beam was left in the horizontal position for two days in order to allow hardening of the material. Further penetration of the sealant into the crack could not be ascertained after a visual inspection.

Method: "AAS I"

The results of the measurements for the three samples with the method "AAS I" were very close together, the volume flow for negative and excess pressure measurements was almost identical. The arithmetic mean volume flow of the excess and negative pressure measurement for all three samples was $V_p = 0.92\ m^3/h$. Hence the improvement expected as a result of injecting sealant in the crack is already apparent.

Method: "AAS II"

The volume flows for the method "AAS II" were considerably smaller than those for the method "AAS I". Evaluation of the three samples showed that one sample differed significantly from the other two. After a visual inspection it was ascertained that the sealant did not penetrate the crack as deeply as in the other samples. A volume flow of $V_p = 0.38\ m^3/h$ was ascertained for the average of the excess and negative pressure. As in the preceding test, there was no significant difference between the results of the excess and negative pressure measurements.

Comparison of both methods with AAS

A comparison of both methods shows that the crack in the beam can be filled better and more deeply with a narrower cartridge nozzle and lower viscosity of the sealant.

Thus a 59% lower leakage volume flow results for the average value of the excess and negative pressure measurement (for all three samples) with the method "AAS II" compared with the variant with "AAS I".

Method: Butyl rubber tape + adhesive primer

Adhesive primer was first applied on the sample beams in the same way as in the preceding tests. After the primer had dried, the sample beam was sealed to the cover using butyl rubber tape. The high adhesive force of this tape requires great care since it is very difficult to remove the tape once it has been stuck on. The butyl rubber also gives the tape a high level of flexibility so that it is possible to apply this around the beam in one piece (Figure 18). Cutting to size and joining of several pieces of tape, as is necessary with the acrylate based adhesive tapes, is therefore unnecessary with butyl rubber tape. However, reduction of the leakage area is hardly possible with this as the material cannot be pressed deep enough into the crack in the beam. Smaller irregularities can, however, be levelled out quite well with this type of tape.

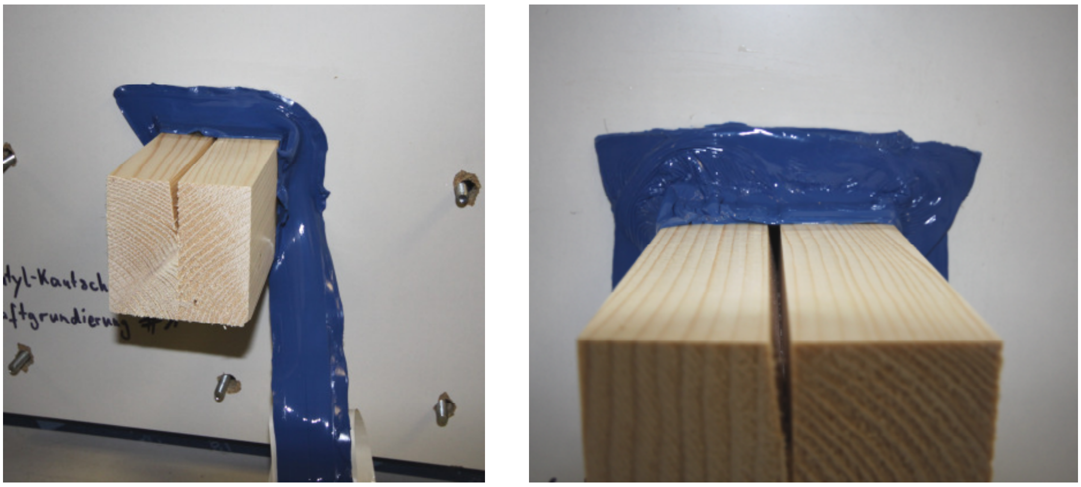


Figure 18: Procedure with butyl rubber tape (left: application in one piece; right: very small penetration depth of the elastic adhesive material into the crack)

Evaluation of the three samples shows a 20% lower leakage volume flow at negative pressure, compared with excess pressure. The reasons for this have already been explained in the previous sections. There are no large differences between the three separate measurements.

A volume flow of **Vp = 1.65 m³/h** results for the arithmetic mean of the excess and negative pressure measurements. This measured value is similar to that achieved with the method with adhesive tape only (reference value). Since it was not possible to seal the crack any further with the butyl rubber tape the result was within the expected range.

Method: Butyl rubber tape + sealant

In the method with butyl rubber tape + sealant, the crack in the beam was filled in with sealant as deep as possible before butyl rubber tape was applied to the beam. The same sealant as used in the method "AAS I" and the same butyl rubber tape as in the method with butyl rubber tape + adhesive primer were used. The procedures are described in the relevant preceding sections.

Based on the average values, no difference was ascertained between the negative and excess pressure measurements. A leakage volume flow of Vp = 0.94 m^3/h (arithmetic average of excess and negative pressure for the three separate samples) resulted at a pressure difference of 50 Pa. The recorded volume flow was thus at the level of the method "AAS I". This result would have been expected on account of the small penetration depth of the sealant. A significantly better result equal to that of method "AAS II" can be expected if a low-viscosity sealant is used.

Figure 19: Filled in crack with small penetration depth of the sealant (left) and application of the butyl rubber tape (right)

Method: "Special solution"

The procedure for the "special solution" (pure acrylate dispersion) was carried out in three steps. First of all, an initial coat of the paste-like compound was applied to the cover and the wood beam with an ordinary brush. The crack in the sample beam was also filled in completely with this. The sample beam was positioned vertically for this purpose. The special-purpose non-woven material was applied around the beam and pressed onto the already applied primary coat of dispersion. The material was pressed into the crack using a thin wooden stick for maximum sealing. The third and last step involved completely saturating the non-woven material with a second application of the paste-like compound. In doing so, particular attention was given to loops in the material, in accordance with the manufacturer's instructions, as otherwise leaks would occur in these areas. The steps described here for the procedure with the special solution are shown in the pictures below.

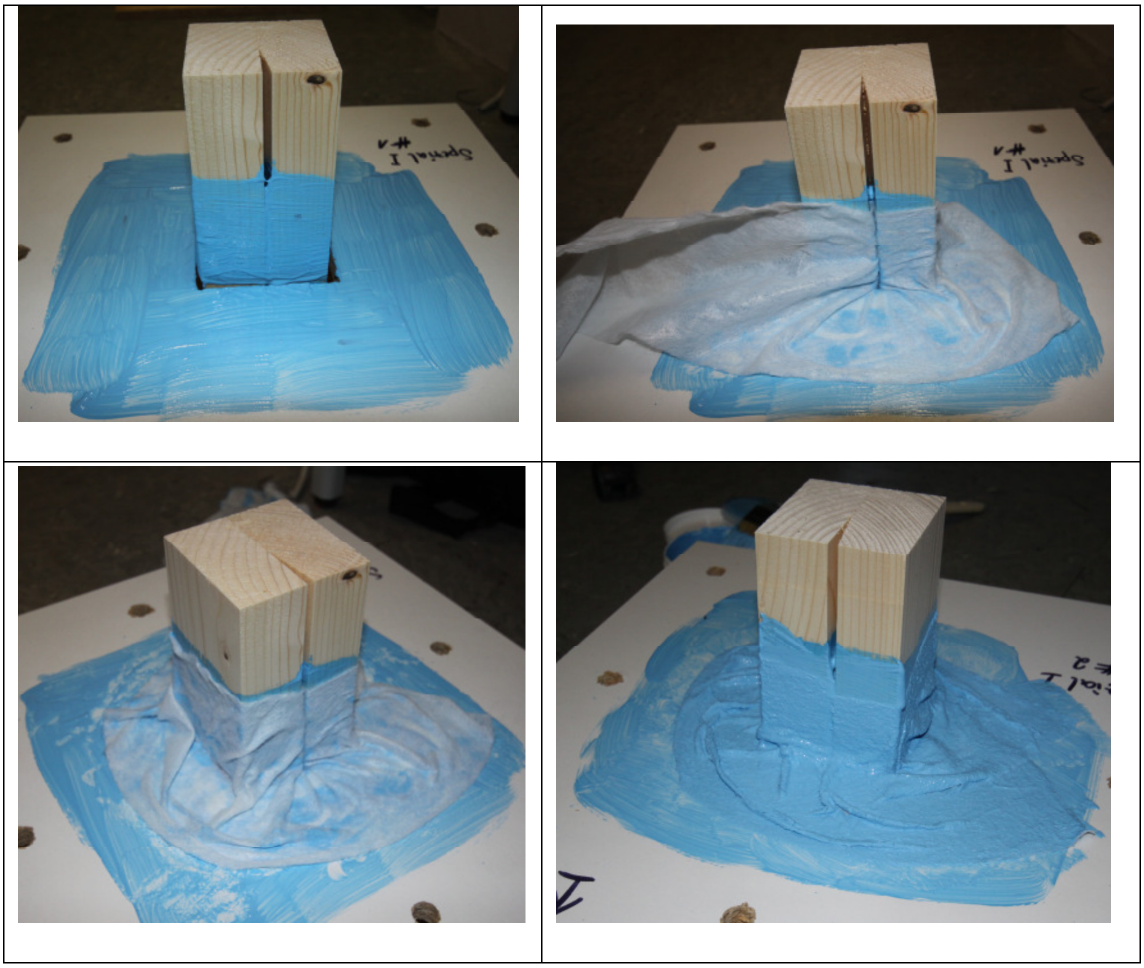


Figure 20: Pictures showing the procedure for the "special solution" (above left: initial layer of paste-like compound on the beam and cover; above right: fitting of the material into the gaps and crack; below left: material fitted and pressed on, folds can be seen clearly; below right: second coat of paste-like compound/saturated material)

The relatively strong odour of the compound necessitates thorough ventilation of the room where the product is being used. Apart from the odour, a positive characteristic of the material was its viscosity. This is almost ideal for the purpose of sealing cracks since it can fill the crack completely (see Figure 21) without running down the vertically positioned beam. However, there are certain limitations to be considered for overhead work carried out under the beam.

Further more, it should be noted that large amounts of materials are necessary for thorough saturation of the material especially with regard to the resulting folds. In addition, the extra effort due to the necessity for carrying a bucket of the compound (usually a 5 litre container) and the corresponding non-woven material should be taken into account. This may result in practically relevant disadvantages for the use of the "special solution" on ladders or other work areas with limited possibilities for setting aside of equipment.

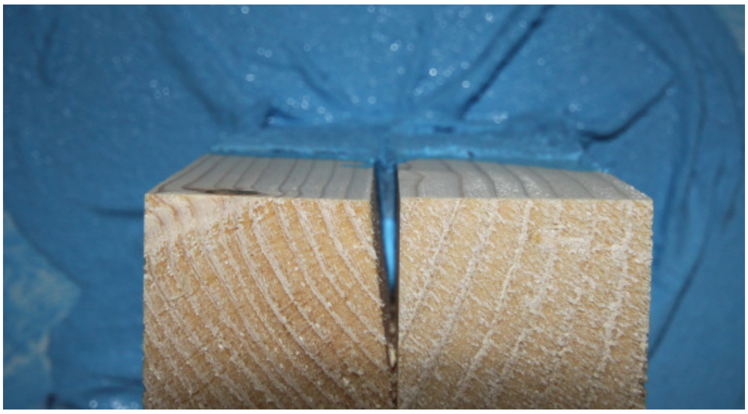


Figure 21: Crack completely filled with compound

With Vp = 0.38 m^3/h, the result of the measurement is in the low range and demonstrated the effectiveness of this sealing method. The residual leakage is the same as with the method "AAS II" which was best up till now. The measurement results do not show any serious differences between sealing at negative pressure and at excess pressure. These differ by just 5%. The poorer result for one of the samples was more striking, which points to the influence of the workmanship.

The leakage volume flow in one measurement (Vp = 0.58 m^3/h) is more than twice as high as the average value of the other two samples, which is conspicuously high. For verification, another measurement of the conspicuous sample was carried out a few days after the first measurement. In this way, through **reproducibility** of the measurement result it was possible to rule out a faulty measurement. Again the result was significantly higher than in the other two original measurements, therefore an incorrect measured value could be ruled out. The difference between the two measurements was just 5.2%.

A visual inspection of the sealing of the crack was carried out for further verification. No difference between the three samples could be ascertained thus. When a light source was held behind the beam, light did not pass through the crack with any of the samples. In order to visualise any leakage that existed, the test stand was filled with fog and excess pressure was generated using a pump. Leaks could be localised quickly by observing the escaping fog. Fog escaping in the whole area of the transition of the beam to the cover could be ascertained. It appeared that in spite of good workmanship, saturation of the non-woven material here was less intensive than in the other two samples. In order to confirm this, the procedure with the fog as described above was also repeated with one of the other samples. Here too, the smoke escaping in the whole area of the transition of the beam to the cover could be seen, but this was much less than in the first sample.

Heavy saturation of the material is thus decisive for the success of this method of sealing a penetrating beam. Weak points may still occur despite visibly correct implementation.

Method: "Special solution II”

The "special solution II" consisted of an adhesive with mineral fillers in the form of a bead. The material is also available as a sealant in a tubular bag. The airtight transition of the beam to the cover cannot be achieved with this product alone. Complete sealing of the sample beam is only possible with the additional use of airtight sheeting.

For the procedure with the "special solution II", the material was applied as a bead all around the beam. At the point where the bead passed over the crack, a loop was formed with the material in accordance with the manufacturer's instructions in order to smooth out any unevenness. The excess material was flattened over the crack and pressed into the crack (see Figure 22).

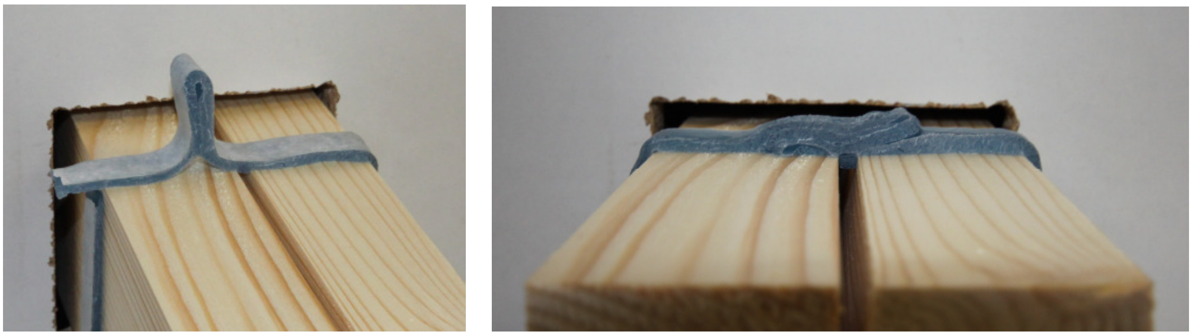


Figure 22: Procedure for the "special solution II"

After this, an attempt was made to create an airtight connection between the beam and the cover using ordinary airtight sheeting. Application of a matching piece of sheeting around the beam without having to cut it up is hardly possible. The solution with a sealing membrane collar described further on is conceivable here.

Since the adhesive material hardly be pressed into the crack at all (see Figure 22, right), the crack area could not be reduced significantly. The result was expected to be similar to the solution with adhesive tape alone (reference value), therefore a series of measurements for this method was not carried out.

For the application of airtightness sheeting on rough substrates such as uneven plaster, the special solution II has a number of advantages over conventional adhesive tape. Due to the elasticity of the bead, small irregularities can be evened out and a greater level of bonding can be achieved. However, due to the reasons mentioned before, this method is not advised for the filling and sealing of cracks in wood beams.

Method: Plaster sealing tape + sealant

Plaster sealing tape which can be plastered over on one side (non-woven PET material) can be used for joining a beam with an airtight layer (e.g. interior plaster). Here the tape was used for sealing the gap between the beam and the cover, without subsequent plastering over. The procedure for applying this is similar to that for an ordinary airtight adhesive tape.

First of all the sealant was injected into the crack in the sample beam for maximum sealing. The compound used for this is identical to that used in the method "AAS II". The plaster sealing tape was then applied all around the beam in one piece by means of its adhesive strip. Detailed instructions for this are provided by the manufacturer. In order to allow application all around using a single piece of plaster sealing tape, the tape should be formed into small triangles at the corners of the beam, which are normally plastered over in practice (see Figure 8.2.9). The part of the tape which is non-adhesive was then stuck to the cover using airtight adhesive tape of the same manufacturer (instead of plastering over as would normally be done).

Figure 23: **Beam sealed using plaster sealing tape (light blue) and joined to the cover using airtight adhesive tape (dark blue). In the detail on the right, a triangle formed with surplus sealing tape at the corner of the beam is shown (procedure in accordance with the manufacturer's instructions)**

Formation of the triangles at the corners of the beam proved to be difficult. The guidance provided by the manufacturer with a series of pictures seems to be idealised and impracticable. The subsequent plastering over of the protruding triangles in particular would only be possible with an extremely thick layer of plaster.

In addition, it was striking that the viscosity of the freshly opened sealant was very low at first. The viscosity improved with the sealing carried out for the two other samples which took place immediately after the first sample had been sealed, corresponding with the experiences in the preceding experiments. One reason for this may be that the compound was not mixed well enough in the beginning. The storage temperature can be ruled as out as the reason since the compound was already stored in the test room for a long time.

Upon evaluation of the sample, only a slight variation in the leakage flows at excess or negative pressure could be ascertained for each sample. Nevertheless, there are large differences between individual results of the three samples: with reference to the highest of the volume flows of the three samples, the volume flow was only 22 % and 73 % for the other two samples.

The causes for this strong variation in the individual measurements will be discussed in detail below. As already explained above, when the test for the first sample took place, the viscosity of the sealant was lower than it was for the other samples. When tested with backlight in order to determine the penetration depth, no light could be seen through the crack in the first sample. This results in a high standard of sealing which is reflected in the measured values. With the other two samples, the penetration depth of the sealant was very small, therefore the measurement results are reasonable.

Altogether, for the method with plaster sealing tape + sealant, the average of the three different measurements gives a volume flow of **Vp = 0.50 m³/h** for the measurement result; the best value of the three samples is just 0.16 m³/h.

Method: Drilled hole for sealant

Sealing of the crack cross-section has a decisive influence on the leakage flow, regardless of the (appropriate) method used for joining the beam with the cover. It is thus expedient to carry out maximum sealing of the crack cross-section in a separate procedure, if necessary. The solution with the injected sealant as recommended by the consultant of a manufacturing company was therefore tested. For this purpose, the crack in the later sealing level was drilled down to the end and the drilled hole was then injected with a suitable sealant using a nozzle. Alternatively, a piece of rounded wood or a **wooden dowel** can be used to seal the crack.

This method is thus not comparable with the previous methods of sealing with the cover. Rather, this is a method for direct sealing of the crack area which must be combined with another sealing method. All those methods which do not appreciably seal the crack can be combined with this procedure and thus improved considerably.

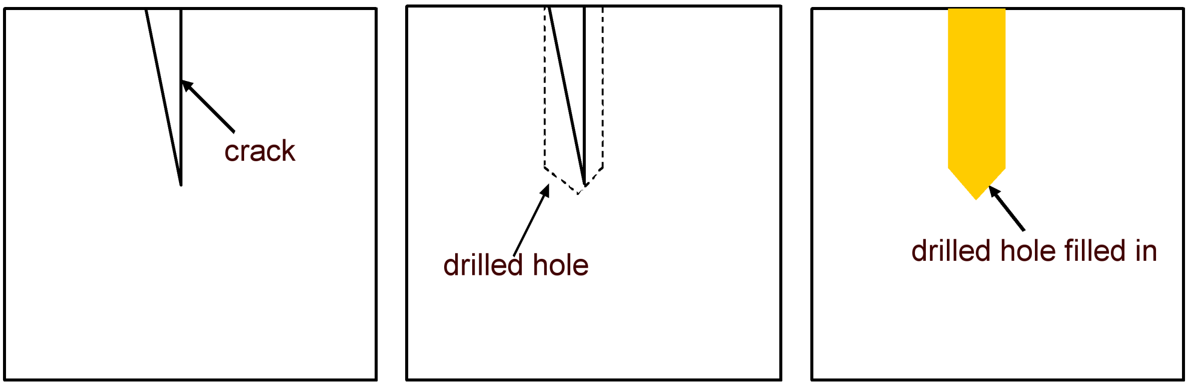


Figure 24: Schematic diagram (beam section) of the procedure for the solution with a drilled hole for sealant, with drilling and filling of the crack in the beam. Filling the hole with a wooden dowel is also possible.

The cracks in the samples were drilled to a depth of 36 mm using a 10 mm drill bit. The injection nozzle used for filling the crack was about 10 mm wide at the widest point (where it is screwed on to the cartridge). The bore chips should be removed completely out of the drilled hole. Drilling and filling of the crack must take place at exactly the same level where the beam is to be joined with the cover or wall.

This method involves spot drilling in the beam which inevitably weakens the beam, therefore the **structural stability of the beam** must be checked prior to this in order to avoid lasting damage.

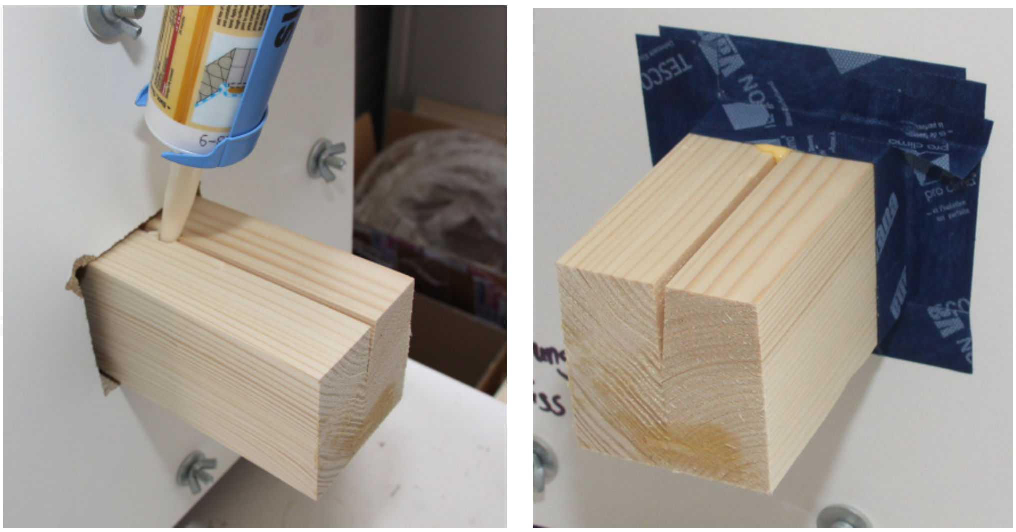


Figure 25: A hole is drilled in the crack at the later sealing level and filled with sealant (solution for drilled hole with sealant, left). The beam is then sealed with the cover using adhesive tape (right)

The result was excellent due to optimal sealing of the crack area and the appropriate adhesive tape. On average, a leakage flow of just **Vp = 0.03 m³/h** resulted for the three samples. It was possible to measure this small volume flow with the smaller volume flow measuring device. The difference between the three samples was very small.

Method: Sealing membrane collar

Another possibility for sealing between a beam and a wall area is the use of sheeting. This must be joined to all sides of the beam and the wall areas. The use of a sealing collar which matches the side of the beam and the gap between the beam and the wall area is a practical and simple solution for this purpose. In order to avoid the need for various product sizes and special products, this can be made easily with the aid of two or three templates (rectangular piece of board). The long side of the template can also be used for measuring the four identically long strips of adhesive tape.

The work steps are given below with the relevant sketches and pictures:

1. A hole is drilled in the beam crack in accordance with the injection + sealant method described above and the hole is filled completely with sealant.

2. A rectangular piece of airtight sheeting is cut to size (using a template if necessary)

3. Strips of adhesive tape are applied on all four sides of the piece of sheeting. In doing so, 50 % of the adhesive strip width is applied to the sheeting while the other half is left for affixing to the cover. In order to prevent sticking of these parts of the strips, it is helpful to use adhesive tape with a non-adhesive paper backing which is divided down the middle.

4. Two diagonal cuts (X-shape) are made in the middle of the rectangular piece of sheeting using a cutter/Stanley knife so that the beam can pass through this. The length of the cuts should be the same as the diagonal length of the beam cross-section.

5. A lateral incision is made in the piece of sheeting with the adhesive tape up to the x-shaped cut so that the sealing collar can be pulled over the beam.

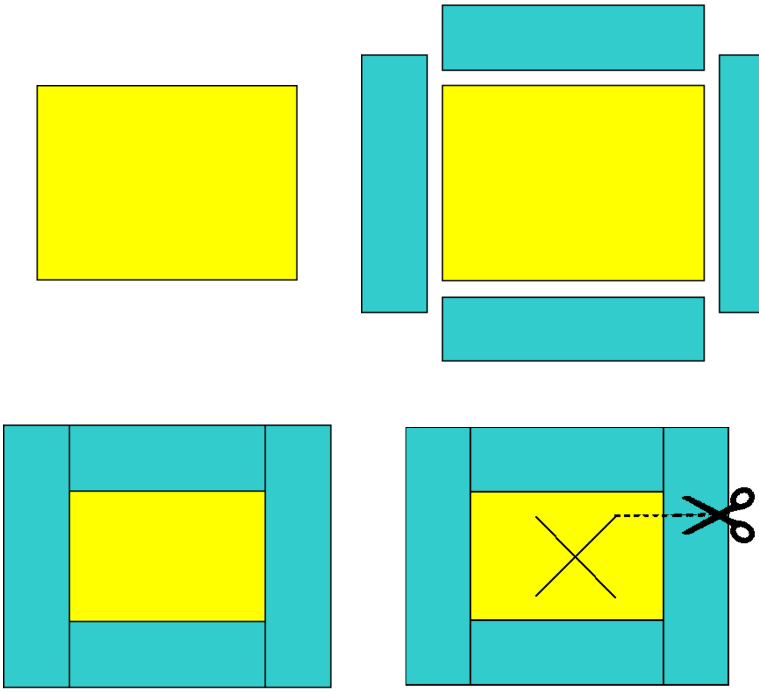


Figure 26: Schematic diagram of the work steps for creating a sealing membrane collar (yellow: sheeting, turquoise: adhesive tape). See text for explanations.

6. The piece of sheeting with the strips of adhesive tape is pulled over the beam; the X-shaped incisions are adjusted if necessary. Triangles of sheeting will result on each side of the beam.

7. The backing from the remaining parts of the adhesive strips is removed and the sealing collar is affixed to the cover at the sealing level without any strain or folds. The lateral incision in the sheeting and adhesive tape is closed with a strip of adhesive tape.

8. There is no surplus sheeting at the corners i.e. the four ends of the x-shaped incision. Sealant is applied at these corners to avoid potential leaks.

9. As a last step, adhesive tape is applied in one piece all around the beam over the surplus sheeting.

10. Care should be taken that the adhesive tape around the beam is wide enough (at least 2 cm). If the triangles of sheeting are too big due to the size of the beam, their tips must be cut off or another layer of adhesive tape must be applied.

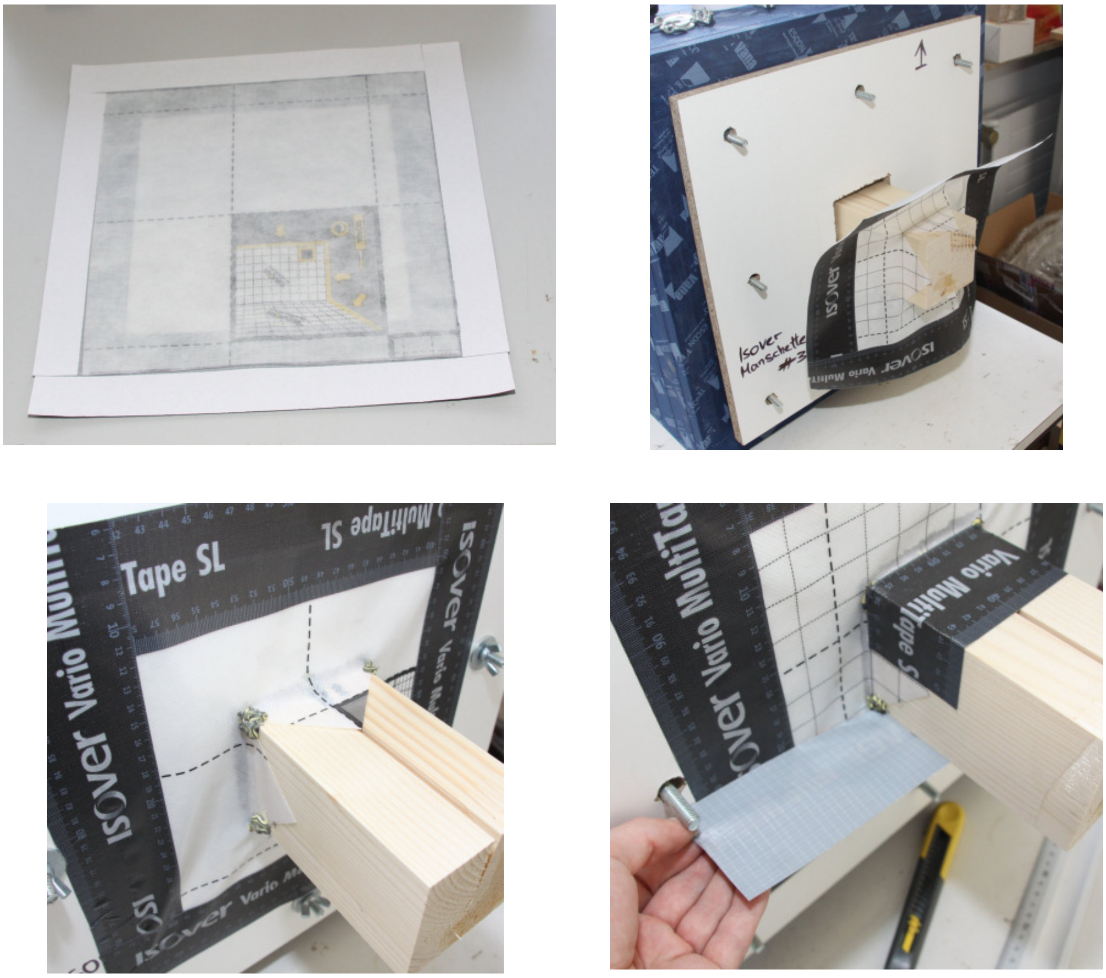


Figure 27: **Pictures showing the work steps for a creating a sealing membrane collar (see text for explanations)**

This method too does not just involve one or several products; instead it is a manual procedure combined with the injected sealant method, therefore the result is not directly comparable with the previous sealing methods.

The test result of the three samples created in this way resulted in a leakage flow of just **Vp = 0.22 m³/h**, thus this method provides a good result as expected, and is practicable at the same time. The differences between the three samples are only slight and are due to the workmanship.

Method: Poured gypsum plaster

It is also possible to use poured plaster to seal the various cracks in a beam. This method is only possible if the sealing level is horizontal. In this way, cracks in penetrating beams, for example in an unheated attic floor, can be sealed. Thin-mixed liquid gypsum plaster is particularly suitable for pouring; this does not shrink after hardening.

In this case the airtight layer is extended up to the beam and fixed. A barrier consisting of nailed strips of wood is then created at a few centimetres distance from the penetration; this will serve as shuttering. This is then poured with the thin liquid plaster which penetrates into all big and small cracks and seals the cracks completely. Large cracks must be plugged up using paper for example, so that the liquid plaster cannot drain away. Fine cracks that may occur due to structural movement are minimal since the material will remain in position.

For creating this sample, vertical positioning of the beam was necessary.

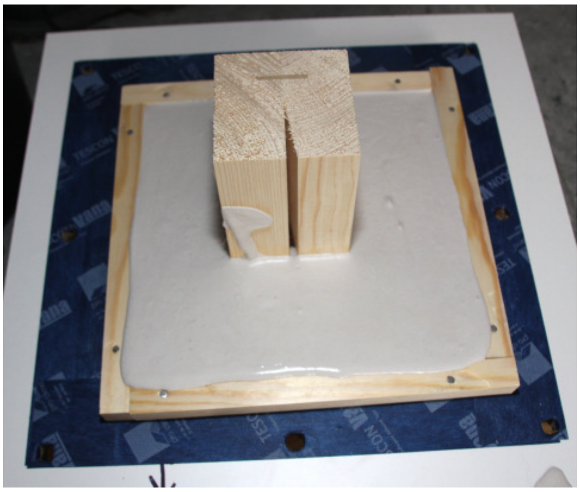


Figure 28: Horizontal poured gypsum plaster (thin liquid, with wooden frame)

This method gives an overall leakage flow measurement result of **Vp = 0.39 m³/h**. The quality achieved with one of the three samples was considerably poorer. The gypsum plaster was probably not thin enough to penetrate deep into the crack.

This solution too is for specific situations on account of its limitations (horizontal sealing level). This method was applied successfully in a refurbishment project in Nuremberg (Germany) [Feist 2003] as shown below:

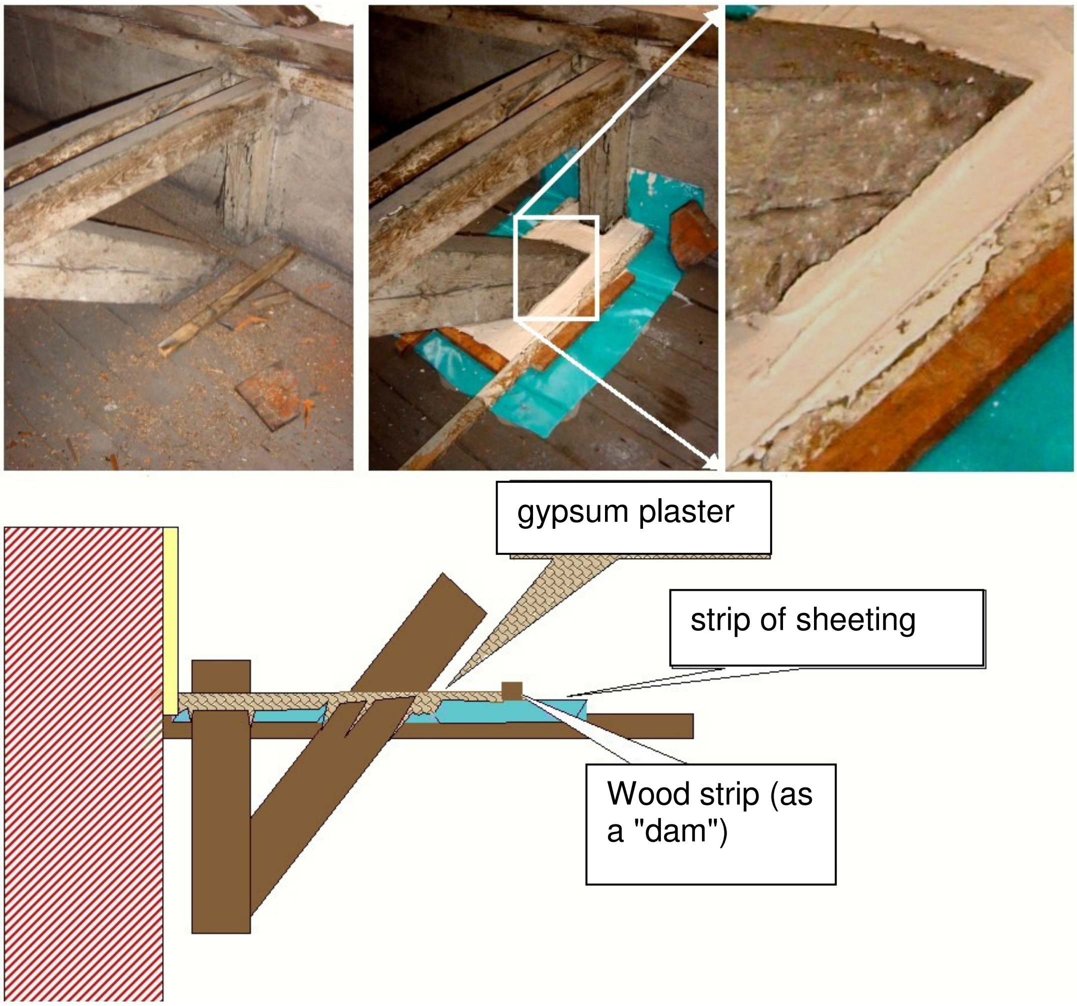


Figure 29: **Poured gypsum plaster used in the refurbishment project Jean-Paul-Platz 4 in Nuremberg (Germany). Penetrating struts in the airtight layer of the top floor ceiling were sealed in this way (above left: initial situation with a strut; above centre: poured gypsum plaster; above right: detail showing the plaster which has poured into all cracks; below: schematic diagram (from [Feist 2003]).**

Method: Thick bituminous coating

Commercially available bitumen-based thick coating which is normally used for sealing masonry ("black tank") was used as another possibility for sealing beams. This is a polymer-enhanced bitumen emulsion - an industrially produced mixture of bitumen and synthetic polymers. Suitability of this material for interior use was not studied within the framework of this examination.

The thick bituminous coating can be processed in the cold state and was applied generously all around the beam using a spatula. The gap between the beam and the cover could be bridged without the need for any further materials. A good level of sealing could be achieved between the cover and the beam. In doing so, the material was pressed into the crack using the spatula in order to seal this. It must be ensured that the layer of material is thick enough.

There is considerable variation between the three separate measurements here too; again, the performance in one sample was significantly poorer. It was clear that filling the cracks has a decisive influence. However, the average is quite low with a leakage flow of **Vp = 0.33 m³/h**. The material is easy to use and has proved to be effective over a long time, and is permanently flexible after hardening.

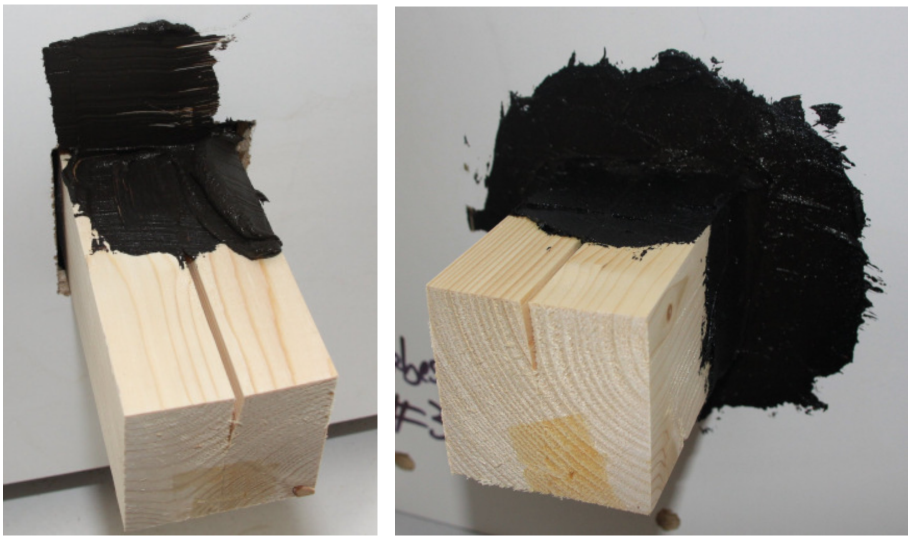


Figure 30: Application of the thick bituminous coating for sealing the beam

This method for sealing beams was used successfully in a refurbishment project in Wartin near Prenzlau (Germany) [Hasper 2010].

Figure 31: Example for the use of thick bituminous coating for sealing beams in the refurbishment project "Schloss Wartin" (Germany) [Hasper 2010]

5.3 Comparison of methods

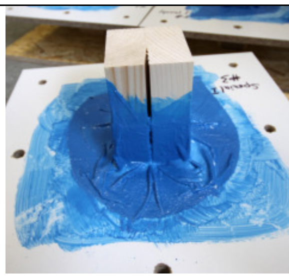
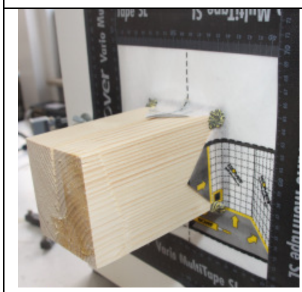
The comparison of the studied methods took place on the basis of the measurement results as well findings gained during the procedures with reference to practicability.

Comparison of the measurement results

For comparing the measurement results of the tested methods, the arithmetic mean of the excess and negative pressure measurements for the three tested samples was used. The values have already been stated in the descriptions for each of the methods. Figure 32 shows the average value of the three measurements and the minimum and maximum values.

As described further above, the measured values had to be corrected slightly compared to previously published results on account of an error in the measuring device. The statements and general findings of the previous publications are not affected by these minor corrections.

Table 4: Overview of the different methods carried out for sealing sample beams

			
Adhesive tape	Butyl rubber tape	Special solution (pure acrylate dispersion)	Plaster sealing tape
			
Sealing membrane collar	Drilled hole for sealant	Thick bituminous coating	Poured gypsum plaster

The measurement in which the crack was not sealed and only adhesive tape was used to join the beam with the cover (method with adhesive tape only) was used as a

reference value or benchmark. At a pressure difference of 50 Pa, a leakage volume flow of around 1.6 m^3/h remains with this method.

From the results of the method with the butyl rubber tape + adhesive primer (light blue bars) and the method with the adhesive tape + adhesive primer (yellow bars), it can be ascertained that the different tapes in these methods led to comparably airtight sealing. The difference here is barely 9 %. All in all, both these results are the same as the reference value, and are unsatisfactory since the crack area is not reduced.

Compared with the use of adhesive tape alone, a significant improvement can be ascertained as soon as the crack in the sample beam is additionally filled in with sealant, on account of the reduction of the leakage area. In the overview of the results (Figure 32), it is apparent that the largest reduction (purple and blue bars) in the leakage volume flow with **standard solutions** is possible with the methods adhesive tape + adhesive primer + sealant II ("AAS II") and "special solution" (pure acrylate dispersion with non-woven material). With corresponding sealing of cracks, around 24 % of the reference leakage volume flow remained with barely 0.4 m^3/h; a reduction of 76 % in the leakage volume flow was thus achieved. The "special solution" is fundamentally different from the other two methods, but is just as effective in relation to the quality of sealing.

A higher residual leakage volume flow remains if the crack area is only partly filled in. This is apparent from the variants adhesive tape + adhesive primer + sealant I ("AAS I") (green bars) and butyl rubber tape + sealant (brown bars): these achieve a reduction of ca. 43 % in the leakage volume flow compared with the case where the crack is not sealed. Both methods differ in relation to the way airtightness between the beam and the cover is achieved, but not in the way the crack is sealed. Here, the same material belonging to one manufacturer was used in both cases. This is the reason why the measured leakage volume flows of both variants differ only marginally from each other.

The comparison of products from two manufacturers which was carried out with the measurements for the method adhesive tape + adhesive primer + sealant shows the influence of different manufacturers' products. Due to the narrower cartridge nozzle of the sealant used in "AAS II" as compared to that used in "AAS I", it was possible to inject the sealant more deeply into the artificially created crack. Furthermore, the lower viscosity of the sealant used in "AAS II" resulted in better sealing. This difference, which was already apparent from a visual inspection, is also reflected in the measurement results for both variants. The leakage volume flow ascertained in "AAS II" is less by almost 60 % compared with that in "AAS I". The ascertained differences between both products relate only to the sealants; no leakages were noticeable at the two tape products.

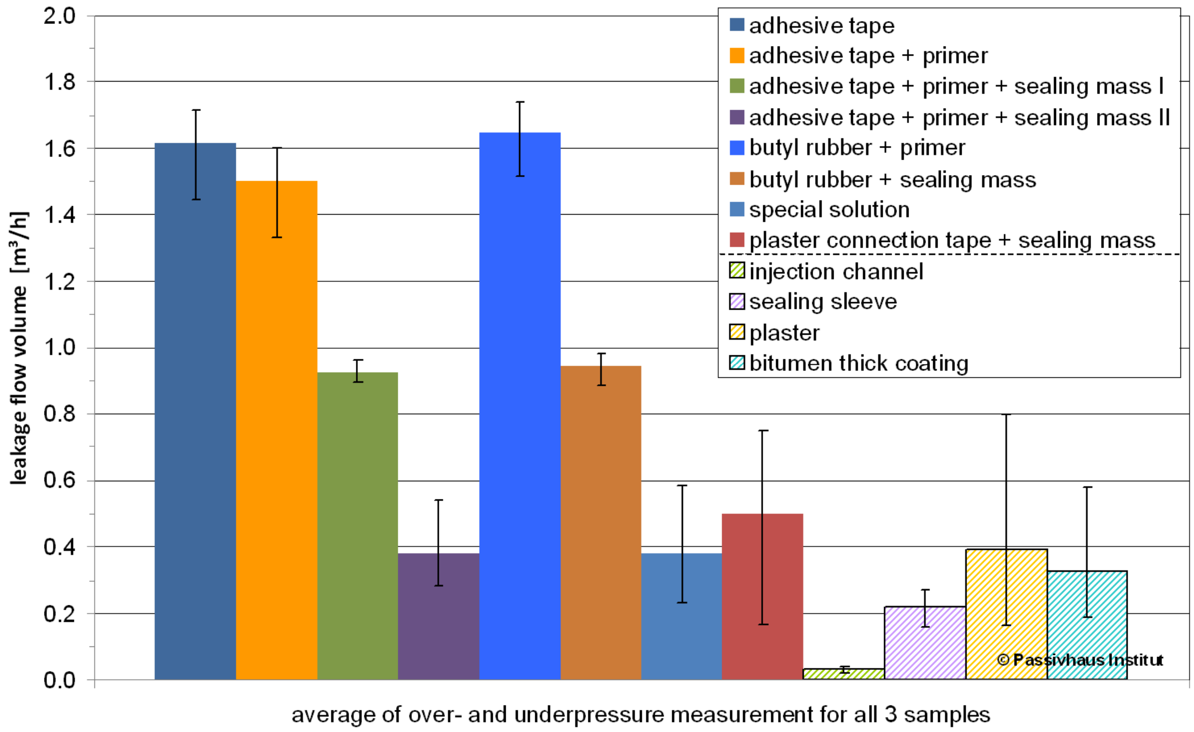


Figure 32: **Comparison of the leakage flows in the measurements carried out, standardised for a differential pressure of 50 Pa (average value of the excess and negative pressure measurement for the three samples respectively). The thin black line shows the respective minimum and maximum value that was measured.**

Results of the "Alternative Solutions"

The comparison of the measurement results for the four "Alternative Solutions" give very good results which are at least the same as or better than the previous results. These methods include combinations of the previous methods (sealing membrane collar) or additions to these (drilled hole with sealant). The poured gypsum plaster solution is limited on account of the horizontal application, while the thick bitumen coating solution is successfully and universally applicable. The best average value - i.e. the smallest leakage volume flow - results with the drilled hole with sealant solution with just 0.03 m³/h (corresponding to a 98 % reduction). This method of sealing cracks can be combined with all other methods. However, the structural stability of the beam must be checked in advance of any drilling work.

In all four "Alternative Solutions", the crack was filled more or less completely down to the end. The biggest difference between all studied methods was whether the crack could be filled with the chosen technique or not.

Special products were used for creating airtight connections in all the experiments that were carried out. All in all, it was ascertained that rather than the type of material of the selected special product for sealing, it is the maximum possible sealing of the crack area which matters. It is obvious that airtightness will increase noticeably as soon as the crack cross-section is reduced. No conclusions could be made within the framework of this study regarding the possibly varying durability of the tested connections. All tested samples were put into storage protected against UV light and could be examined again at a later point in time.

Comparison of ease of use

The tested methods for sealing wood beams differ considerably with regard to ease of use. If sealing of the crack is not carried out specifically, it should be possible to join the beam with the airtight layer (vapour retarder, engineered wood board etc.) relatively quickly. In contrast, a qualitatively high standard of sealing work – for which accessibility of the beam and thorough cleaning of the wood surface are a prerequisite – requires more time and care.

Due to its variability and fast application, butyl rubber tape proved to be excellent for achieving airtightness between the beam and the cover (without filling of cracks). It is expected that even in the case of extremely uneven substrates, the butyl rubber tape can be adjusted duly to the penetrating beam on account of the relatively thick layer of butyl rubber. Conventional acrylate-based airtight adhesive tape must be applied as several smaller strips around the penetration in such cases, as was done in the present series of tests. This requires time for cutting to length of the strips of tape and is prone to small leaks (see Section 5.2.1) if the strips are not applied carefully on top of each other. Besides the use of butyl rubber tape, the use of plaster sealing tape is also conceivable in order to avoid having to cut lots of strips of adhesive tape, but this may lead to the problems mentioned in Section 5.2.8 regarding the work at the corner areas of beams.

In practice, the use of a cartridge with sealant may mean extra effort but it is possible to fill in deep cracks quite quickly to a good standard by means of this. A prerequisite for this is a sufficiently narrow tip of the nozzle and corresponding viscosity of the sealant. In order to achieve a comparable level of sealing of any cracks, the use of the "special solution" (pure acrylate dispersion) is also conceivable, but this requires several layers and a sufficient quantity of material must be applied, which is not easy to check visually. It must also be considered that carrying the materials (container of adhesive and non-woven material) may present an additional obstacle. However, of the products tested in this series of tests, this was outstanding with regard to adaptability for a wide variety of penetrations; only the thick bitumen coating is assessed as equally good.

A very good standard of sealing can be achieved with the sealing membrane collar which is a simple possibility that requires very few materials (which are used for sealing work in any case).

Since sealing of the crack is decisive for a good result, the methods should always be combined accordingly. Sealing using the method with the drilled hole and sealant provides the best results and ease of use. Excellent results are obtained if this is combined with the application of adhesive tape, butyl rubber tape or the sealing membrane collar. The drilled hole method can also be implemented with a wooden dowel, which is certainly positive with regard to preservation of historical buildings.

One again, it is necessary to note that completely exposing and thorough cleaning of the beam is a prerequisite for all the methods and work.

5.4 Transfer of the results to large sample beams and old beams

The study with the small sample beams with just one leak was carried out in order to allow comparison of the various methods. In the process, influences other than those of the sealing procedures were intended to be excluded or kept to a minimum as far as possible. This was therefore a deliberately idealised situation compared with the situation with beams in historical buildings. In order to allow translation of the results to typically occurring situations, some measurements were carried out using larger beams.

For this purpose, out of the measurements described above, the two most successful sealing methods of the manufacturers' solutions, i.e. "AAS II" (see Section 5.2.3) and the "special solution" (see Section 5.2.6), were tested on an old sample wood beam (ca. 16 x 12 cm) (referred to here as old or real beam) and a large sample beam (16 x 15 cm). This larger sample beam had several small cracks of different shapes: diverse small and a few large cracks which all tapered off to zero, in order to approximate as closely as possible the actual natural crack shapes. The total leakage area of this large beam was ca. 11.5 cm^2; in contrast to this the small sample beam in the more extensive study only had a leakage area of 0.9 cm^2.

Figure 33: Sealed "large" sample beam (left) and "old" or "real" beam (right)

The sealing method with the adhesive tape without any other measures for sealing cracks was again used as a reference value. On account of the limited pump output, airtightness of the large sample beam could not be measured at the desired pressure difference using this method, therefore the leakage flow had to be extrapolated to 11.3 m^3/h. All other measurements could be carried out in the same way as for the measurements with the small sample beam as described further above. However, only one sample was prepared and tested in these indicative measurements instead of three samples. The reference case with simple application of adhesive tape resulted in a leakage volume flow of 6.6 m^3/h for the old beam.

After filling of the crack with injected sealant and application of adhesive tape, a reduction of 89 % in the leakage volume flow was achieved with the larger sample beam; the remaining leakage volume was just 1.2 m^3/h. With the old beam the remaining leakage volume with this method was 0.4 m^3/h, corresponding with a 95 % reduction.

The sealing method with the "Special Solution" using pure acrylate dispersion and special-purpose non-woven material was also carried out for the large sample beam. An even better level of sealing was achieved with this; a leakage flow of just 0.5 m^3/h remained, which corresponds with a 96 %reduction. The results of the measurements are presented in Figure 33. As expected, the success of this sealing measure can therefore be translated to this larger beam with other crack shapes.

The scale of the leakage flows which occur in reality can be estimated by this translation of the sealing methods. However, in doing so, it must be taken into account that the measurements at the test stand were carried out using completely exposed beams. The is no masonry or the like which would hinder or reduce air flow towards the sealing area. On account of such conditions, completely different leakage volume flows would result in reality - with identical sealing and an assumed pressure difference of 50 Pa (which does not actually occur). What is more, reduction of the volume flow to zero is even possible.

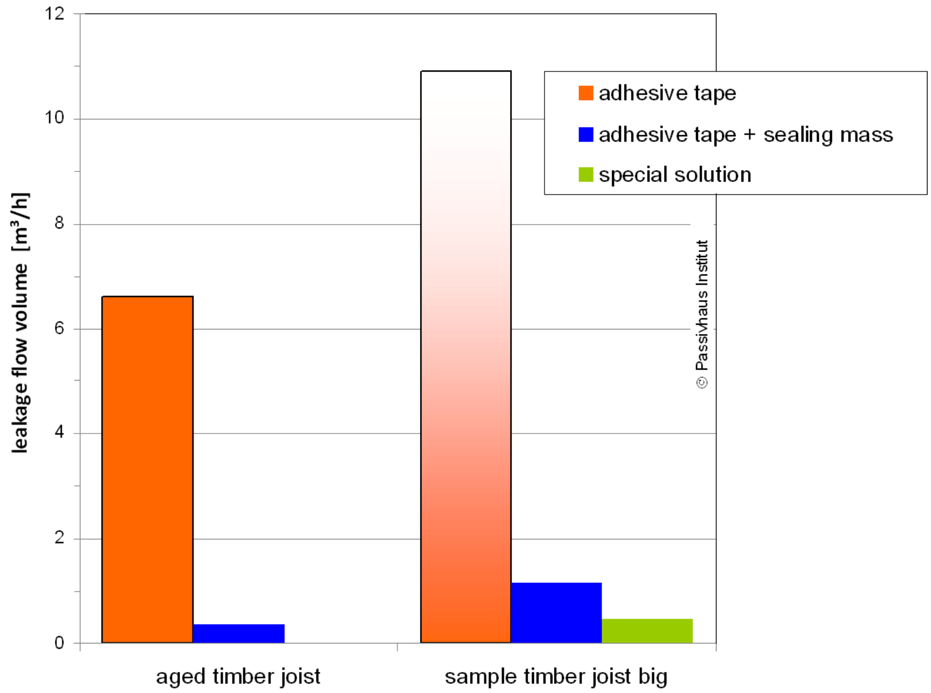


Figure 34: Leakage volume flow at a differential pressure of 50 Pa for the "real" beam and the "large" sample beam with the sealing using the methods adhesive tape only (without filling of cracks), adhesive tape + sealant and the "special solution" (pure acrylate dispersion)

5.5 Recommendations

The integration of cracked wood beams in the airtight layer of the building envelope to an adequate standard is conceivable with the use of a suitable sealant (AAS II), and with the tested "special solution" consisting of a spreadable paste-like compound and special-purpose non-woven material. In contrast with the sealing method with adhesive tape (without filling of the crack), a 74 % reduction in the leakage volume flow was possible with both variants for the small sample beam. Even better results were achieved with the methods with injected sealant, sealing membrane collar and the thick bitumen coating. The injected sealant method was very successful and can be combined well with other sealing techniques.

The paste-like compound (pure acrylate dispersion) used in the "special solution" together with the special-purpose non-woven material must be adaptedn differently to each penetration in the building so that with sufficient application of the materials, a good standard of airtightness can be achieved. However, this may have some practical disadvantages due to the odour and susceptibility to mechanical impacts before the paste-like compound has dried completely. It is recommended that the procedure is used in well-ventilated rooms on account of the odour. The area of deployment on-site may be limited due to the need for accommodating the containers with materials since a relatively large quantity of materials is necessary.

The use of an injectable sealant for sealing cracks in the wood has the advantage that the user only has to carry the sealant cartridge in the applicator gun besides the materials which are required anyway (e.g. vapour retarder, airtight adhesive tape etc.). Furthermore, another positive aspect is that filling of any unevenness and cracks is quickly accomplished. However, compared with the "special solution", sealant can be used less variably and cannot remedy every leak satisfactorily. Filling the crack will be problematic if the tip of the cartridge nozzle is too wide. A practical solution to this problem is to drill a hole and fill it or use a narrower tip; however this requires additional expenditure of time. For reasons of structural stability (statics), there are limits to the use of drilled holes for injecting sealant. In the case of thick bitumen coating, it should be checked whether this is suitable for inside use in individual cases.

The fact that existing cracks have to be filled in besides being taped over is of fundamental importance; this is not surprising. Only in this way will it be possible to reduce the leakage volume flow significantly. The procedure for sealing can be reduced to the following steps:

- Expose the beam
- Clean the beam area which is to be integrated
- Fill cracks
- Carry out sealing of the beam to the wall level

The use of suitable materials (special products) is always a prerequisite for this. The decision in favour of a particular method or combination of methods for sealing wood beams must always remain subject to a case-by-case assessment.

5.6 Application area and reversibility

The main focus of sealing procedures for wood beams in particular is the preservation of the building substance, and improvement of thermal comfort for the occupants (absence of draughts). heating energy and CO_2 emissions are also saved at the same time. Of particular significance for protected historical buildings is the issue of the application area and reversibility of these measures, i.e. whether they can be reversed or removed entirely.

This method can be applied for all buildings with wood beams in the ceiling and/or in the roof area if the beams penetrate the airtight layer, e.g. the interior plaster. An essential prerequisite for this is that beams in the area of penetration (sealing area) are exposed completely and cleaned thoroughly. Opening up of the wooden floor in the wall area - at least from one side - is often necessary for checking the statics during a refurbishment in any case. The procedure for exposing the floor and filling the intermediate spaces with insulation is described in [Fingerling 1995].

The sealing measures only affect a limited area of the exposed surfaces of the wood beams at the point of penetration of the airtight layer (about 5 to 10 centimetres wide). The surface of the adjacent airtight layer, e.g. the surrounding wall area (reinforced or new plaster etc.), is also affected. The building characteristics are specifically altered by these measures; airtightness is increased, leading to a reduction in the ventilation heat losses and a decrease in the amount of water entering into the construction.

The purpose of sealing is to create a permanent connection to the airtight layer. The area of the wood beams and the wall (for example) affected by this is relatively small. Depending on the method and workmanship, most of the sealing work is reversible; only small residues will remain on the surface. Depending on the individual case, drilled cracks in beams can be sealed with wooden dowels instead of sealant in order to avoid inserting foreign materials. Besides the use of wooden dowels, special products which are designed for durability can also be used. Long-term exposure to UV light may be problematic depending on the products used for such connections. Protection against this is usually assured within the building in the construction (e.g. floor build-up).

Examinations regarding the permanence of the materials used for such applications did not take place within the framework of this study. There are studies by some manufacturers relating to the durability of their products and by e.g. [Maas/Gross 2010]. The PHI has studied the permanence of realised airtightness concepts in the context of entire buildings [Peper et al. 2005]. With a good concept and correct use of special products, excellent results could be obtained here.

The costs of such measures depend greatly on the different boundary conditions and materials used. The costs will mainly be labour costs since the work has to be carried out by craftsmen on site. All the materials used are commercially available and easily acquired.

As a preliminary study, an airtightness measurement (blower-door test) and, if necessary, infrared thermographic are advised in advance. This will help to assess whether air leakage exist at the connection of the beam to the wall. It may also make sense to insert sensors for measuring moisture at random points in some beams (resistance measurement using two metal pins) in order to monitor these measures over the following years.

5.7 Classification and outlook

The results obtained here provide information about the scale of the residual leakage volume flows of beam sealing procedures. For normal conditions of the building due to wind pressure and thermals, the results must be transposed for lower differential pressures (e.g. 3 to 8 Pa).

The scope of the measurements carried out within the framework of this study gives initial indications regarding the residual leakage volume flows; in the context of these measurements, it was not possible to aim for a statistically sufficient number of samples. The range of permanence of the studied constructions was not separately examined, therefore no conclusions could be made regarding this.

The quantities of water entering into the construction on account of the remaining leaks depend on several parameters. The metrologically ascertained residual leakage volume flows were used for further investigations relating to the range of the convective moisture gain in the wall build-up; these findings are a prerequisite for assessing this. Research on this subject is being carried out at the University of Innsbruck and at the Passive House Institute in Darmstadt simultaneously within the framework of the 3EnCult research project.

6 Airtightness of OSBs

As mentioned previously, OSBs (oriented strand boards) were used for the construction of the test box for measurement of the sealing procedures for beams. During the first measurements it was realised that non-airtightness of the test box could not be disregarded for this study. In particular, the reason for this was non-airtightness of the OSBs used. For this reason, airtight adhesive tape was applied all over the surface of the test box (see Section 4.1.1). In order to be able to assess the non-airtightness of the OSBs more accurately and assess the effects of their use in constructions, airtightness of the boards was further examined. The same test box was used for this purpose.

The increased requirements for airtightness of buildings also mean increased requirements for airtightness of the areal building components. Concrete, interior plaster (on masonry), sheeting and building paper as well as (hard) engineered wood boards are considered to be airtight all throughout (see [Peper/Feist/Sariri 1999/2009]). OSBs which are considered airtight are often used when engineered wood boards are necessary. In recent years, several times optimal measurement values could not be ascertained in timber constructions. One of the reasons for this was the fact that the OSBs used were not sufficiently airtight. As a simple test, a piece of sheeting (e.g. 1 m x 1 m) was applied in an airtight manner on the inner of the OSB for this purpose. The sheeting bulged noticeably at negative pressure inside the building, indicating that the board was non-airtight all through. These findings match with those gained with the test box during the measurements for beam sealing carried out by the PHI.

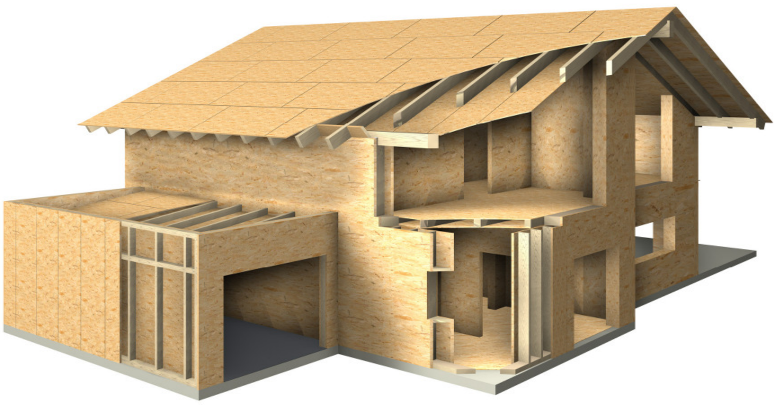


Figure 35: An "extreme case": a single-family home built entirely with wooden OSBs (Picture: Norbord)

In a systematic study [Langmans 2010] concerning the airtightness of OSBs, products from eight manufacturers supplying the European market were tested.

Commonly available Type 3 OSBs with a thickness of 18 mm were tested. These did not demonstrate a sufficient level of airtightness. Questions and uncertainties remained, and still exist, despite (or because of) the measurements carried out by Langmans. Considerations and statements relating to the procedure for the use of OSBs are becoming frequent: is additional sealing of the surfaces necessary (using sheeting, cardboard, coatings)? What is the quality of the OSBs available on the (German) market? Is it sufficient to use Type 4 OSB in place of Type 3 OSB? One manufacturer now supplies a product with an additional cellulose layer as an airtight OSB [Kronospan].

In an attempt to clarify some of the questions raised, measurements for testing the airtightness of OSBs were carried out using the test box. For this purpose, Type 3 and Type 4 OSBs with a thickness of 16, 18 and 22 cm belonging to the four major manufacturers were purchased from bulk suppliers in Germany. Three or four samples with a size of 315 x 305 mm were cut from each board. The board to be tested was installed airtightly in the test stand by using screw clamps to press it against the EPDM sealing gasket mentioned earlier (see Section 4.1.1). The area of the OSB which remained inside the 200 x 200 mm sealing gasket was tested. The attachment rested on the edge of the board and did not affect the testing area.

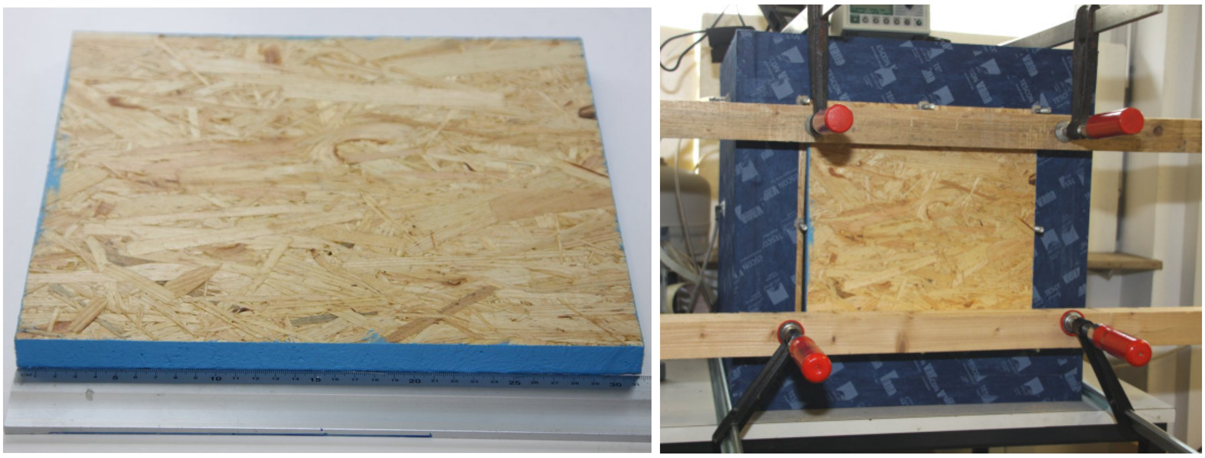


Figure 36: OSB sample with sealed edge (left) OSB sample attached to the test box using two-by-fours and screw clamps (right)

Measurement of the leakage volume flow took place at pressures between 100 and 600 Pa in order to obtain sufficiently high values. Excess pressure and negative pressure measurements were again carried out for each sample. The leakage from the test set-up itself was measured regularly using a completely airtight board and the result was deducted from the measurement values as an offset value. Again, evaluation of the leakage volume flows took place with a standardised pressure of 50 Pa. After deduction of the offset value the leakage volume flow was divided by the area of the board in order to obtain the p_{50}-value.

As expected, during the tests it turned out that the edges of the boards have a significant influence on the result due to the "edge volume flow", therefore the edges of the boards were airtightly sealed with a coating before the measurements. Due to the small size of the samples in comparison with the boards used in actual construction, this influence would have been considerably over-estimated otherwise. A total of over 80 measurements (one each for excess and negative pressure), including control and reproducibility measurements, were carried out.

In [Zeller 2012], a maximum q_{50}-value of 0.1 m³/(m²h) is postulated for areic tightness, while 0.06 m³/(m²h) is required for Passive Houses; in [Langmans 2010] this value is given as 0.09 m³/(m²h). In Canada the requirement for areic tightness of construction materials is just q_{50} = 0.048 m³/(m²h). The present study is based on a moderate target value of 0.1 m³/(m²h).

The following figure shows an overview of the measurement results of all tested OSBs:

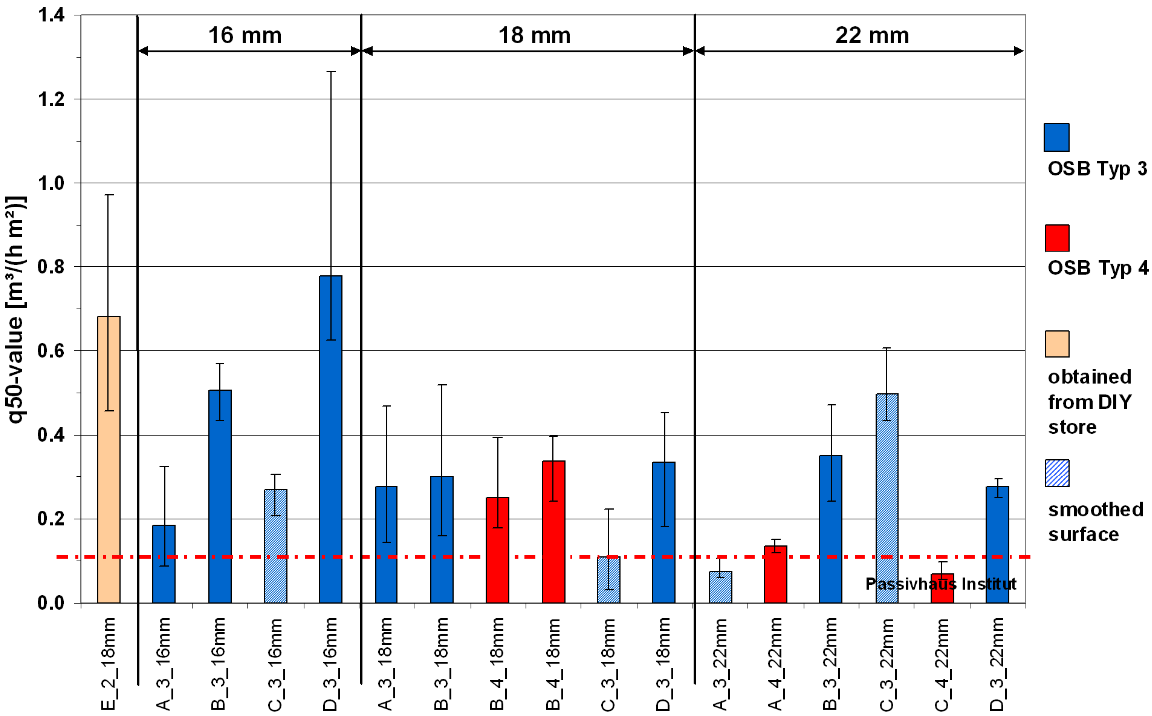


Figure 37: Measurement results of airtightness (q_{50}-value) of Type 3 and Type 4 OSBs from four manufacturers (A...D) sorted in order of board thickness with 16, 18 and 22 mm. The result for a board obtained from a DIY store is also shown additionally. The mean value of three measurements (bar) and the minimum and maximum value (line with I) are shown. The target value is 0.1 m³/(m²h) (red dotted line-).

The results for the q_{50}-value in Figure 37 show – similarly to the study by [Langmans 2010] – extremely high variations of each of the three single values for a board. The reason for this is presumably the non-homogeneous material with the typically rough wood chips. The range of the results is also comparable with the results in [Langmans 2010]. The average value (bar) of the measured values for each board are between 0.08 and 0.78 $m^3/(m^2h)$ for the **Type 3** OSB, that for the single measurements (line with I) is between 0.03 and 1.27 $m^3/(m^2h)$. The average value is shown with the respective minimum and maximum q_{50}-values. The four manufacturers are indicated with the letters A to D. The average values (red bars) for the four series of measurements for the **Type 4** OSBs are between 0.07 and 0.34 $m^3/(m^2h)$, the respective single measurements (line with I) show values between 0.06 and 0.4 $m^3/(m^2h)$. A board that was obtained from a DIY store was measured and depicted additionally (beige bar).

Only three of the seventeen average values of the boards are less than or the same as the target value of q_{50} = 0.1 $m^3/(m^2h)$. These include two 22 mm boards (Type 3 and 4) and an 18 mm board (Type 3). All other measured values are significantly higher than the target value. The board obtained from a DIY store (18 mm) is considerably worse than the other 18 mm boards but still better than the worst 16 mm board.

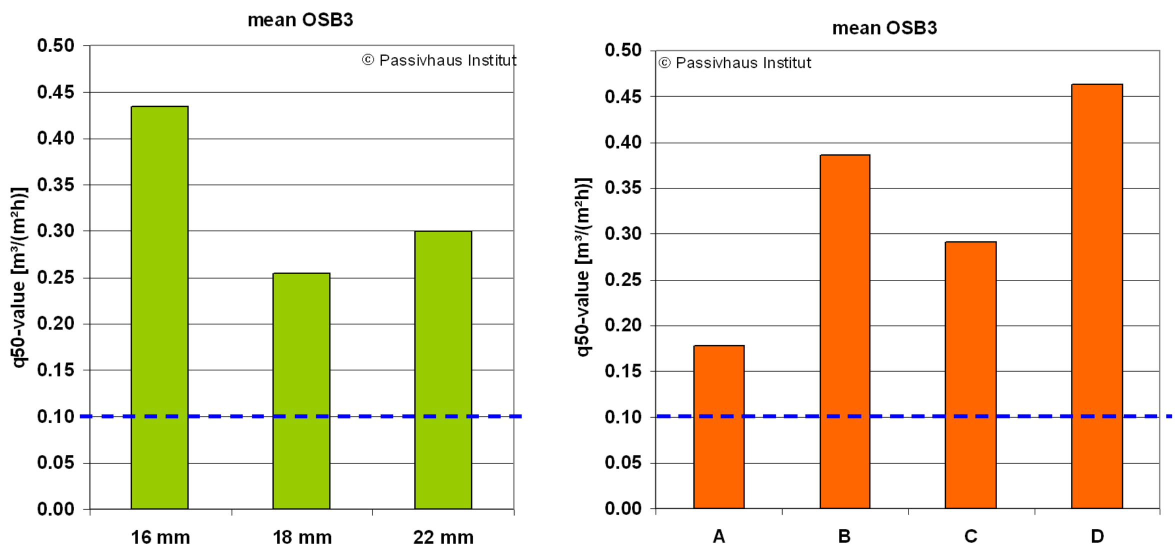


Figure 38: Average values of the measured values for Type 3 OSBs shown in Figure 37, according to board thickness (left) and manufacturer (right); averaged with the board from the DIY store; blue line target value q50 = 0.1 $m^3/(m^2h)$.

If all measured values for the **Type 3 OSBs** with the same board thickness are averaged, this results in the chart shown in Figure 38 (left): rather than the thickest boards, as might have been expected, the results for the 18 mm boards are the best. All values are considerably higher than the target value. Averaging of the measured values for all board thicknesses of each manufacturer also shows significant differences: on average, the boards from Manufacturer A have a volume flow that is half that of the board from Manufacturer D (Figure 38 / right). But here too, it is apparent that the average of the two best manufacturer values is **higher** than the target value by 78%, while that for the worst is even higher by 360 %.

Figure 39 results if the same charts are prepared for the **Type 4** OSBs. Altogether, the measured values are considerably lower than those for the Type 3 OSBs. The average value for the 18 mm boards (two batches from one manufacturer; three single measurements carried out twice) results in a significantly worse average value than for the 22 mm boards (two manufacturers; these even comply with the moderate target value. However, the chart on the right (sorted according to manufacturers) shows that only the board from one manufacturer shows a value that is lower than the target value.

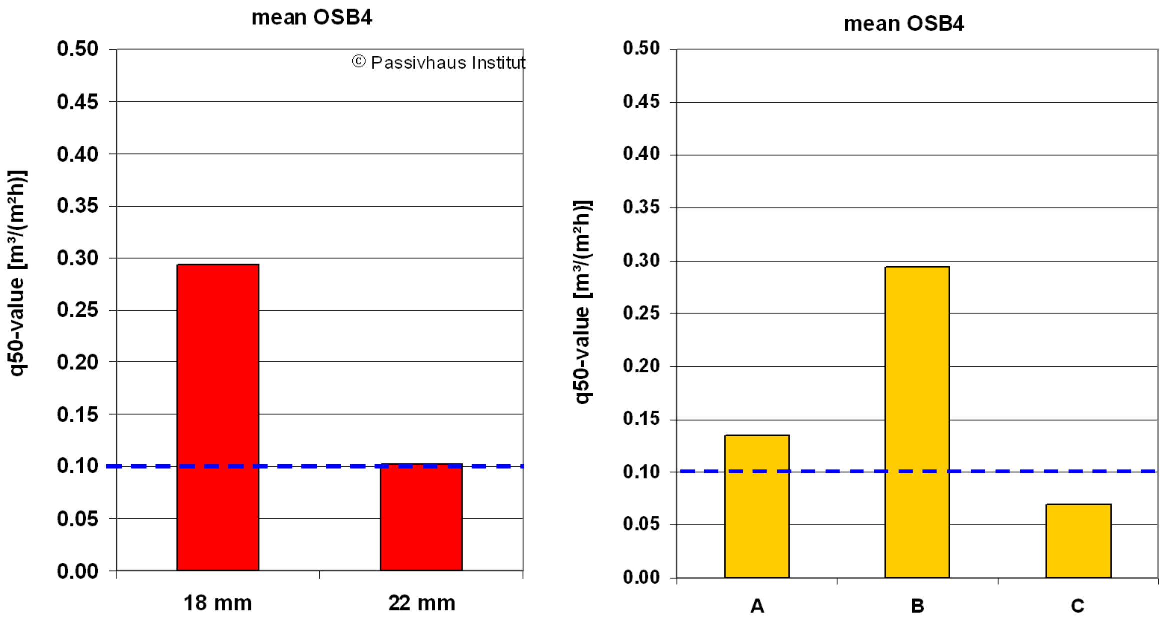


Figure 39: **Average values of the Type 4 OSBs shown in Figure 37 according to board thickness (left) and according to manufacturers (right). Blue line: target value q50 = 0.1 m³/(m²h).**

The random test of a total of four boards with four samples each (16 measurements) from three manufacturers, although very small, provides initial indications for assessing the airtightness of Type 4 OSBs. Here too, it must be stated that the use of Type 4 OSBs also does not represent a general solution with reference to compliance with the target value. Only a board from one manufacturer clearly shows a value lower than the target value and can therefore be recommended for this.

Example of single-family home

In order to illustrate the influence of airtightness of OSBs on airtightness of buildings, the effects on the airtightness in a sample building were demonstrated for some measurement results:

A Passive House single family home built as a timber construction, with two storeys and an attic floor, has a interior surface of 252 m² consisting of OSBs. The requirement for airtightness is $n_{50} = 0.6\ h^{-1}$. If the OSBs meet the intended target value of $q_{50} = 0.1\ m^3/(m^2h)$, this will result in a partial share of the n_{50}-value of $0.05\ h^{-1}$ on account of the OSB areas. This leakage volume flow is acceptable.

If the average value for all manufacturers for a board thickness of 18 mm for the Type 3 OSB in Figure 38 is set as $q_{50} = 0.25\ m^3/(m^2h)$ for all areas, this results in a n_{50}-value proportion of $0.13\ h^{-1}$. Thus the airtightness requirements can still be complied with, but the desirable safety margin is considerably smaller. With elaborate optimisation of all connection details, $0.13\ h^{-1}$ is an unnecessarily high and avoidable figure (22 % of the n_{50} limit value) due solely to the material in these areas. For the values of the manufacturer with the highest average values for all thicknesses of Type 3 OSBs ($q_{50} = 0.46\ m^3/(m^2h)$, the proportion of the n_{50}-value increases to a significant $0.24\ h^{-1}$ (equating to 40 % of the n_{50}-value). In the interest of sufficient reserves for joints and unexpected leaks, this is an unacceptably high value.

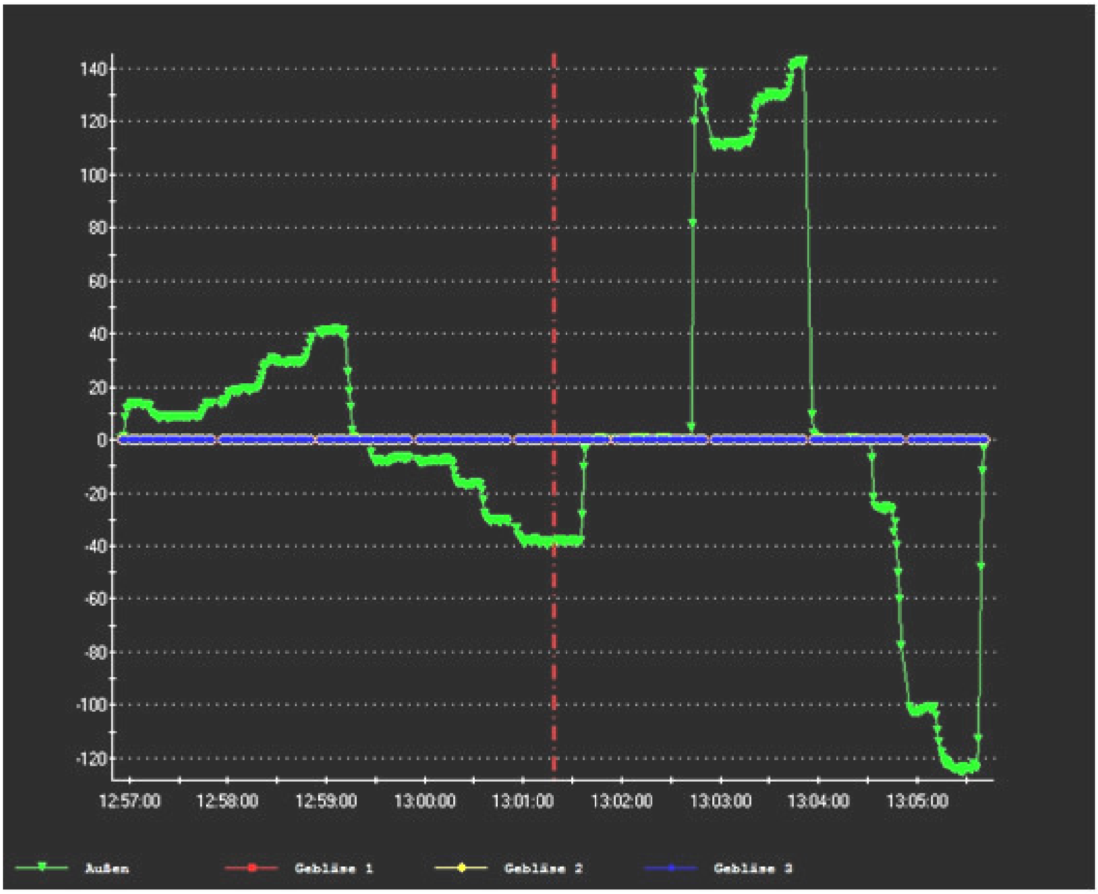
Constructing energy efficient buildings such as Passive Houses, which have high requirements for airtightness of timber constructions, is still possible with OSBs. However, the safety margin against breaching the required value decreases further with these qualities and will have to be compensated for elsewhere with much effort through complicated and exact work etc.

The designer, the supplier and the craftsman carrying out the work usually do not have any knowledge relating to the quality of airtightness of the OSBs used. In the interest of a higher level of airtightness of the building envelope for ensuring structural integrity and planning reliability, it is imperative that mandatory information is provided by manufacturers regarding airtightness; imprints on the boards themselves would be most practical for this purpose. Alternatively, it is also conceivable for manufacturers to work out other solutions in order to provide the necessary quality and certainty for designers, building contractors and investors

7 Appendix

7.1 Appendix A: Differential pressure measurement (example)

Screenshot of an example differential pressure measurement using the software application "Teclog".



7.2 Appendix B: Evaluation of measurement data in Excel

Section from the evaluation tool with data pairs for excess and negative pressure, specification of the coefficients "C" and "n" for ascertaining the leakage volume flow at 50 Pa, and the graph with the measured data.

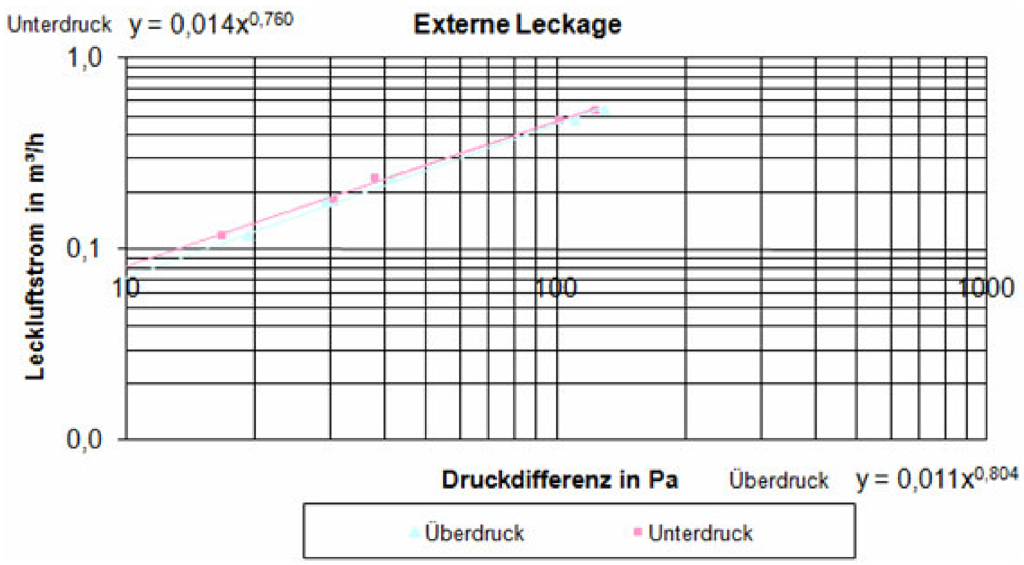
			1	2	3	4	5	6
Überdruck	Druckdifferenz zur Umgebung	Pa	8,6	19,3	29,5	41,7	110,8	129,8
	Leckluftstrom gesamt	m³/h	0,06	0,12	0,18	0,24	0,48	0,54
			1	2	3	4	5	6
Unterdruck	Druckdifferenz zur Umgebung	Pa	6,7	16,7	30,5	37,9	101,7	123,8
	Vergleichsmessung Leckluftstrom gesamt	m³/h	0,06	0,12	0,18	0,24	0,48	0,54

Leckluftstrom bei **Überdruck** : $\dot{V}_{L,\text{Über}} = 0{,}0111 \cdot \Delta p^{0{,}804}$ in m³/h

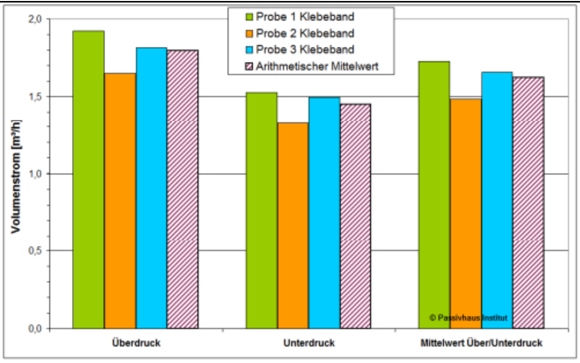
Leckluftstrom bei 50 Pa: $\dot{V}_{L,\text{Über},\ 50\ \text{Pa}} = 0{,}26$ **m³/h**

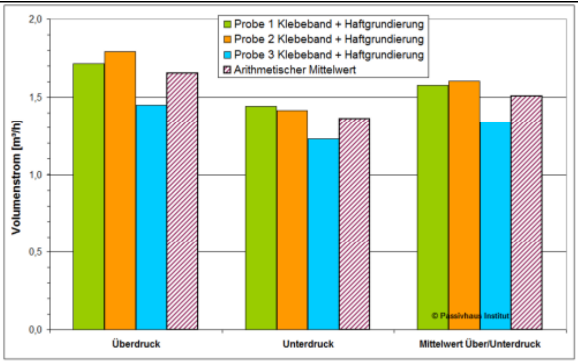
Leckluftstrom bei **Unterdruck** : $\dot{V}_{L,\text{Unter}} = 0{,}0141 \cdot \Delta p^{0{,}7604}$ in m³/h

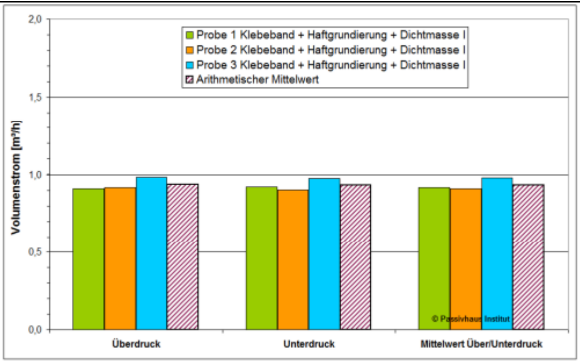
Leckluftstrom bei 50 Pa: $\dot{V}_{L,\text{Unter},\ 50\ \text{Pa}} = 0{,}28$ **m³/h**

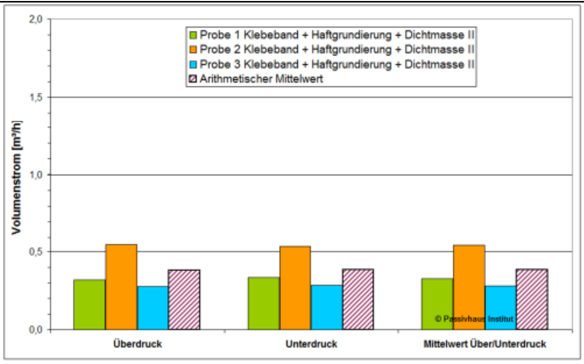


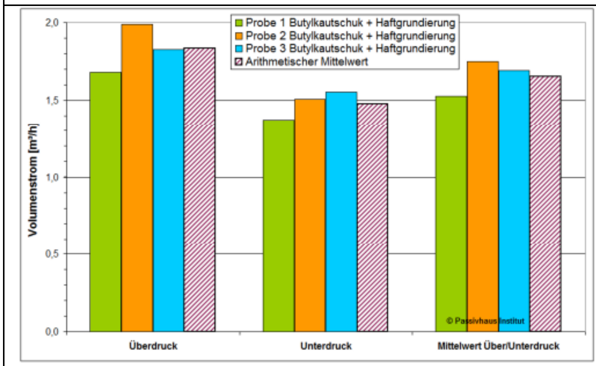
7.3 Appendix C: Results of individual measurements

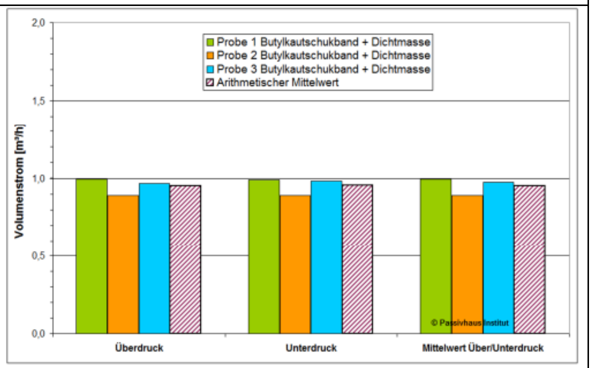


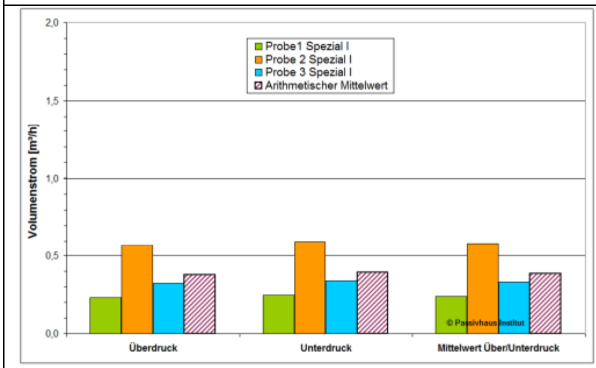


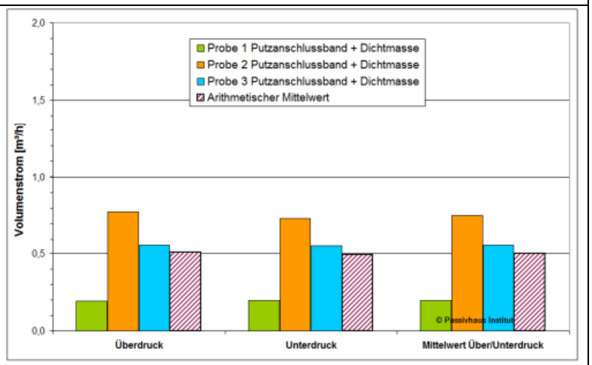


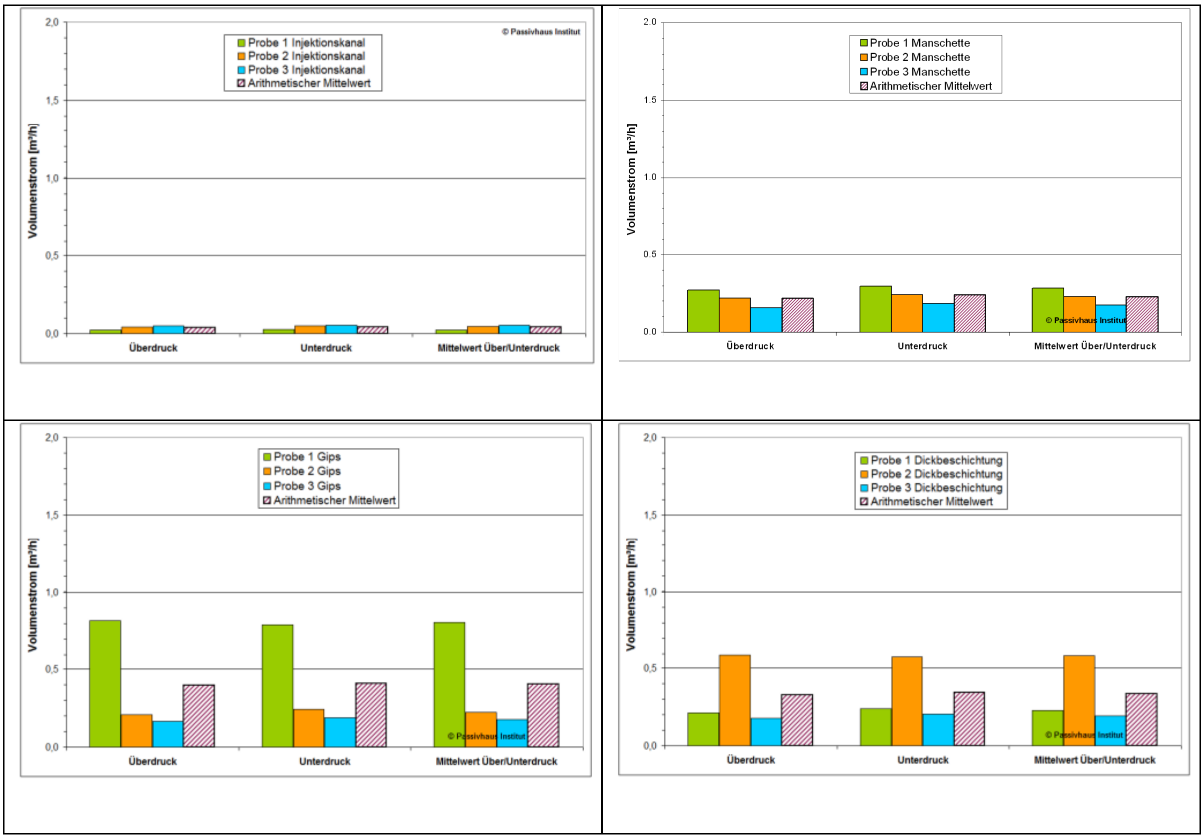








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Probe 1 Injektionskanal
Probe 2 Injektionskanal
Probe 3 Injektionskanal
Arithmetischer Mittelwert
Volumenstrom [m³/h]
2,0
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Mittelwert Über/Unterdruck
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Probe 3 Manschette
Arithmetischer Mittelwert
Volumenstrom [m³/h]
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Überdruck
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Mittelwert Über/Unterdruck
Probe 1 Gips
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Probe 3 Gips
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Volumenstrom [m³/h]
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Überdruck
Unterdruck
Mittelwert Über/Unterdruck
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Probe 3 Dickbeschichtung
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Volumenstrom [m³/h]
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8 Glossary

Adsorption: Adsorption refers to the process by which a substance from a gas or liquid collects on the surface of a solid, generally at the boundary between two phases.

Air change rate: The air change rate (unit: 1/h) is a measure of how many times the air within an interior space is replaced in an hour.

Anisotropy: Anisotropy is the term used to describe direction-dependent properties of materials or processes.

Capillary: A capillary is a very narrow elongated hollow space.

Condensation: Condensation refers to the transition of a material from the gaseous to the liquid aggregate state, resulting in condensate.

Cone: A cone is technical component which has the shape of a cone or truncated cone.

Convection: Convection is a mechanism for heat transfer of thermal energy from one place to another. Convection is always associated with the transport of molecules carrying thermal energy.

Dew point: Temperature at which air becomes saturated with water vapour (attains 100% humidity), below which the water vapour condenses into droplets and deposits on surfaces as dew.

Dispersion: A dispersion is a mixture of at least two materials that do not (or only partially) dissolve in one another or chemically combine with one another.

Energy efficient refurbishment: Energy efficient refurbishment refers to the modernisation of a building with the objective of minimising the energy consumption for heating, hot water and ventilation.

Fibre saturation point: The fibre saturation point is a certain moisture-related condition of wood; below the fibre saturation point, moisture is simply stored in the cell walls in the form of bound water. If the moisture content is higher than the fibre saturation point, further moisture in the form of free water can only be absorbed by the wood in its cell lumens, which only has a small influence on its physical and mechanical properties.

Heat capacity: The heat capacity is the measurable physical quantity of heat energy required to change the temperature of an object by a given amount. (The heat capacity is the amount of heat energy a body can store with reference to the change in temperature.)

Hygroscopy: Hygroscopy refers to the property of binding moisture from the environment (usually in the form of water vapour from humidity).

Infiltration: Infiltration is the unwanted entry of air through openings in the facade (opposite of exfiltration).

Leak: A leak is an unintended hole in a product or in a technical system through which solids, liquid or gases can enter or escape.

Partial pressure: In a mixture of gases, each gas has a partial pressure which is the pressure that would be exerted by that gas if it alone occupied the volume of the mixture.

Relative humidity: Relative humidity is defined as the percentage ratio of the water vapour density to the saturation water vapour density (at air temperature) above a flat surface of pure water.

Saturated vapour pressure: Saturation vapour pressure is the pressure of the vapour phase of a material if the liquid and vapour phases are in equilibrium.

Turbulent flow: Turbulent flow describes the movement of liquids and gases when swirls appear on many scales (opposite: laminar flow)

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