# Air- and water tightness of prefabricated envelope modules for the renovation of buildings

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**Abstract.** Prefabricated lightweight building envelope modules have a large potential for the renovation of existing buildings in a fast way, by simply installing the modules against the existing façade. By this, the on-site phase is limited and the building may remain in operation. Several systems based on wood and steel have been developed in the building industry and their application is well documented in literature. Components used in industrial buildings, e.g. lightweight concrete or structural insulated panels, also seem to have potential to renovate repetitive buildings in a fast way. Despite of this potential, these systems are seldom applied. An important cause is the lack of knowledge concerning air- and water tightness that can be obtained and the extent to which it can be realized without external scaffolding or measures on site.

In the laboratory, 8 solutions were evaluated to close joints between prefabricated panels: sealant tape, airtight coating, systems with silicon strips, (semi)-closed EPDM foam strips, PVC-foam around a wooden slat and open-cell EPDM and polyethylene foam seals. These products were applied in a set-up with horizontal and vertical joints with crossings between panel joints. Mainly flush joints were tested, but tongue-in-groove configurations have been evaluated as well. The relative impact of production, installation tolerances and typical installation errors were examined by introducing realistic tolerances in the test setups. Finally, the degree of prefabrication and potential applications in prefabricated systems are also discussed. Future research will focus on the application of these systems in the connection between the prefabricated façade panel and the existing building.

## Introduction

In 2050, the greenhouse emissions should be decreased with 90%, compared to the level in 1990 (1). The renovation of buildings can contribute to achieve this objective, however, only 1% of the residential buildings are refurbished yearly in Flanders (2). Prefabricated lightweight building envelope modules have the potential to renovate existing buildings in a fast way, by simply installing the modules against the existing façade. By this, the on-site phase is limited and the building may remain in operation. In the past decade, several research projects have shown the potential and applicability of prefabricated elements for renovation of multifamily buildings and schools (3) (4) (5) (6). In Belgium however, the lack of experience and technical knowledge hampers the full application of these systems.

One of the technical issues indicated by Belgian contractors is the creation of air- and watertight junctions when only one side is accesible. This is a crucial factor in the case prefabricated panels are installed against an exisiting façade where the interior side is not accesible, but also for new constructions where scaffolding needs to be avoided. Secondly, the closing materials should be able to accommodate movements and installation tolerances of the prefabicated modules. For example, timber frame and concrete prefabricated panels are typically installed with a wide joint (e.g. 15 mm between concrete panels of 4.8 m width (7)). Tongue-and-groove configurations in the junctions are frequently used in structural insulated panels. However, irregularities in the junction can cause insufficient closing of the junctions. The airtightness system needs to bridge the wide gap between panels and tolerate irregular surfaces in the surface and movements of the elements. Finally, to fully exploit the potential of prefabrication, the solutions of air- and watertight junctions need to be as far prefabricated as possible or at least easy to install on site.

In this paper, the applicaton of 8 concepts to close joints between prefabricated panels is evaluated by means of air- and watertightness tests in laboratory conditions (Figure 1). The systems were tested in three set-ups, each with a different objective.

In set up 1, the focus lied on the closing of wide flush junctions and crossings. Tape is frequently used in timber frame constructions and mainly in inside environments. However, (8) has highlighted the potential of using airtightness tapes on the outside of a timber frame construction to ensure the airtightness. Silicon strips are currently used at window-wall interfaces but can potentially also be used to close wide gaps at junctions. Liquid applied airtightness coatings are a rather new solutions in the building industry, whereas spray in place polyurethane foam is frequently used to close wide gaps and joints between concrete panels (9).

In set-up 2, a variety of EPDM foams were tested to close vertical junctions and crossings of junctions. EPDM foams can be used in prefabicated panels with façade cladding integrated. However, up to now it is unclear what characteristics EPDM foams should have to guarantee the water- and airtightness of prefabricated systems. Different compression rates, execution with single or double foam strips, the difference between closed and semi-closed cell foam band and the use of tape to the non-adhesive side and was assessed (10) (11). Next to that, three different executions of crossings with closed-cell EPDM foams were examined.

Finally, in set-up 3, three systems to close tongue-in-groove junctions between structural insulated panels were examined: a wooden slat with PVC foam around (12), a polyurethane foam band with polyethylene (PE) film and an open-cell EPDM foam (13). These three systems have in common that they are easy to install and façade cladding can be integrated.

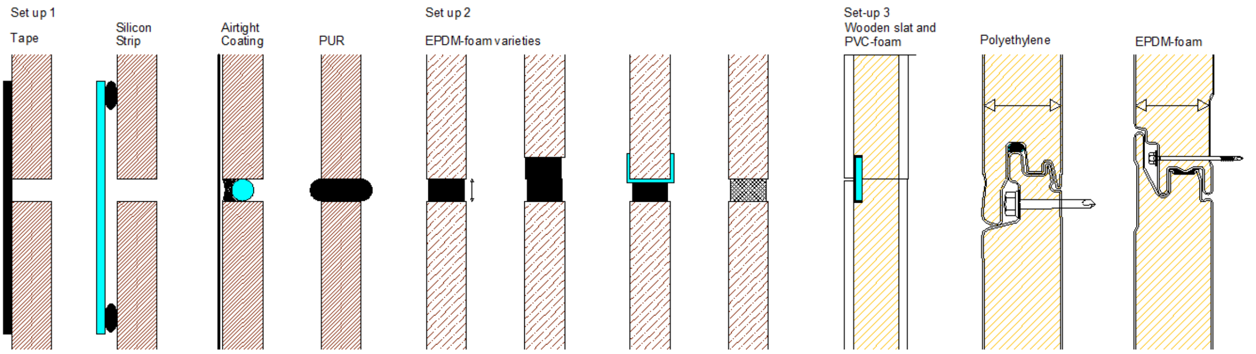


**Figure 1 Overview of the tested systems to close wide junctions and tongue-in-groove systems.**

## Evaluation Criteria

**Airtightness.** The systems were tested according to EN 12114. However, there are no standardized evaluation criteria available for junctions between opaque building components in Belgium. In the Netherlands (14), NEN 2687 offers evaluation criteria for the airtightness of junctions between building components, according to three classification levels: basic (level 1), good (level 2) and excellent (level 3)(Table 1). Only level 3 for building volumes up to 250 m³ is in accordance with the conditions for passive houses ($n_{50} < 0.6\ h^{-1}$) (indicated in grey on Table 1). Consequently, the conditions of this classification were chosen in this paper.

**Table 1 Classifications according to NEN 2687 for residential buildings (14)**

| Classification | Building volume(m³) | | Maximal air leakage flow at 10 Pa ( $q_{v;10}$) | Maximal Air leakage flow (m³/h) at 50 Pa | Air changes per Hour $n_{50}$ ($h^{-1}$) | |
|---|---|---|---|---|---|---|
| | Larger than | Up to | [dm³/s] | [m³/h] | Larger than | Up to |
| Level 3 (Excellent) | - | 250 | 15 | 147.66 | - | 0,591 |
| | 250 | - | 30 | 295.31 | 3,937 | - |

Once the classification is chosen, NEN 2687 imposes an air leakage coefficient (C, [$m^3/h.Pa^n$]). This value is formulated for window-wall junctions, foundations and roof connections (14). From the air leakage coefficient C, the air leakage flow at 50 Pa pressure difference ($V_{50,joint}$) was calculated with equation 1. For level 3, the allowed leakage rate is 0.042 m³/h.m at 50 Pa for junctions between prefabricated panels (Table 2). This is ten times smaller than the air leakage flows allowed in level 1-buildings (0.415 m³/h.m), which is already considered as 'a basic airtightness level' according to NEN 2687 (14).

**Table 2 Air flow coefficient (C) and allowed leakage rate $V_{50,joint}$ for residential buildings, NEN 2687 (14)**

| | Level 1 Basic | Level 2 Good | Level 3 Excellent | |
|---|---|---|---|---|
| Air flow coefficient (C) of junctions between roof panels and between façade and structural wall | 0.01 | 0.005 | 0.001 | [$dm^3/s.m.Pa^n$] |
| Maximal allowed leakage flow at 50 Pa ( $V_{50,joint}$) | 0.415 | 0.208 | 0.042 | [m³/h.m] |

$$V_{50,joint\_allowed} = C.\Delta P^n \text{ [m}^3\text{/h.m] with } \Delta P^n = 50^{0.625} \text{[Pa]} \quad (1)$$

**Water tightness.** In terms of water tightness, there are very little performance criteria to be found in the standards. Only for window and curtain walls, test standards and performance criteria are typically available. To evaluate the water tightness performance in lab conditions, the EN 1027 for window frames was used. The corresponding standard EN 12208 defines water tightness classifications. According to the Belgian standard NBN B25-002-1, the application of a specific performance level depends on the exposure and height of the window. In this project, performance level 9A was chosen as evaluation criterion (no water leakage on the inside to 600 Pa). This level corresponds to buildings located at the sea and with connections of windows or window-wall interfaces at 25 m height above ground level. This performance level covers a large majority of the Belgian building stock.

Next to water leakage (visible water on the other side of the element during the test), the EPDM foams (Set-up 2) and all tongue-in-groove systems (Set-up 3) (Figure 1) were also tested on water infiltration (water between the closing system and the substrate). Water infiltration can lead to water leakage to the interior, if no measures are taken to let the infiltrated water drain outside. Next to that, water infiltration can also signalize future air- and water leakages.

## Methods and Materials

The air- and water tightness test of the systems on Figure 1 was executed according to standard EN 12114 and EN 1027 respectively. All systems were installed in a plywood frame (Figure 2) to create a closed box, as suggested in EN 12114. In total, three set-ups were built to evaluate the samples.

**Set-up 1.** In Set-up 1, the use of tapes, silicon strips, airtightness coatings and PUR-foam was examined. This set-up consisted of 16 tiles of 29.5 x 29.5 cm, fixed in a plywood frame. With the tiles, 9 crossings and 7.5 m of joints were created. The joints had an average width of 18 mm. The tiles were independently fixed to the frame to create an uneven surface. It was expected that the crossings would be the weakest points in the set-up (e.g. Figure 2a) (9).

**Set-up 2** In this set-up, a variety of EPDM foams and their execution details were tested (Figure 1). In a first serie of tests, the EPDM foams were used in vertical joints (Figure 2b) to assess the impact of the compression rate (between 30% and 70%), double or single placement, difference between semi-closed and closed cells, foams with a rough or smooth surface and the use of tape on the non-adhesive side of the foams (10).

Next to that, the EPDM foams were installed between wooden tiles of 4.5 cm thickness which created vertical and horizontal joints with crossings (11) (Figure 2c). The compression rates of the foams varied from 20% to 70%. Some of the crossings were reinforced with butyl tape or with silicon pasta. By this, the crossings were tested on the sensitivity to execution details and the compression rate.

**Set-up 3** In the third set-up, three varieties of tongue-in-groove systems were tested (Figure 2d). The system with the PVC film around a wooden slat was tested on airtightness to address the impact of execution flaws on the overall airtightness. The execution flaw here was the use of shorter wooden slats instead of one at panel height (12). This includes a risk of insufficient closing, which can also happen when the panels are deformed or when a screw is introducing deformations locally.

For the systems with a PE-closing and open-cell EPDM foam in set-up 3, the impact of panel thickness and sealing material on the air- and watertightness was assessed (13). Panel thicknesses of respectively 60,80,100 and 150 mm (PE-film) and 60,80,100 and 120 mm (open-cell EPDM foam) were tested (13). Additionally, a short watertightness test of 10 minutes at 600 Pa pressure difference and 2 l/min/m² was executed to see whether the pressure difference or the water spray rate triggers water infiltration in the system. The cross-cut ends were closed with polyurethane foam to prevent air- and waterleakages through the upper and lower side of the panel. The panels were installed with a hidden connection, as recommended in the technical documentation (See also Figure 1).

Table 3 gives an overview of the executed tests per system.

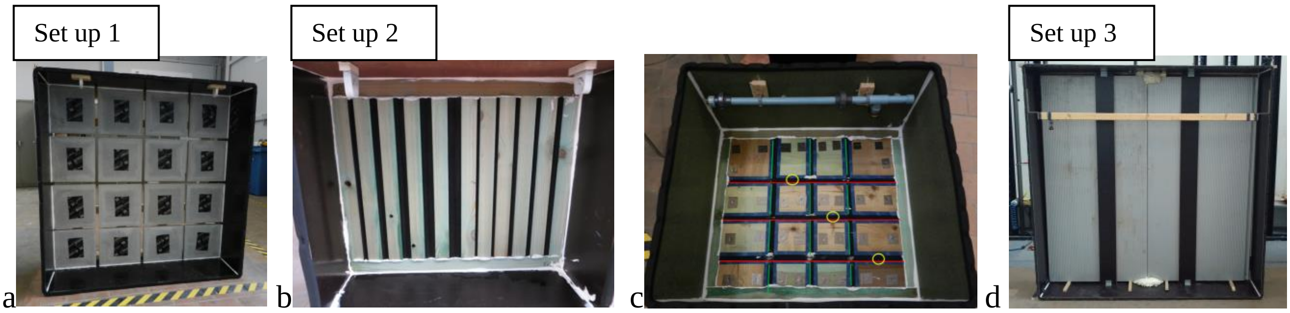


**Figure 2 (a) Set-up 1 (b) Set-up 2: vertical joints (c) Set-up 2: Crossings (d) Set-up 3: Tongue-in-groove systems**

**Table 3 Overview of the executed tests.**

| | Substrate | Airtightness (EN 12114) | Watertightness leakage (EN 1027) | Watertightness Infiltration (EN 1027) | Execution varieties |
|---|---|---|---|---|---|
| **Set-up 1 Flush joint (figure 2a)** | | | | | |
| Tape | OSB, Fibreboard, Concrete | x | x | | vertical-horizontal closing and vice versa |
| Silicon Strip | OSB | x | x | | |
| Airtight Coating | OSB | x | x | | |
| Polyurethane Foam | Concrete | x | x | | |
| **Set-up 2 Flush joint (different compression rate (figure 2b) and crossings (figure 2c)** | | | | | |
| EPDM foam | MDF (vertical junctions) | x | x | x | different cell-structure, double-single, compression rate, use of tape on non-adhesive side (in total 5 test boxes) |
| | MDF (junctions and crossings) | | x | x | Three ways to reinforce the crossing (+ 3 test boxes with increasing compression rate) |

| | | | | | |
|---|---|---|---|---|---|
| **Set-up 3 Tongue in Groove (figure 2c)** | | | | | |
| PVC foam around wooden slats | SIP (Fibreboard-PUR) | x | | | Use of separate wooden slats in one panel |
| Polyethylene | SIP (Alu-PUR) | x | x | x | thickness of 6,8,10 and 15 cm |
| EPDM Foam | SIP (Alu-PUR) | x | x | x | thickness of 6,8,10 and 12 cm |

**Airtightness test procedure**.The airtightness tests were executed according to EN 12114, with 10 pressure differences from 50 to 500 Pa in steps of 50 Pa. The measured air leakage flow $V_{tot}$ is composed of several parts, according to equation 2.

$$V_{tot} = V_{substrate} + V_{frame} + V_{frame\text{-}testwall} + V_{joint} \quad [m^3/h] \tag{2}$$

In order to estimate the air leakage rate through the junctions ($V_{joint}$), the airtightness tests were executed in several steps. Generally, the following procedure was respected:

- Airtightness test ($V_{tot}$);
- Watertightness test;
- Airtightness test ($V_{tot\_1}$) with joints covered with airtightness coating (Set-up 1 and 2) or tape (Set-up 3). Based on additional measurements, it was shown that the joints with airtight coating can be considered as perfectly airtight; $V_{joint} = 0$ m³/h

$V_{tot\_1}$ is then composed of the following parts (equation 3) :

$$V_{tot\_1} = V_{substrate} + V_{frame} + V_{frame\text{-}testwall} \quad [m^3/h] \tag{3}$$

In Set-up 1, it was necessary to assess the airtightness of the substrates (9). When the substrate is also covered with an airtightness coating, $V_{tot\_2}$ is directly measured. This air leakage flow is composed of the air leakage through the plywood frame and the connection between frame and testwall (equation 4). Afterwards, the measured air leakages were fitted on the power law (equation 5). Chauvenet's criterion was used to evaluate the measurement points (16).

$$V_{tot\_2} = V_{frame} + V_{frame\text{-}testwall} \quad [m^3/h] \tag{4}$$

$$V_f = C.\Delta P^n \quad [m^3/h] \tag{5}$$

The fitted values of $V_{tot}$ and $V_{tot,1}$ were substracted from each other to calculate the air leakage rate through the junctions.

$$V_{joint,fit} = V_{tot,fit} - V_{tot,1,fit} \quad [m^3/h] \tag{6}$$

**Watertightness** For the watertightness test, Set-up 1 and 3 were exposed to a spray rate of 2 l/min/m² in a sequence of pressure differences, according to Figure 3a (EN 1027). In set-up 2, the foam bands were tested under pressure difference of 750, 900, 1050, 1500, 2000 and 2500 Pa (10). According to EN 1027, the systems fails when water leakage is established (when water is visible on the backside of the set-up).

However, for Set-up 2 and 3, an additional criteria was water infiltration in the joint (water between the closing material and substrate). This was evaluated by using blotting papers (Set-up 2) installed between the foams and the substrate and with water indications stickers (Set-up 3), attached all over the cross section of the tongue-in-groove junction. With blotting papers in a flush joint, it was possible to visualize water infiltration during the test (Figure 3b). With the tongue-in-groove configurations, the set-up could not be opened during the test. To asses water infiltration after the test, water indicator stickers were used. These stickers turn from white into red when they get in contact with water (Figure 3c).


**Figure 3 (a) Procedure water tightness test according to standard (EN 1027 2000) (b) installation of blotting paper on half depth between the EPDM foam and the substrate (c) Use of water indicators in the tongue-and-groove junction (13)**

## Results

**Airtightness** Figure 4 provides a general overview of the results of the airtightness measurements of Set-up 1, 2 and the wooden slat with PVC foam in Set-up 3. The results in red are airtightness systems that did not meet the requirements for airtightness level 3 (14). However, all systems in Figure 4 are suitable for airtightness level 2 (0.208 m³/hm) (Table 2). For the airtightness tapes, an average of the three tapes tested in (9) is displayed per substrate. The combination of tapes on stiffer substrates like OSB and concrete show a lower air leakage flow than the tape on woodfibre panels. The attachment of the tape on the woodfibre was less strong, because of the small fibers in the substrate. The adhesion of tapes to different substrates and the impact of durability are discussed in detail in (15).

Concerning the EPDM-foams of set-up 2, all air leakage flows are within the same accuracy range. Therefore, it is not possible to compare the impact of the various characteristics. However, when only the measurement data is concerned, it seems that foam bands with a semi-closed cell structure showed the best performance at 50 Pa pressure difference.

In Set-up 3, the air leakage flow measured through the junction with wooden slat and PVC foam were smaller than the accuracy range. Consequently, this means the system is airtight. Even executed as 5 smaller parts over the height of the junction, the air leakage flow remains very small.

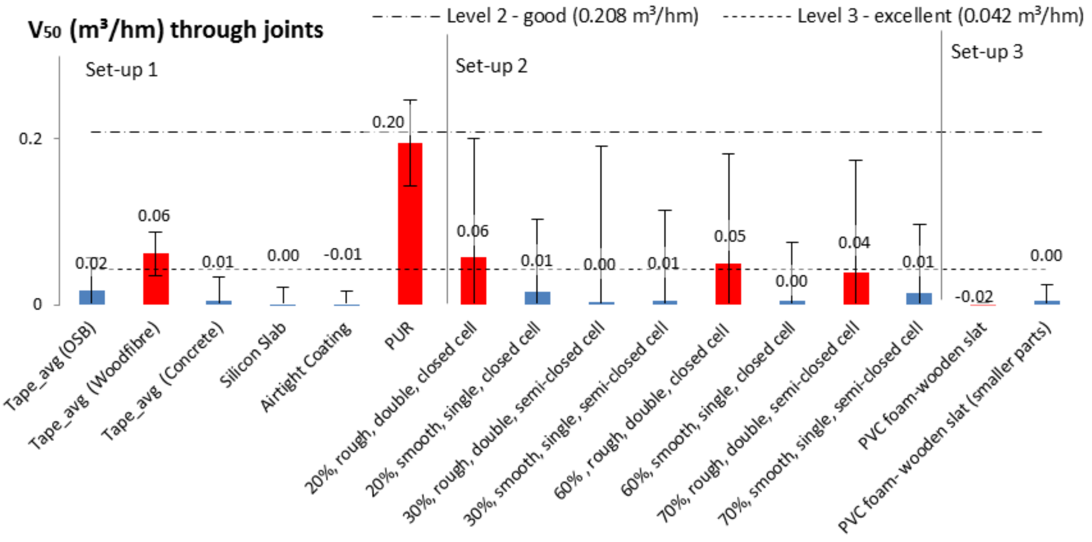


**Figure 4 Overview of the air leakage flows at 50 Pa pressure difference ($V_{50}$) for the systems tested in Set-up 1, Set-up 2 and the wooden slat with PVC foam in Set-up 3.**

The tongue-in-groove junctions with PE-film and open-cell EPDM foam are displayed separatly (Figure 5), because they clearly show a larger leakage flow in comparison to the other closing materials tested (Figure 4). Both tongue-in-groove systems did not meet the requirements for airtightness level 1 in NEN 2687 (14)(Figure 5).

All panels showed nonetheless the same air leakage flow, with exception of the panel with PE-film at 60 mm thickness, which is due to a short PU-band in the joint (Figure 10a). In general, to reach the criteria for residential buildings, extra measures to close the junction of the tested tongue-and-groove systems are necessary.

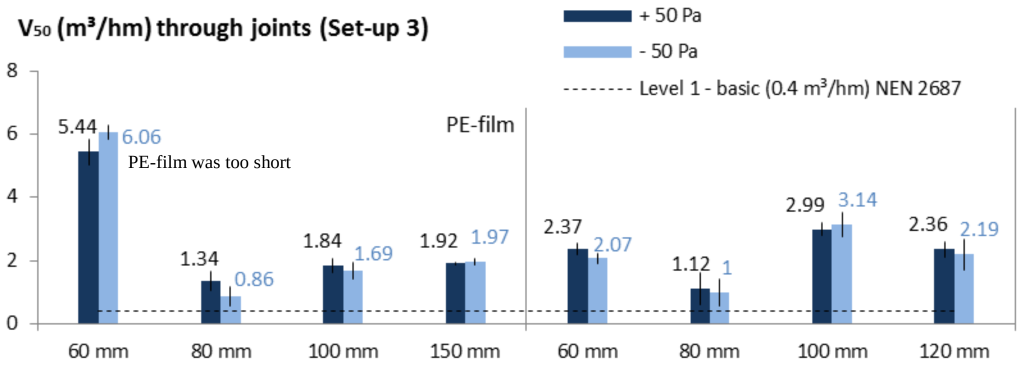


**Figure 5 Overview of the air leakage flows in over- and underpressure of the PE-film and open-cell EPDM-foam in the tongue-and-groove junctions, Set-up 3**

Nonetheless, when putting these air leakage flows (Figure 4,Figure 5) against the allowed $n_{50}$-value of a regular building, the measured air leakages are small. Take e.g. a one-story rectangular building (50 x 10m) built with 24 prefabricated panels of 5 m width and 3 m height, thus creating 72 m of vertical joints and 240 m of horizontal joints. If the building volume is 1500 m² and the vertical junctions of the façade are built with EPDM-foams in a tongue-and-groove configuration (e.g. at 100 mm thickness with 2.99 m³/hm at +50 Pa), the total air leakage caused by this system is 215.28 m³/h or 24% of the allowed $n_{50}$-value according to passive house standards.

**Water tightness** Table 4 gives an overview of the results of the water tightness tests. In set-up 1, the crossings are the weakest points concerning water tightness. Next to that, local deficiencies in the junction also caused water leakage. This was for example the case with the silicone strips and the airtight coating, where local deficiencies hindered the full covering of the liquid silicones.

For Set-up 2, the vertical junctions failed in compression rates below 70%, with only one single band installed and when there was no tape at the non-adhesive side of the foam. The tape smoothens the irregularities of the wooden surface, which causes a better contact between the substrate and the EPDM foam band. Therefore, executions without tape (without smoothening) heightens the risk on local deficiencies, and thus on water leakages. The foam bands with the closed cell structure showed no leakages at all. In general, under 200 Pa, EPDM foam bands above 30% compression showed no water leakages. However, the higher the compression rates, the higher the pressure difference at which the foam band showed water leakages. In the application, it is therefore recommended to use high compression rates (> 70%) and in combination with another foam band or with a smoothening material on the non-adhesive side, e.g. tape.

Concerning the crossings in EPDM foam, all crossings failed the EN 1027 in test-boxes with low compression rates. In high compression rates, the crossings with butyl and silicon reinforcement showed no water leakages under 600 Pa pressure difference.

Lastly, in Set-up 3, all panels passed the water leakage tests according to EN 1027. However, most of the test samples showed infiltration of water beyond the closing. A short water infiltration test showed that the panels with the PE-film showed infiltration at high pressure differences, while the panels with the EPDM-foam showed infiltration after a long exposure to water.

In the following sections, the causes of failure and recommendations in the installation of the closing systems tested in all three set-ups are more discussed.

**Table 4 Average pressure difference at which the system showed leakage and/or infiltration**

| | Watertightness leakage (water on the other side) (EN 1027) | Watertightness infiltration (water between the closing material and substrate) (EN 1027) | Watertightness infiltration (water between the closing material and substrate) (10 min, 600 Pa, 2l/min/m²) |
|---|---|---|---|
| **Set-up 1 Flush joint (3 substrates) (figure 2a)** | | | |
| Tape ( on OSB) | between 0 -300 Pa at crossing | | |
| Tape (on woodfibre) | between 0-150 Pa crossing | | |
| Tape (on concrete) | between 0- 50 Pa crossing | | |
| Silicon Strip | 150 Pa Crossing and joint | | |
| Airtight Coating | 50 Pa Deficiencies backerrod | | |
| Polyurethane Foam | 0-50 Pa Crossing | | |
| **Set-up 2 Flush joint (different compression rate) (figure 2b)** | | | |
| EPDM foam (vertical juntions only) | 200 Pa , all single EPDM foams without tape at non-adhesive side, <70 % compression, semi-closed cells | 50 Pa Single EPDM foams, non-adhesive side without tape. Infiltration at the non-adhesive side | |
| EPDF foam (crossings (figure 2b) | (10-60%)250 Pa (crossing, stump finish + silicon luting) At low compression rates (< 60%) all crossings. (20-70%) 300 Pa for stump finish At higher compression rates (20%-70%), stump only | 100 Pa (20-50%) junction | |
| **Set-up 3 Tongue in Groove (figure 2c)** | | | |
| PVC foam SIP (Fibreboard-PUR) | Not tested | Not tested | |
| Polyethylene SIP (Alu-PUR), thickness of 6,8,10 and 15 cm | All passed | All over section (only 8 cm: only before closing material) | Infiltration untill halfway the section |
| EPDM Foam SIP (Alu-PUR) thickness of 6,8,10 and 12 cm | All passed | All over section | No infilitration (except at local damages) |

## Main causes of failure and recommendations

**Stiffness of airtightness materials** Figure 4 shows that more flexible airtightness materials (such as silicon strip, airtightness coating (Set-up 1), EPDM foams with semi-closed cells (Set-up 2), wooden slat with PVC foam in a narrow groove (Set-up 3)) showed lower air leakage flows at 50 Pa pressure difference.

Flexible materials seem to be more able to fill irregularities at the surface of the substrate. This is certainly the case for silicon materials like airtightness coatings that are applied as pasta to the substrate (Set-up 1).

A second example is EPDM foams with a semi-closed or open cell structure. Compared to closed-cell structures, EPDM foams with a semi-closed structure are easier to compress.

In set-up 3, the PVC-foam around the wooden slat was also easy to compress. During the installation, the wooden slat was placed in a groove with smaller dimensions. Consequently, the PVC-foam was compressed in the whole groove. On the other hand, the PE-film and open-cell EPDM-foam were fixed in the tongue-and-groove system before installation. Therefore, it was more difficult to get the ideal compression when installing the prefabricated elements.

On the other hand, the more flexible a closing material is, the higher the compression rate should be to get the connection airtight. This is illustrated by comparing the air leakage rates at 600 Pa of Set-up 2 (Figure 6). Here, the EPDM foams at 20% and 30% compression showed a higher air leakage flow than the foam bands at 60% and 70%. Next to that, in contrast to the air leakage flows at 50 Pa (Figure 4), the closed-cell foams showed a lower air leakage rate than the semi-closed structures at 600 Pa, in the compression rates of 60% and 70% (Figure 6). Finally, the EPDM-foams with closed cell structure did not show water leakage at any point (Table 4).

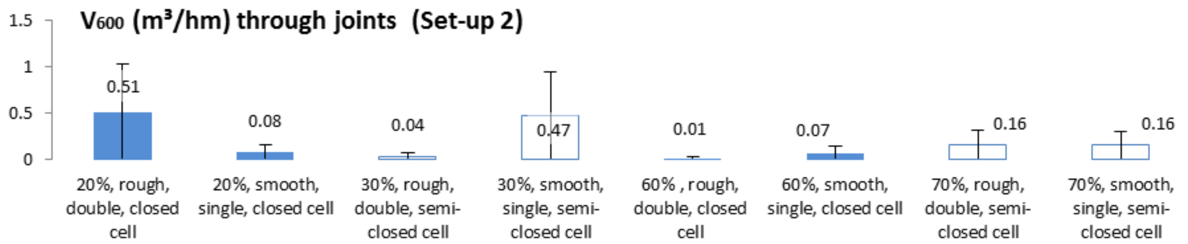


**Figure 6 Air leakage flow (m³/hm) at 600 Pa, set-up 2, vertical joints**

**Detailing of crossings** The majority of the crossings failed at pressure differences below 600 Pa during the water tightness test (Set-up 1 and Set-up 2) (Table 4). Depending on the material used, the crossings showed weak points in the overlap of materials (silicon strip, tape…Figure 7a) or in the corners (EPDM foams, PUR, airtightness coatings)(Figure 7b). The water tightness can be improved by reinforcing the crossings with extra material, e.g. a piece of diagonal tape across the crossing, additional silicone in the corners or using airtightness coating locally at the crossings. The possible adjustments on crossings with tape are further discussed in (9) (15).
Concerning the EPDM-foams (Set-up 2)(Figure 7c), it is recommended to install extra material in the corner-edges of the panels, to guarantee a sufficient filling of the joint when the elements are installed against each other on-site.

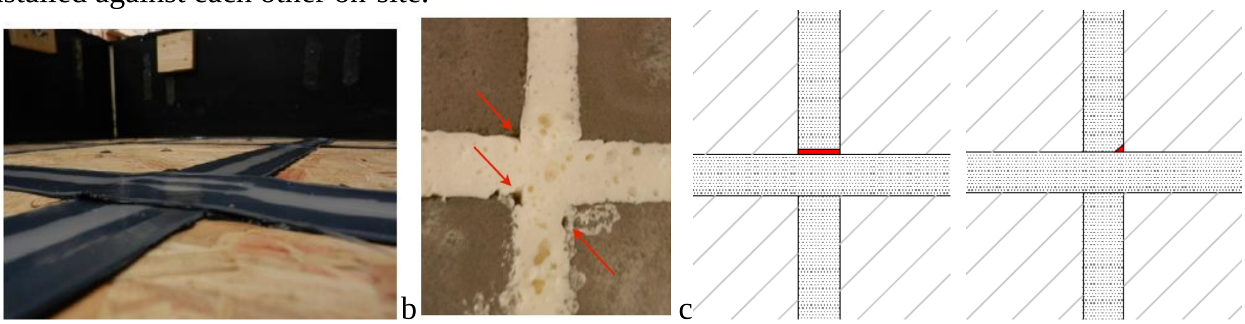


**Figure 7 (a) Set-up 1: in overlap of the closing material (b) insufficient filling in the corners, PUR foam (c) Insufficient filling in the corners, EPDM foam (Set-up 2)**

From the tests on the crossings with EPDM-foams (Set-up 2) (11), it seemed that the crossings reinforced with butyl tape and silicones performed better than the crossings without reinforcement in higher compression rates (Box C, compression rates between 20%-70%, Figure 8). In lower compression rates however, all crossings showed water leakage in pressure differences under 600 Pa (Box A, compression rates between 10-50%, Figure 8). Again, when EPDM-foams are used, high compression rates and extra reinforcement in the corners is recommended. Additionally, airtightness coating could be applied locally at the crossings to close all the small gaps.

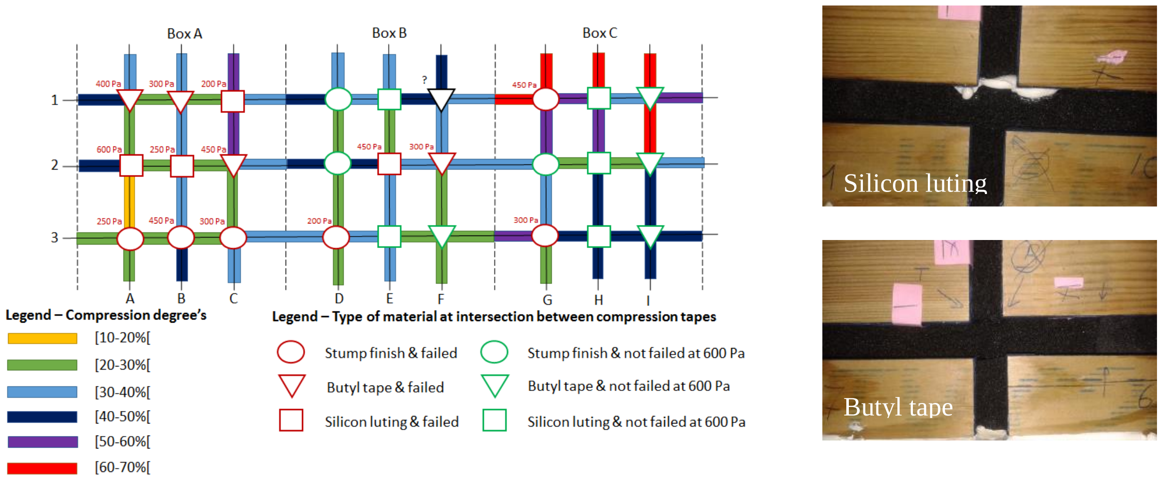


**Figure 8 (a) Sheme of the three test boxes of Set-up 2, with crossings executed with a stump finish, butyl tape or silicon luting (11) (b) Image of the crossings with silicon luting and butyl tape**

**Local deficiencies in the joint** Next to crossings, local deficiencies in the joints can also cause water leakages. Figure 9a shows a local compression at the backerrod, caused by an irregularity in the OSB-panel (Set-up 1) (9). Therefore, a flat surface at the flush joint should be guaranteed to obtain a perfect cover of the airtightness coating. In Set-up 2, it was shown that the use of tape on the non-adhesive side of the EPDM-foam prevented water infiltration. With the use of tape, irregularities in the surface were smoothened and the closing system was more evenly attached to the surfaces in the joint (Figure 9b) (10).
A second problem that can cause infiltration in the joint, is water accumulation in the horizontal joints (Figure 9c) (11). This can evolve to water infiltration at higher pressure rates or when a local deficiency is present.

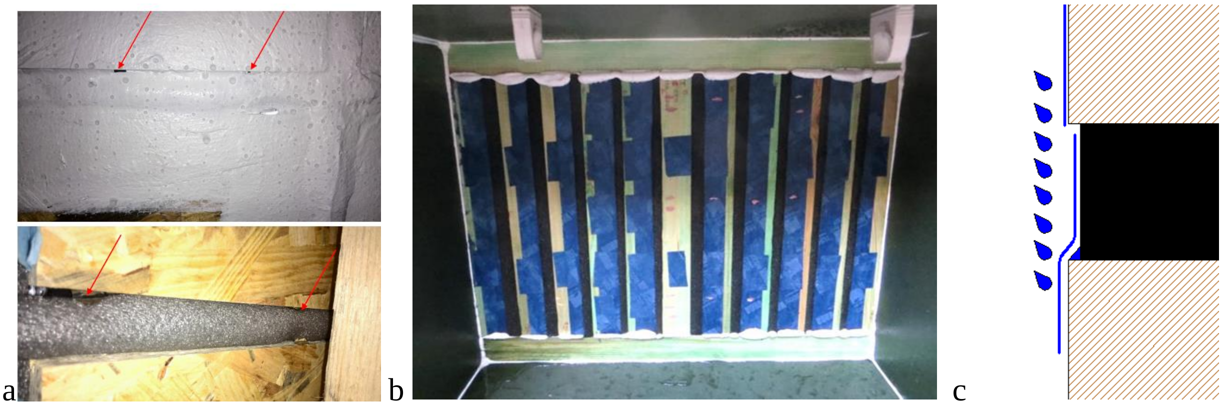


**Figure 9 (a) Airtightness coating (above) and backerrod (below) (9). (b) Set-up 2: testing vertical joints of the EPDM foam, with tape on the non-adhesive side of the foam (10). (c) Accumulation of water in a horizontal joint, causing water infiltration between the foam and the substrate.**

In tongue-and-groove systems (Set-up 3), local deficiencies in the closing material abase the air- and water tightness (Figure 10). Because the closing materials are already integrated in the panels, it is nearly impossible to adjust the meeting surfaces in-situ. The risk on local deficiencies in the joint is higher with increasing panel thickness. However, as stated above, there was no significant relation between panel thickness, airtightness system (PE or EPDM foam) and air leakage flows in these tests (Figure 5).
**Material characteristics and water infiltration (Set-up 3).** Concerning water tightness of tongue-in-groove systems, all samples tested (Set-up 3) showed water infiltration after the standardized test (EN 1027) was executed to 600 Pa (Table 4). Water infiltration could only be determined after dismantling the panels. Therefore, an additional test of 10 minutes, at 2 l/min/m² with 600 Pa overpressure was executed. By this, the mechanism behind water infiltration could be determined.
Concerning the tongue-in-groove joint with the PE-film, the sample of 150 mm thickness showed that water infiltration occurred until halfway the section during the 10 minutes-test (Figure 10b). This indicates that water infiltration in the tongue-in-groove system with the PE-film occurs at high pressure differences and at local damages of the closing system. In comparison, the sample of 80 mm thickness with the PE-film was the only one without water infiltration and also showed the lowest air leakage flow (Figure 5).
In contrast, water infiltration was not established in the samples with the EPDM-foam (Set-up 3) after the 10-minutes test. Only one sticker indicated water infiltration, but this was located beneath a local damage and the EPDM foam around was saturated (Figure 10c). This showed that infiltration across the whole section only occurs when the EPDM foam is saturated, e.g. after a water tightness test of 50 minutes (as is the case when following the procedure in EN 1027).
In any case, water infiltration was established in all the panels after the standardized test (EN 1027). In practice, this means that cross-cavity flashing should be provided to let the infiltrated water drain out the joint at regular intervals. However, the installation of a cavity flashing can introduce other problems like thermal bridges in the building envelope.

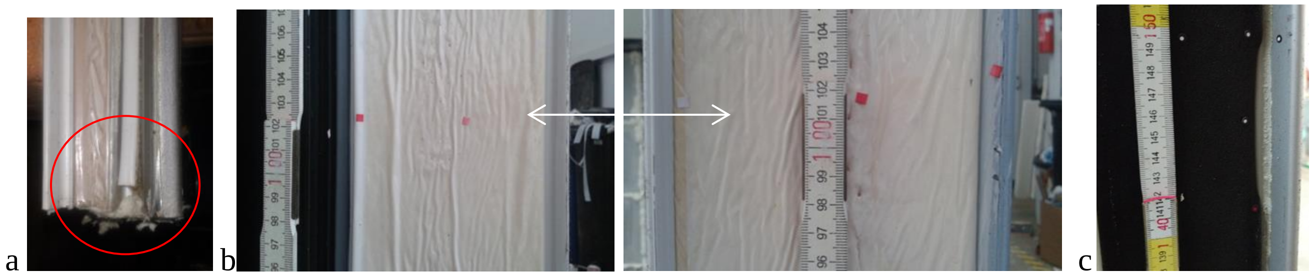


**Figure 10 (a) Sample S1,6: short PE-foamboad caused the high air leakage flow (Figure 9). (b) Sample with PE-film at 150mm thickness after 10 minutes test. The water stickers indicate water infilration untill halfway the section. (c) Sample with open-cell EPDM foam at 120 mm thickness. After 10 min, there was only water infiltration at local damage at a saturated area.**

**Execution steps** It is clear that execution flaws are the main cause of air and water leakages in all three set-ups. Concerning the systems from Set-up 1, attention must be paid to the adhesion of the tape, backerrod and silicones to the substrate. Even small gaps can cause severe water leakages. This makes the methods very labor intensive, which undermines the potential of these systems for prefabricated panels.

Most systems from set-up 1 can partially be integrated in a prefabricated system. However, additional handlings are necessary on site to close the junction (e.g. adding silicone). By consequence, it is not possible to integrate façade cladding when only one side is accessible on the construction site. Next to that, from the test it is clear that the execution of the joint sealant must be strictly checked before installing the façade cladding.

The EPDM-foams of Set-up 2 can be used in case façade cladding is integrated in the prefabricated elements. However, attention should be paid to the smoothness of the surfaces in the joint. Adhesive materials like tape help to smoothen the surfaces, as shown in Set-up 2. For the crossings, it is advised to add extra material (e.g. extra EPDM-foam or reinforcements with butyl tape or silicone or airtightness coating locally) to guarantee a sufficient closing. Nonetheless, the closing at crossings should be checked during installation of the panels on-site.

In Set-up 3, the most advanced prefab systems were tested. However, the performances were very sensitive to the way the panels were installed and the condition of the closing system. Next to that, the results clearly indicate that additional measures are necessary to achieve the basic airtightness level of NEN 2687 (14).

## Conclusion

This paper discussed 8 different solutions to close junctions of prefabricated elements. Table 5 summarizes the attention points, possible measures, degree of prefabrication and possibilities to improve prefabrication of the systems. Not all closing systems tested are suitable for integration in a fully equipped prefabricated façade panel. However, in cases where a temporary cladding is used (e.g. when building in phases), the systems can be applicated.

Future research will focus on the air- and watertight connections between prefabricated panels and existing buildings.

**Table 5 Practical evaluation oft he systems through the air- and watertightness tests**

| | **Attention points during installation** | **Extra measures for optimal air- and watertightness?** | **Degree of prefabrication** | **Possiblity to integrate façade cladding?** |
|---|---|---|---|---|
| **Set-up 1 Flush joint (3 substrates) (figure 2a)** | | | | |
| Tape | Crossings, sufficient adhesion | Reinforce the crossings | External scaffolding necessary | Partially |
| Silicon Strip | Crossings, sufficient adhesion | | | |
| Airtight Coating | Local deficiencies | | | |
| Polyurethane Foam | Hardening process | | | |

| | Attention points during installation | Extra measures for optimal air- and watertightness? | Degree of prefabrication | Possiblity to integrate façade cladding? |
|---|---|---|---|---|
| **Set-up 2 Flush joint (different compression rate) (figure 2b)** | | | | |
| EPDM foam | Local deficiencies and crossing compression rate > 70% | Airtightness coating at the crossings<br>use of tape to smooth the surfaces at non-adhesive side | Integration possible | Yes |
| **Set-up 3 Tongue in Groove (figure 2c)** | | | | |
| PVC foam and wooden slat<br>SIP (Fibreboard-PUR) | | Closing of the upper and under egde | Wooden slat is placed in groove in-situ, easy to handle on site | Yes |
| Polyethylene<br>SIP (Alu-PUR), thickness of 6,8,10 and 15 cm | Deficiencies in the junction | Closing the upper edge, provide a drip at the bottom.<br>Extra sealing for airtightness necessary. | Integrated | Yes |
| EPDM Foam<br>SIP (Alu-PUR) thickness of 6,8,10 and 12 cm | Deficiencies in the junction | Closing the upper edge, provide cross cavity flashing at the bottom.<br>Extra sealing for airtightness necessary. | Integrated | Yes |

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