AIRTIGHTNESS OF BUILDING PENETRATIONS: AIR SEALING SOLUTIONS, DURABILITY EFFECTS AND MEASUREMENT UNCERTAINTY

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ABSTRACT

During field measurements on the airtightness of passive houses, ventilations system's roof penetrations showed to be one of the major leakage paths, as they were not sealed using the appropriate, durable techniques. Therefore, a series of laboratory measurements was conducted on wood-frame walls to study different air sealing solutions. The use of special airtight gaskets is compared to less advanced sealing methods such as sprayed polyurethane foam and the use of pieces of tape.

The airtightness of different solutions is tested on two different test setups at the Test Centre for Façade Elements, Ghent University. One large-scale setup, designed to measure the air leakage rate of windows, was used and an additional smaller-scale test setup was built. For both setups, measurement principle, test setup and results are reported.

As workmanship quality is an essential aspect for achieving airtight building connections, the repeatability of the sealing methods was addressed by installing multiple identical setups. The quality was reviewed with the use of a smoke generator and the samples were subjected to multiple water tightness tests under static and pulsating pressure. To evaluate the durability of the different solutions, the impact of the water tightness tests is discussed.

A classification for the airtightness of building penetrations is reviewed together with the impact of the air leakage through building penetrations on the overall air leakage of buildings. In the laboratory, all tested solutions could be classified in the best airtightness classification, though large differences between executions methods were evident. The use of standard, rigid airtightness tape is not recommended for sealing 3-dimensional connections such as building penetrations, and is not regarded as a durable sealing method. However, specific flexible tapes are on the market which perform very well and sprayed PUR also showed excellent results when executed correctly. EPDM gaskets showed a higher leakage than flexible tape and PUR, but are also a very good choice. The adaptability of the penetration is a great advantage regarding the durability of the connection.

KEYWORDS

Airtightness, penetrations, laboratory test results, durability

1 INTRODUCTION

A blowerdoor measurement campaign in Belgium on the durability of airtightness of passive houses (ACH_{50} < 0.6 upon completion), showed that the average air leakage of the houses had raised by 30% only two years after completion. Though this raise can be attributed to durability effects of various building components (windows, doors, …) and interventions of the inhabitants (installation of outdoor lighting, hanging of paintings, …), the roof penetrations were responsible for a significant part of the additional leakage. Large air

leakages were observed around the air supply and exhaust pipes of the ventilation system (Bracke et al., 2013).
In one house, which was tested on a regular basis during 18 months to investigate seasonal and durability effects, the leaky roof penetration of the air exhaust was replaced with an airtight, flexible EPDM gasket. This small intervention caused the total air leakage of the house to drop from 254 to 239 m^3/h @ 50 Pa, meaning this one penetration was responsible for 6% of the overall air leakage.
Even though an air leakage rate of 15 m^3/h @ 50 Pa might seem relatively small, as multiple other roof and wall penetrations can exist (e.g. ventilation ductwork, solar boiler connections, drain-waist-vents) these can be responsible for a significant share of the total air leakage, causing energy losses, malfunctioning of the ventilation system, draft and sound insulation problems.
Though it is clear that problematic connection such as wall-wall, wall-roof and window-wall interfaces are typically responsible for a larger share of the total air leakage, the leakage around roof and wall penetrations should not be disregarded. From field measurements it became clear that with very little effort and investment, a significant improvement could be achieved.
This paper starts with a review of the research that was published in literature on this topic. Laboratory measurements were performed on two different scales for which the test method, test setup and results are reported. Subsequently, test results are compared to an airtightness classification scale found in literature, and finally workmanship reproducibility and durability are discussed.

2 LITERATURE REVIEW

A good overall airtightness is considered as an essential requirement to obtain energy efficient and comfortable buildings. A lot of research has been done on the air leakage of buildings but little to none focusses on the air leakage of individual building components or building envelope interfaces. As the total air leakage is the sum of various smaller leakages, the isolation of a particular building element can help to acquire certain insights so the overall air leakage can be improved. This approach was also used by Van Den Bossche (Van Den Bossche et al., 2012) to propose an airtightness classification for different solutions to seal the window-wall interface, which is often a weak spot in the airtightness of buildings.
Very little is written on the airtightness of building penetrations. In one study performed by Kalamees (Kalamees et al., 2008), the air leakage distribution of 32 houses in Finland was analysed qualitatively using thermography and smoke detection. Air barrier penetrations for ductwork were held responsible for 3 to 10% of the total air leakage, depending on the building type (detached/apartment) and the presence of other critical connections such as the junction between intermediate floors and external walls.
To the knowledge of the authors, no test standards, classification systems or performance requirements exist for air barrier penetrations in the European framework for standards and codes. The American standard ASTM E2357 describes a test method for the assembly of air barrier systems, wherein two penetrations are part of a standard test wall, but are not tested separately.
In the Netherlands, three airtightness performance levels are specified according to NEN 2687: Class 1 (basic), Class 2 (good) and Class 3 (very good, passive houses). SBR, a Dutch research foundation, has published practical information on how to achieve the different air tightness classes. For several building components and interfaces, maximum air leakage rates are available to ensure the feasibility of the aspired maximum overall leakage of the building. Table 1 shows the maximum leakages for roof, wall and floor penetrations according to different penetration diameters. The values were derived from an area-based leakage rate for a gap of a few millimetres around the penetration.

Table 1: Maximum penetration leakages according to SBR

Diameter (mm)	Air leakage @ 50 Pa (m^3/h)		
	Class 1	*Class 2*	*Class 3*
15	9.3	3.4	0.7
25	15.6	5.4	1.1
50	27.8	10.7	2.1
80	91.9	17.1	3.4
100	112.9	21.5	4.3
125	139.7	27.4	5.5
150	167.1	32.2	6.4
200	220.4	43.0	8.6

The air flow of 15 m^3/h @ 50 Pa through the 200 mm roof penetration of the air exhaust, as mentioned in the introduction, can thus be regarded as too high for a Class 3 passive building. The air sealing probably complied with airtightness Class 3 after installation, but was not executed in a durable way. The question rises whether durability aspects should be taken into account when classifying airtightness solutions. Currently, very little is known about the durability of sprayed PUR foam, tapes and glues and no normative documents exist which prescribes a test protocol. It is still unclear how artificial ageing correlates with the expected aging in practice and how mechanical impacts (wind pressures, contractors working on the penetrations, …) should be translated in standard test protocols. In Germany, the FLiB (Fachverbandes Luftdichtheit im Bauwesen) is working on a test method to evaluate the durability of tapes and glues, which should result in a future normative document DIN 4108 part 11. At Ghent University, about 5000 tests on the peel and tear strength of the bonding of different tapes to different substrates were executed (Van Den Bossche et al., 2009). The samples were subjected to different temperatures and relative humidity levels in a climate chamber to evaluate the durability. Large differences in bonding strength were observed, not only between different products and different substrates, but also between different manufacturers of very similar products.

3 EXPERIMENTAL RESEARCH

Appropriate sealing materials are available on the market, but in practice, the poorly sealing of air barrier penetrations can cause significant amounts of air leakage due to the use of wrong materials and/or bad workmanship. The sealing of certain penetrations is often done by a variety of contractors, which may have a lack of awareness about the importance of airtightness.

In the context of a Belgian research project 'DO-IT' on wood-frame constructions, laboratory measurements on the airtightness of wood-frame building components were performed in the Test Centre for Façade Elements at Ghent University. A part of these measurements focus on the air leakage of wall penetrations, for which the results are reported in this paper.

Two test setups were used: one large-scale setup where a wood-frame wall was built and a variety of penetrations were installed together, and one small-scale setup where different specimens could be installed with one penetration in each specimen.

3.1 Test method and error analysis

A. Large-scale test setup

The airtightness of the wall penetrations was measured in a standard calibrated test rig according to EN 12114. Because the setup is unable to obtain a certain pre-set pressure, the airflow was measured at 10 random pressure differences in the interval 0 – 600 Pa. The airflow was derived by measuring the pressure difference over a calibrated orifice opening.

These measurement points are controlled for outliers using Chauvenet's criterion (Taylor, 1982), a power law function is fitted through the results after which the leakage is calculated for a 50 – 100 – … – 500 Pa pressure difference. A standard deviation is defined, taking into account the error on airflow measurements and the fitting to a power law.
The air leakage through the tested wall penetrations was not measured separately for every penetration. Instead, a wall was built in a steel test rig, in which different penetration diameters and sealing solutions were installed. After each newly installed penetration, an airtightness test was conducted according to EN 12114. The air leakage of a certain penetration can be derived by subtracting the air leakage of the previous measurement from the new measurement. The error on the leakage through the tested penetration will thus be a combination of the error on the previous and on the new measurement. As the errors are primarily the result of the fitting of the power law, which is uncorrelated for different measurements, the total error is calculated by adding in quadrature the errors of both measurements.
The penetrations tested in Figure 1 are almost perfectly airtight. The power laws fitted through the measurement points of the previous and the new measurement cross each other, meaning the test setup is unable to measure the difference between both measurements accurately.

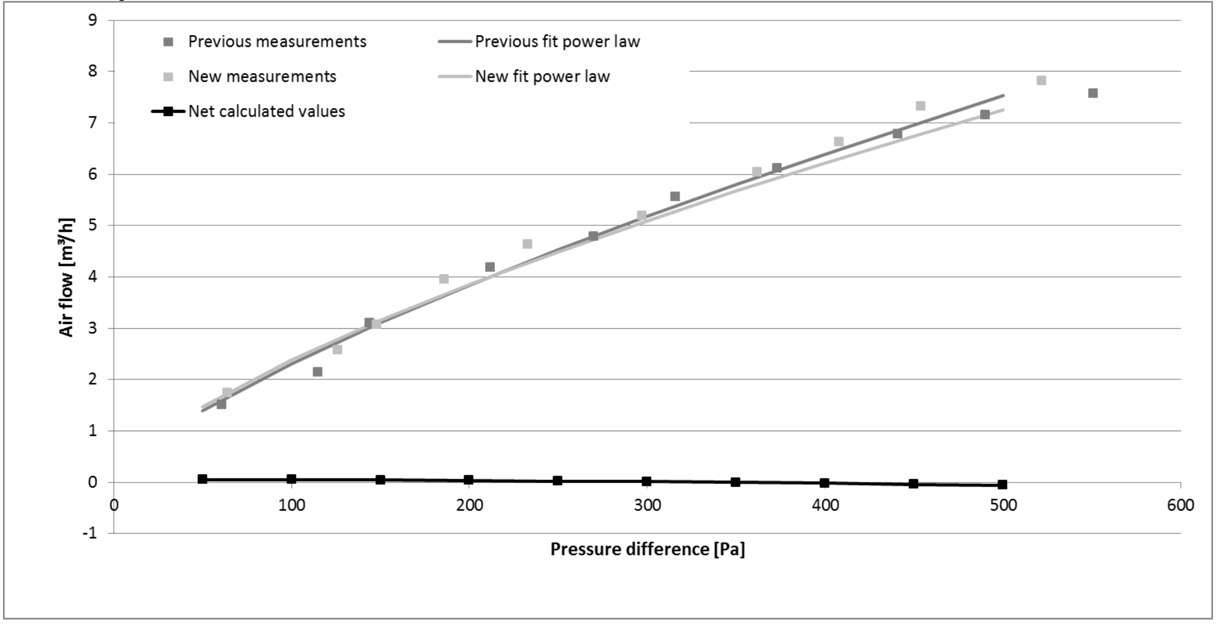

Figure 1: Measurement principle and calculation of net leakage (2 x EPDM gasket Ø 75 mm)

B. Small-scale test setup

The measurements are conducted using a Lindab LT600, a test instrument designed to measure the airtightness of ductwork and chimneys. The instrument calculates the airflow by measuring a temperature difference over a hotplate, which is heated and cools down as the air passes over it. The hot plate principle is a more accurate solution to measure very small airflows than measuring a pressure difference over an orifice opening.
As the Lindab LT600 is able to measure the airflow at a given pressure difference, no complete pressure sequence was performed and no power law was derived. Measurements were taken at 3 pressure differences: 50 Pa, 250 Pa and 500 Pa.
Because the device is designed to test the air leakage of ductwork, it follows EN 12237, which states that the pressure difference should be applied for 5 minutes to obtain a stable airflow. The measurements were logged to Excel, and the average airflow is calculated over the last 2 minutes of the measurement. Every measurement was executed 5 times and the average value and standard deviation are calculated.

Before the measurement of the wall penetrations, the extraneous air leakage through the test setup is determined. The net leakage through the different specimens is derived by subtracting the extraneous air leakage from the measured leakage and the standard deviation is calculated by adding in quadrature the standard deviation of both measurements.

3.2 Test setup

A. Large-scale test setup

The tests were executed on a full-scale setup built in a steel test rig. A wood-frame wall of 228 cm by 196 cm was built consisting of a framework and exterior sheathing of 18 mm bituminous impregnated fibreboard. As the fibreboard contains more bitumen than most similar products, it does not only act as a rain screen, but also as an additional air barrier next to the interior barrier and provides enough structural stiffness to avoid the need of OSB sheathing on the interior side. To make an abstraction of the real-world situation, the use of OSB panels and interior insulation was omitted in the test setup.

Four different penetration diameters were tested: 4 mm (single electrical cable), 20 mm (ribbed conduit pipe for electrical cables), 75 mm (PVC pipe) and 130 mm (PVC pipe). The openings for the different penetrations were respectively 6 mm, 22 mm, 85 mm and 140 mm. Every case was sealed using three different methods

- gasket: A piece of flexible EPDM rubber with an opening smaller than the penetration’s diameter is stretched over the penetration. The EPDM slab is taped to the fibreboard using a standard airtightness tape.
- PUR: Flexible polyurethane foam is sprayed with a PU-pistol on the joint between the penetration and the fibreboard. As the board has a limited thickness, the PUR is not truly applied in the cavity between the penetration and the wall, but is rather sprayed on the surface of the fibreboard. Water was sprayed to increase the humidity, which enhances the expansion of the foam and the bonding to surrounding surfaces.
- tape: Multiple pieces of tape were radially applied on the fibreboard and penetration. The tape is designed to seal the 2-dimensional joints of vapour retarder membrane and consists of a reinforced PE membrane and a acrylate adhesive.

The last method, which is not typically recommended, was executed to compare test results with better solutions, and investigate durability effects and workmanship quality. To test the worst-case scenario, the air leakage without applying any air sealing was also evaluated. Especially in this case, the diameter of the openings in the fibreboard is of great influence. In most of the test cases, the penetration was executed multiple times to extract a reliable average value for the air leakage rate.

Figure 2 shows the tested wall with different penetration diameters and sealing solutions. The wall is connected airtight to the test rig using butyl-aluminium tape and the joints between the different fibreboards are also sealed to minimize extraneous air loss and resulting measurement uncertainty.

Figure 2: Wood-frame wall with different air sealing solutions in steel test rig

B. Small-scale test setup

A small test box measuring 300 x 300 x 300 mm was built using plywood with an epoxy coating. To minimize extraneous air leakage, silicone sealant and butyl tape are used to seal every joint. The different test specimens were clamped against the test box and the connection was made airtight by compressing a closed-cell foam band attached to the specimens.

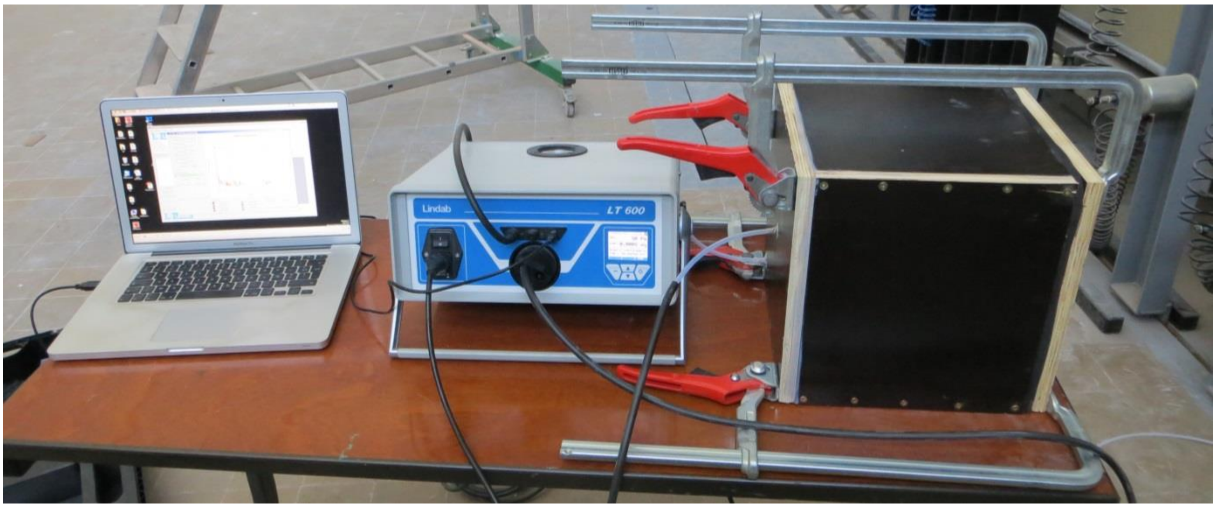

Figure 3: Small-scale test setup

Four specimens were built to test different methods to seal a 75 mm PVC pipe wall penetration in a 90 mm opening.

- PUR: PUR foam was sprayed in the gap (7,5 mm wide) between the PVC pipe and the wall element. Plywood with an epoxy coating was attached to a PUR foam board to provide enough thickness for the expansion of the sprayed PUR.
- gasket: An EPDM gasket with an opening of 55 mm was pulled over the PVC pipe and taped to the plywood.
- tape (1): The PVC pipe is sealed to the plywood using pieces of tape. The tape is designed to seal the 2-dimensional joints of vapour retarder membrane and consists of a reinforced PE membrane and an acrylate adhesive.
- tape (2): The PVC pipe is sealed to the plywood using pieces of tape. The elastic tape is designed to seal difficult corners and 3-dimensional connections and consists of an elastic PE membrane and a butyl rubber adhesive.

Figure 4: Test specimens: tape (1), tape (2), PUR, gasket

3.3 Measurement results

A. Large-scale test setup

As explained in paragraph 3.1, the calculated net leakages are accompanied by large error intervals. As different penetrations are tested, and thus additional leakages are created during the testing sequence, the total air leakage and accompanying errors are increasing. Sometimes, due to measurement uncertainty, small negative net leakages are calculated for a certain pressure difference as Figure 1 illustrates. For a better interpretation and comparison, the calculated leakages at 50 Pa, 250 Pa and 500 Pa and associated standard deviations are presented in the following tables.

For a first test, the air leakage through the bituminous fibreboard was measured. Joints around the wall and between the boards were sealed so only the air leakage through the material itself was measured.

Table 2: Test results bituminous impregnated fibreboard

	50 Pa		**250 Pa**		**500 Pa**	
	Air leakage ($m^3/h.m^2$)	**σ** ($m^3/h.m^2$)	**Air leakage** ($m^3/h.m^2$)	**σ** ($m^3/h.m^2$)	**Air leakage** ($m^3/h.m^2$)	**σ** ($m^3/h.m^2$)
fibreboard	*0.266*	0.028	*1.249*	0.091	*2.341*	0.160

When a hole is cut out of the fibreboard, airtight tape or EPDM is placed over the board and the leakage through the test wall will be lower due to a smaller fibreboard surface. In the following tests, the covered surfaces are measured and multiplied with the measured characteristic air leakage through the fibreboard. The results are subtracted from the newly measured air leakage to correct for this smaller fibreboard surface.

Table 3 shows the test results for the 4 mm electrical cables. For every case, 16 cables were installed, the total air leakage is measured and the average leakage rate for one penetration is calculated. At 50 Pa, both the tape and gasket seem to perform very well, but for higher pressure differences the EPDM gasket is clearly the best solution. Applying the sprayed foam around the electrical cables was very inconvenient and resulted in a large air leakage rate.

Table 3: Test results 4 mm electrical cable

	#	**50 Pa**		**250 Pa**		**500 Pa**	
		Air leakage (m^3/h)	**σ** (m^3/h)	**Air leakage** (m^3/h)	**σ** (m^3/h)	**Air leakage** (m^3/h)	**σ** (m^3/h)
no seal	16	*0.030*	0.006	*0.115*	0.026	*0.206*	0.049
tape	16	*0.001*	0.005	*0.017*	0.018	*0.039*	0.033
PUR	16	*0.026*	0.006	*0.077*	0.022	*0.123*	0.040
gasket	16	*0.001*	0.004	*0.003*	0.017	*0.005*	0.032

The leakage results for the 20 mm conduit pipes are reported in Table 4. Two types of EPDM gaskets were tested: 8 single gaskets (gasket_1) for 1 penetration, and 1 gasket for 9 penetrations (gasket_9). The gasket with multiple penetrations was harder to install correctly, because the holes in de EPDM might not be completely aligned with the conduit pipes coming through the fibreboard. Probably this caused a higher leakage than the single gaskets, but both types are a better solution than using pieces of tape or sprayed PUR foam.

Table 4: Test results 20 mm conduit pipe

	#	**50 Pa**		**250 Pa**		**500 Pa**	
		Air leakage	**σ**	**Air leakage**	**σ**	**Air leakage**	**σ**
		(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)
no seal	9	*0.600*	0.012	*1.788*	0.043	*2.850*	0.076
tape	16	*0.140*	0.042	*0.343*	0.154	*0.488*	0.275
PUR	16	*0.118*	0.014	*0.327*	0.050	*0.501*	0.088
gasket_1	8	*0.001*	0.007	*0.003*	0.027	*0.005*	0.049
gasket_9	9	*0.005*	0.007	*0.017*	0.029	*0.030*	0.053

The results of the 75 mm PVC pipe penetrations are shown in Table 5. Again, tape and PUR show similar results and perform worse than the gasket. The net air leakage rate for the gasket calculated at 50 Pa is higher than the leakage rate at 250 Pa, and for 500 Pa, a negative result is calculated. Because the gasket is almost perfectly airtight, the difference between both measurements could not be quantified by the test setup and subtracting both fitted power laws rendered these physically impossible results. The power laws and calculated net leakage are visualised in Figure 1.

Table 5: Test results 75 mm PVC pipe

	#	**50 Pa**		**250 Pa**		**500 Pa**	
		Air leakage	**σ**	**Air leakage**	**σ**	**Air leakage**	**σ**
		(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)
no seal	2	*6.275*	0.186	*16.130*	0.566	*24.148*	0.930
tape	2	*0.128*	0.043	*0.325*	0.106	*0.477*	0.176
PUR	2	*0.077*	0.056	*0.298*	0.119	*0.526*	0.194
gasket	2	*0.049*	0.068	*0.022*	0.131	*-0.057*	0.208

For the 130 mm PVC pipe, two pipes were again installed and sealed with tape, PUR and a gasket. The pipes sealed with pieces of tape and sprayed PUR foam were installed and tested one by one, as visible in Table 6. Although the intention was to execute the sealing in exactly the same way, a large spread is evident between the results. This is an indication that workmanship quality is a very important factor but also that the solutions are very prone to errors. The results from the EPDM gasket are again unreliable, as air leakage at 500 Pa is lower than that at 50 and 250 Pa. It is clear however that the sealing with a gasket is by far superior over the sealing with PUR or pieces of tape.

Table 6: Test results 130 mm PVC pipe

	#	**50 Pa**		**250 Pa**		**500 Pa**	
		Air leakage	**σ**	**Air leakage**	**σ**	**Air leakage**	**σ**
		(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)
tape (1)	1	*1.847*	0.115	*4.698*	0.333	*6.988*	0.552
tape (2)	1	*0.837*	0.219	*1.581*	0.636	*1.982*	1.026

PUR (1)	1	*1.475*	0.046	*4.252*	0.109	*6.695*	0.181
PUR (2)	1	*0.048*	0.090	*0.302*	0.214	*0.603*	0.360
gasket	2	*0.092*	0.092	*0.113*	0.174	*0.045*	0.286

B. Small-scale test setup

The net air leakage of the different specimens is shown in Table 7, together with the extraneous leakage through the test setup. Contrary to the results from setup 1, the specimen with sprayed PUR foam showed the lowest air leakage, followed by the specimen with the elastic butyl tape. The leakage through the EPDM gasket is relatively higher but in absolute value it is still negligible. The penetration with reinforced, rigid tape is clearly the worst solution. Only 1 test was conducted, as additional leakages were created during the 5 min tests at 50, 250 and 500 Pa.

Table 7: Test results 75 mm PVC pipe (setup 2)

	# tests	**50 Pa**		**250 Pa**		**500 Pa**	
		Air leakage (m^3/h)	**σ** (m^3/h)	**Air leakage** (m^3/h)	**σ** (m^3/h)	**Air leakage** (m^3/h)	**σ** (m^3/h)
extraneous	5	*0.0006*	0.0001	*0.0020*	0.0003	*0.0038*	0.0008
PUR	5	*0.0003*	0.0002	*0.0005*	0.0006	*0.0021*	0.0013
gasket	5	*0.0019*	0.0001	*0.0108*	0.0010	*0.0211*	0.0018
tape (1)	1	*0.0211*		*0.0712*		*0.1308*	
tape (2)	5	*0.0016*	0.0002	*0.0042*	0.0005	*0.0057*	0.0011

4 AIRTIGHTNESS CLASSIFICATION

According to the classification as proposed by SBR, all tested solutions belong to Class 3 and are thus appropriate for application in a passive house. Even a 20 mm conduit pipe in a 22 mm opening without any air sealing can be classified in Class 3. The 75 mm PVC pipe in a 85 mm opening without air sealing resulted in an air leakage rate of 6.3 m^3/h @ 50 Pa, whereas 3.4 m^3/h is allowed for a 80 mm Class 3 penetration. Class 3 seems achievable without special airtightness solutions, if the opening in the airtightness layer is not too large. Consequently, it cannot be regarded as a very ambitious airtightness level.

To evaluate the maximum leakages according to SBR, a fictional passive house with a volume of 500 m^3 is considered. With a maximum air change rate of 0.6 h^{-1}, the allowed air leakage @ 50 Pa is 300 m^3/h. Such a house typically has the following building penetrations: 3 x 200 mm (ventilation inlet and exhaust, chimney), 2x 125 mm (sewage pipes), 1 x 80 mm (waist-drain-vent), 4 x 50 mm (solar boiler inlet and outlet, water supply, gas supply), 10 x 25 mm (electricity for solar panels, outdoor lighting, …). When summarizing the maximum penetration leakages, the total air leakage for the three different classes is given in Table 8.

Table 8: Maximum total penetration leakages according to SBR

	Air leakage @ 50 Pa (m^3/h)		
	Class 1	*Class 2*	*Class 3*
Total air leakage	744.6	178.3	35.7
share of allowed leakage	321.1%	99.2%	19.8%

For this example, the penetrations executed with an airtightness according to Class 3, are responsible for 19.8% of the total allowed leakage. This does not seem dramatic, but could be improved with little effort and investment, as only 15 local and easily detectable spots have to be sealed using the appropriate techniques.

5 WORKMANSHIP REPRODUCIBILITY

In the wood-frame research project, of which a part of the results are reported in this paper, the water tightness of building components was evaluated next to the air leakage rate. The results of these tests are also useful to evaluate the difference in workmanship quality between identical sealing solutions, as leakages can be visualised. Water tightness tests were executed according to

- EN 1027: water is sprayed at a rate of 120 l/(h.m^2), first 15 min without pressure, then a static pressure is applied in consecutive 5 min time steps at 50 Pa, 100 Pa, 150 Pa, 200 Pa, 250, 300 Pa, 450 Pa, 600 Pa, …
- EN 12865: water is sprayed at a rate of 120 l/(h.m^2), first 20 min without pressure, then a pulsating pressure (10 seconds with pressure, 5 seconds without pressure) is applied for 10 minutes at 150 Pa, 300 Pa, 450 Pa, 600 Pa, …

As the wall has an area of 4 m^2, a total spray rate of 480 l/h was applied. The following water infiltrations were observed for the water tightness tests. Due to practical reasons, the complete pressure sequence was not executed during some tests, which is indicated with a '/' in Table 9.

Table 9: Failing penetrations as a function of infiltration pressure

			static pressure							pulsating pressure					
	Pressure (Pa)	#	0	50	100	150	200	300	900	0	150	300	450	600	750
4 mm	tape	16	2			1	1	/	/	1		10		1	
	PUR	16					2	/	/			7	3	3	
	gasket	32						/	/			2			
20 mm	tape	4	2				2	/	/	1	2		/	/	/
	PUR	16	6			3	1	/	/	4	12		/	/	/
	gasket_1	4		1			1	/	/		2	2	/	/	/
	gasket_9	9	1					/	/		1	9	/	/	/
75 mm	tape	2	1					1	/	1		1			
	PUR	2	2						/	2					
	gasket	4			2		1	1	/		1	3			
130 mm	tape	2	2							2					
	PUR	1	1							1					
	gasket	2			1							1			1

A large spread in the pressure at which infiltration occurred was visible during most of the tests, suggesting workmanship quality plays an important role in the leakage around penetrations. Applying a positive pressure in combination with a smoke generator confirmed the differences in air leakages which accompany the differences in water infiltration, in particular when PUR or tape were used to seal the penetrations. As the PUR was sprayed on the fibreboard, the foam did not expand into the cavity and in some cases, large openings were present around the penetrations, which could easily be detected using the smoke generator. The installation with rigid tape was also prone to errors, as the overlapping parts of the pieces of tape showed significant leakages.

In general, the water infiltration around the penetrations sealed with EPDM gaskets was much smaller than the penetrations sealed with tape or PUR.

6 DURABILITY

The air leakage rate through the complete wall was measured after the execution of the water tightness tests reported above. In this way, the effect of the sprayed water on the bonding of the tapes and the mechanical impacts of the pressure pulsations were evaluated.

Table 10: Additional air leakage after water tightness tests

	50 Pa		**250 Pa**		**500 Pa**	
	Air leakage (m^3/h)	**σ** (m^3/h)	**Air leakage** (m^3/h)	**σ** (m^3/h)	**Air leakage** (m^3/h)	**σ** (m^3/h)
combined	*0.581*	0.168	*1.188*	0.284	*1.658*	0.462

As the air leakage rate of the installed penetrations could not be measured separately, the individual increase in air leakage was not determined. As shown in Table 10, the overall increase in air leakage was limited, and visual inspection indicated which air sealing solutions were problematic.

No tapes were detached from the surface of the fibreboard as a result of the large amounts of sprayed water, but the impact of the pressure pulsations on the taped PVC pipes was clearly visible. As Figure 5 illustrates, the pipes are pressed through the opening in the fibreboard, and additional leakages are created.

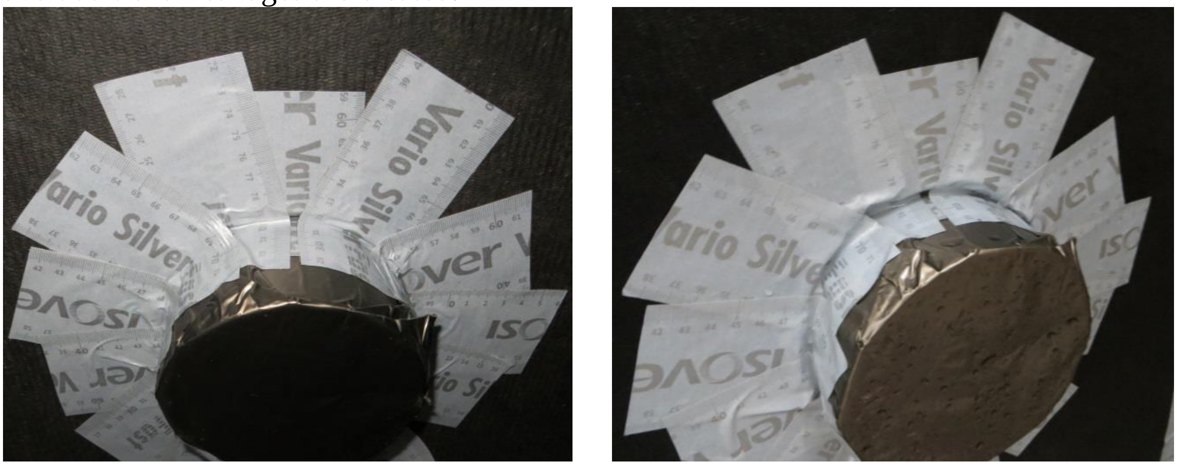

Figure 5: Durability effects taped PVC pipe: before and after water tightness testing

The flexible PUR foam should be able to tolerate mechanical impacts up to a certain level and no degradation was detected after the water tightness tests. However, one can reasonably assume that contractors working on a penetration could damage the foam or the adhesion between the foam and the wall. The execution with an EPDM gasket is less sensitive to these problems. As the penetration is not attached to the wall, it can be moved back and forth through the gasket or even be replaced without damaging the air sealing.

7 CONCLUSIONS

Three different methods to ensure an airtight connection around building penetrations were evaluated in this paper: airtightness tape, sprayed polyurethane foam and EPDM gaskets. Air leakage tests were executed on two setups of a different scale. In one setup, a wall was built and a variety of sealing methods and penetration diameters were installed. This setup was able to compare the quality of the different tested solutions and to investigate differences in workmanship quality between identically installed elements. Due to the measurement principle of the test setup and the calculation method of the net leakages through the installed penetrations, a high measurement uncertainty is involved. A second setup was built on a much smaller scale to test individual components, which was able to measure the air leakage rate through different sealing methods very accurately.

In the large-scale setup, PUR foam was sprayed around the penetration on the surface of the wall. As the foam could not expand into the cavity and fill the connection, significant local leakages were observed. In the small-scale setup, a thicker wall element was used, and the foam could expand in the cavity between the wall and the penetration, resulting in an almost perfect airtight connection.

The use of standard airtightness tape, which is designed to seal joints between panels, is not recommended to seal 3-dimensional connections such as building penetrations. As the tape is very rigid, it is unable to follow the shape of the pipes and large leakages can arise. Air and water tightness tests showed these connections can be very tight, but most of the times they result in large air leakage rates. Furthermore, the use of rigid tape in this situation is very sensitive to mechanical impacts and cannot be regarded as durable.

In the smaller setup, a flexible butyl tape was tested which is designed for 3-dimensonal connections, which proved to be very airtight.

EPDM gaskets showed to be less airtight then sprayed PUR, or flexible butyl tape, but in absolute values, the air leakage rate is still negligible. Contrary to PUR or tape, the connection is not permanent and can be adapted after installation, which is a very important aspect in respect to long-term durability.

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