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THE EFFECT OF INTERIOR AIR- AND VAPOR-CONTROL LAYERS ON ENVELOPE AIRTIGHTNESS IN LOW-ENERGY TIMBER-FRAME HOUSES

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ABSTRACT

The effect of interior air- and vapor-control layers on envelope air leakage using a large field dataset of 450 low-energy timber houses in the Czech Republic is examined in the study. Two sealing concepts were evaluated: vapor-tight polyethylene or aluminum foils, and vapor-retarding board materials such as oriented strand boards and coated gypsum fibre boards. Airtightness was measured using the blower-door method according to ISO 9972 under both pressurization and depressurization. Houses with foil-based barriers reached a mean ACH50 of 1.09 h^{-1}, while houses sealed with board materials achieved values approximately 30% lower. Differences between pressurization and depressurization were primarily related to pressure-sensitive leakage paths in window and door assemblies and in non-adhered areas of foil membranes. Board-based systems exhibited more localized defect patterns, reducing their overall impact on ACH50 at the building scale. The findings highlight the decisive role of construction details and indicate that airtightness performance is more strongly influenced by system continuity and robustness than by nominal material properties.

Keywords: envelope airtightness; blower-door test; air- and vapor-control layer; timber-frame buildings; construction details.

INTRODUCTION

Sustainable and energy-efficient housing has become a major focus of residential construction in recent decades. Timber, as a renewable material with a comparatively low environmental footprint, plays an increasingly important role in this context and is widely used in light-frame and prefabricated building systems. While some countries already make extensive use of timber for residential construction, others continue to rely predominantly on mineral-based technologies (Vinha *et al.*, 2015; Linkevičius *et al.*, 2023; Sikkema *et al.*, 2023).

Recent international analyses highlight that the share of timber-frame houses is steadily increasing, driven by the need to reduce operational energy demand and embodied carbon, as well as by evolving consumer preferences for environmentally responsible housing (Gustavsson and Sathre, 2011; Hurmekoski *et al.*, 2015; Ramage *et al.*, 2017; Loučanová and Olšiaková, 2020; Sikkema *et al.*, 2023).

In the Czech Republic, the share of timber buildings in new residential construction has historically been low, yet recent years have witnessed a substantial increase. According to the Czech Statistical Office, timber houses have accounted for approximately 15 % of all newly built family houses in recent years. In 2023, a total of 2,595 timber-frame family houses were completed (CZSO, 2025). This development aligns with broader European trends, where timber-frame and prefabricated wood-based systems have gained prominence due to their low environmental footprint, rapid on-site assembly and favourable energy performance. Recent European reviews and market analyses report a consistent rise in the adoption of timber construction across various countries, driven by sustainability targets and technological progress in light-frame and panelised timber systems (Sikkema *et al*., 2023). Within the Czech market specifically, low-energy light-frame timber houses form the dominant segment of the timber housing sector, and similar patterns in construction practice and airtightness performance have been documented in previous national studies (Böhm *et al*., 2021).

Airtightness is a key performance parameter for low-energy timber-frame houses because uncontrolled air infiltration increases heating demand, decreases thermal efficiency, and reduces the effectiveness of mechanical ventilation with heat recovery. In lightweight timber-frame assemblies, the effectiveness of the interior air- and vapor-control layer is particularly critical because the wall structure contains hygroscopic materials and thermal insulation that are highly sensitive to moisture accumulation. Although multiple construction-related factors influence the overall airtightness of a building envelope (Srba *et al*., 2016; Kalamees *et al*., 2017; Böhm *et al*., 2021), the type and execution of the interior air- and vapor-control layer play a central role. A continuous and well-installed barrier limits convective moisture transfer into the wall assembly, thereby reducing the risk of interstitial condensation and subsequent degradation of insulation or timber components. Moisture-transport studies have shown that even relatively small leakage paths can significantly increase vapor movement and lead to hidden condensation within wood-based envelopes (Shrestha *et al*., 2019; Pobucká *et al*., 2025). Similar findings were reported in hygrothermal simulations of wood-frame walls, where local leakages increased moisture accumulation under winter boundary conditions (Wang and Ge, 2017).

Moisture that condenses within the building envelope can be absorbed by fibrous thermal insulation, resulting in a substantial reduction of its thermal resistance, particularly during winter conditions. Even relatively small increases in moisture content may significantly increase the thermal conductivity (λ-value) of insulation materials, thereby reducing the overall energy performance of the wall assembly (Viitanen *et al*., 2010). Persistent moisture also creates an environment favorable for mould growth and wood-decaying fungi, both of which can compromise indoor air quality and accelerate the deterioration of load-bearing timber elements. Beyond microbial degradation, severe long-term moisture exposure has been shown to reduce structural capacity and may ultimately lead to premature structural failure (Viitanen *et al*., 2010; Mjörnell and Olsson, 2019; Loukou *et al*., 2024). These risks underscore the need for a continuous, well-executed interior air- and vapor-control layer, which is essential not only for maintaining the durability of timber structures but also for preventing interstitial condensation, as assessed using standard hygrothermal criteria such as EN ISO 13788 (ISO, 2012).

Interior air- and vapor-control layers in timber-frame constructions are most commonly implemented as either vapor-tight membranes (polyethylene or aluminum foil) or vapor-permeable board materials, such as oriented strand board (OSB) and coated gypsum fiber boards. Foil-based systems typically offer very high diffusion resistance and can achieve excellent airtightness when installed without discontinuities; however, their performance depends heavily on the quality of taping, adhesion, and mechanical protection during construction. In contrast, board materials act as rigid, airtight layers that are less susceptible to local mechanical damage and facilitate easier visual inspection of joints. Previous studies have shown that both material type and installation quality strongly influence the resulting air-leakage characteristics and long-term durability of the envelope (Hodoušek *et al.*, 2015, 2019b; Hallik *et al.*, 2023).

Ensuring effective air exchange in low-energy timber houses requires that ventilation occurs predominantly through controlled pathways, such as windows, supply inlets, or mechanical ventilation with heat recovery, rather than through uncontrolled leakage in the building envelope. Uncontrolled infiltration not only reduces the effectiveness of ventilation systems but also increases the overall energy demand of residential buildings, as demonstrated in Mediterranean climates (Feijó-Muñoz *et al.*, 2019b). Because even well-performing air- and vapor-control layer materials cannot compensate for poorly executed junctions or service penetrations, achieving the required airtightness level depends not only on the performance of the primary air- and vapor-control layer, but also on the execution of a wide range of construction details. This is consistent with findings showing that detailed configuration can influence the thermal and overall envelope performance in lightweight timber systems (Brzyski *et al.*, 2022).

These details include junctions between wall and ceiling elements, window and door installations, service penetrations, and panel-to-panel connections in prefabricated assemblies, where inadequate protection or execution can also lead to moisture-related failures in timber components (Kalamees *et al.*, 2025). Previous studies have further demonstrated that poorly executed penetrations or junctions often form dominant leakage paths, sometimes contributing more to overall air leakage than the airtightness of the main barrier itself (Srba *et al.*, 2016; Kysela *et al.*, 2023). As a result, high-quality detailing and careful workmanship are essential prerequisites for durable, reliable airtightness in lightweight timber constructions.

The primary aim of this study is to quantify the influence of two commonly used types of interior air- and vapor-control layers, vapor-tight foil membranes and vapor-permeable board materials, on the envelope air leakage of newly built low-energy timber frame houses in the Czech Republic. Although both systems are widely applied in practice, there is limited published evidence comparing their in-situ airtightness performance across large building samples. Existing studies have typically focused either on laboratory testing, on small datasets, or on specific construction details (Hodoušek *et al.*, 2015), leaving a knowledge gap regarding how different barrier types perform under real construction and installation conditions.

This study addresses this gap by analyzing blower-door test results from 450 completed timber-frame houses built in the Czech Republic. In addition to comparing overall air-leakage rates for the two barrier types, the study evaluates differences between pressurization and depressurization measurements. It identifies characteristic leakage paths associated with each system. These results contribute to a more detailed understanding of how barrier type and installation conditions influence airtightness performance in timber buildings and provide technically grounded findings relevant for improving detailing and construction practice.

MATERIALS AND METHODS

Characteristics of the Studied Buildings and Airtightness Systems:

Airtightness measurements from 450 low-energy, light timber-frame houses intended for family living is analysed in the study. The typical layout included one living room with a kitchenette, three bedrooms, and standard auxiliary rooms. Approximately half of the houses were two-story, while the other half were single-story. All studied houses were located in the Czech Republic, where the mean annual air temperature is 7.9 °C according to the national climatological normal (CHMI, 2025).

All buildings were tested according to Method 2 (formerly Method B) defined in EN ISO 9972. Measurements were performed during the construction phase after completion of the primary airtight layer and installation of windows and doors, but before covering the airtight layer with insulation and gypsum board linings that typically form a service cavity.

Testing at this stage allows direct identification of leakage paths while the airtight layer remains accessible. Only buildings measured at this construction stage were included in the dataset. Buildings tested after completion (Method 1, formerly Method A) were intentionally excluded because of differences in preparation conditions before measurement, which would prevent a reliable comparison of airtightness performance between barrier types. Two types of airtight and vapor-tight layers were represented among the measured houses:

1) Foil-based airtight layer

The first group consisted of houses equipped with polyethylene foil (or its alternative with a reinforcing grid, or aluminum foil). Only foils with a water vapor diffusion-equivalent air layer thickness (Sd) greater than 1 500 m, determined according to EN ISO 12572 (ISO, 2016), were used. These foils are also classified as vapor-impermeable according to ASTM E96 (permeability ≤ 0.05 US perm) (ASTM, 2016).

2) Board-based airtight layer

The second group included houses where board materials served as the main sealing element, most commonly oriented strand board (OSB) or the gypsum fiber board Fermacell Vapor. This board type incorporates a paper-faced hydrophobic moisture barrier. According to EN ISO 12572, the Sd values for Fermacell Vapor are 3.1 m and 4.5 m for board thicknesses of 10 mm and 18 mm. The Sd value of OSB ranges from 2 to 9 m depending on the board type (permeability ≤ 1 US perm according to ASTM E96). Plywood is not used as an air and vapor barrier layer in the Czech Republic.

Airtightness Measurement Procedure:

Air leakage of the building envelope at a pressure difference of 50 Pa was measured using the Blowtest 3000 device (LTM GmbH, Germany) and the TEC Minneapolis Blower Door System equipped with the DG-1000 pressure and flow gauge and TECTITE Express software (The Energy Conservatory, Minneapolis, MN, USA). All measurements were performed using the same standardized procedure, by the same trained personnel, and with calibrated and accredited equipment, ensuring methodological consistency across all 450 houses.

The measurements followed ISO 9972 Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurization method (ISO, 2015). All houses were evaluated according to Method 2 of this standard, meaning that the airtight layer, all construction details, and all built-in components (windows, doors) were completed. Ventilation openings and other penetrations (chimney, drainpipe, water and cable routing) were temporarily sealed. Both pressurization and depressurization tests were carried out in accordance with the standard. All measurements were performed under meteorological conditions compliant with ISO 9972, avoiding high wind speeds and excessive indoor–outdoor temperature differences that could influence pressure stabilization.

The test principle consists of measuring the airflow through the building envelope at different pressure-difference levels, which are artificially induced by a continuously controlled fan in both pressurization and depressurization modes. During the test, the fan is typically installed in the main entrance door using a telescopic frame and an airtight membrane (see Figure 1). The air change rate at a pressure difference of 50 Pa is calculated using Equation (1) and serves as the reference parameter of the measurement.

$$ACH50 = \frac{V_{50}}{V} \quad (1)$$

$ACH50$ is the air change rate at 50 Pa (h^{-1}),
V_{50} is the air leakage rate at 50 Pa ($m^3 \cdot h^{-1}$),
V is the internal building volume (m^3).

Figure 1. Blower-door test: Example of the measuring device installed in the door frame.

Basic data processing was performed in Microsoft Excel (Microsoft Corp., USA), while statistical analyses were performed in Statistica 13.3 Academic (TIBCO, USA). In addition to standard descriptive indicators, the dataset was further evaluated using correlation analysis to examine the relationship between pressurization and depressurization measurements.

RESULTS AND DISCUSSION

Overall Airtightness of Foil-Based and Board-Based Systems:

ACH50 values were successfully determined for all 450 tested houses. The basic characteristics of the dataset, including mean, range and standard deviation for both airtightness systems, are summarized in Table 1. The lower number of board-based houses reflects their lower prevalence in current construction practice within the monitored dataset.

Tab. 1 Basic characteristics of the tested houses and ACH50 values.

Variable	Barrier	Valid N (-)	Mean (h^{-1})	Minimum (h^{-1})	Maximum (h^{-1})	Std. Dev. (h^{-1})
ACH50	Foil	379	1.09	0.15	4.04	0.57
	Board	71	0.76	0.31	1.93	0.31

The measured ACH50 values indicate that both systems achieved airtightness levels typical for modern lightweight timber construction, with results comparable to those reported for timber-frame houses in Finland and Estonia (Kalamees, 2007; Vinha *et al.*, 2015; Hallik and Kalamees, 2019), while studies from Southern Europe generally report higher values (Almeida *et al.*, 2017; Feijó-Muñoz *et al.*, 2019a).

In this context, foil-based houses exhibited a wider distribution and higher variability, whereas board-based systems showed consistently lower and more tightly clustered results. Given the clear difference in the mean ACH50 values between the two groups, the influence of the airtightness system itself (foil-based versus board-based) was examined in more detail. A graphical comparison of the two systems is presented in Figure 2.

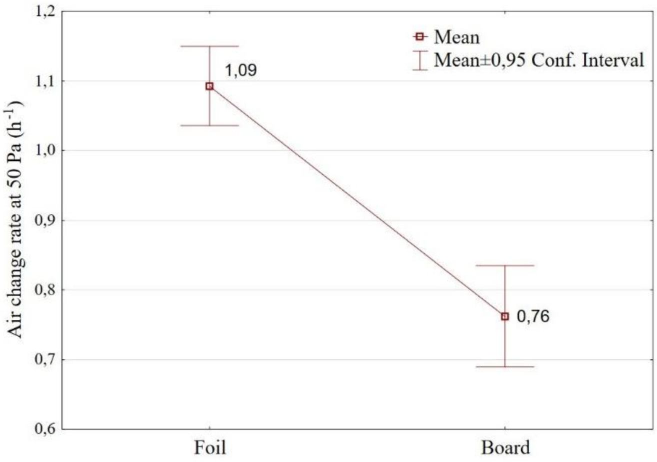

Fig. 2 Air permeability (ACH50) of houses with foil-based and board-based airtightness systems. Error bars represent 95% confidence intervals calculated as mean ± 1.96 standard errors.

The comparison shows that houses with board-based airtight and vapor-tight systems achieved substantially lower ACH50 values than those with foil-based systems. Several factors may contribute to this difference. From a construction perspective, board materials are easier to install and allow more critical junctions to be sealed more reliably than foil. In addition, foil is more susceptible to mechanical damage during installation, increasing the likelihood of leakage.

The airtightness of foil-based systems is affected by several material and application parameters. These include foil thickness, which influences durability, as well as differences in manufacturing quality and adhesive tape performance. The effectiveness of these tapes depends on application temperature, substrate cleanliness, the pressure applied during installation, and the time required for adhesive curing. In practice, insufficient adhesion in any of these aspects often leads to discontinuities that significantly increase air leakage.

For board-based airtight layers, performance is primarily influenced by the board manufacturer, board thickness, and board type. In the case of Fermacell Vapor, the laminated vapor-tight layer must remain undamaged to function effectively. For OSB, a minimum thickness of 15 mm for OSB/4 or the use of coated OSB/3 is recommended to achieve adequate airtightness (Hodoušek *et al*., 2015, 2019a). Board materials also benefit from their rigidity, which reduces the likelihood of deformation or detachment during installation.

These material and installation aspects form the basis for the differences observed between the two airtightness systems. They are further reflected in their behavior during pressurization and depressurization, as described in the following section.

Although foil membranes exhibit substantially higher vapor diffusion resistance (Sd > 1 500 m) than board materials (typically 2–9 m), this intrinsic material property did not translate into lower ACH50 values at the building scale. The results indicate that overall envelope airtightness was more strongly influenced by the continuity and robustness of the airtight system, including its sensitivity to workmanship-related defects and pressure-induced deformation, than by nominal material diffusion resistance alone.

Pressurization and Depressurization Behavior:

ACH50 values were determined for both pressurization and depressurization, and the final reported value represents the average of these two measurements. As expected, the results obtained under positive and negative pressure differed. In most of the tested houses, higher values were recorded during depressurization. Specifically, depressurization resulted in higher ACH50 values in 78.9 % of foil-based systems and in 87.1 % of board-based systems.

The observed difference between pressurization and depressurization is primarily related to the behavior of specific leakage paths. In foil-based systems, non-bonded or damaged sections of the membrane may temporarily separate under negative pressure, thereby increasing the effective leakage area. During pressurization, these locations tend to be pressed against the surrounding insulation or adjacent structural layers, reducing the resulting airflow through the leakage. This pressure-dependent response reflects the deformability of flexible membranes, which can alternately amplify or partially suppress airflow depending on the direction of the load.

The relationship between ACH50 values measured during pressurization and depressurization is shown in Figure 3.

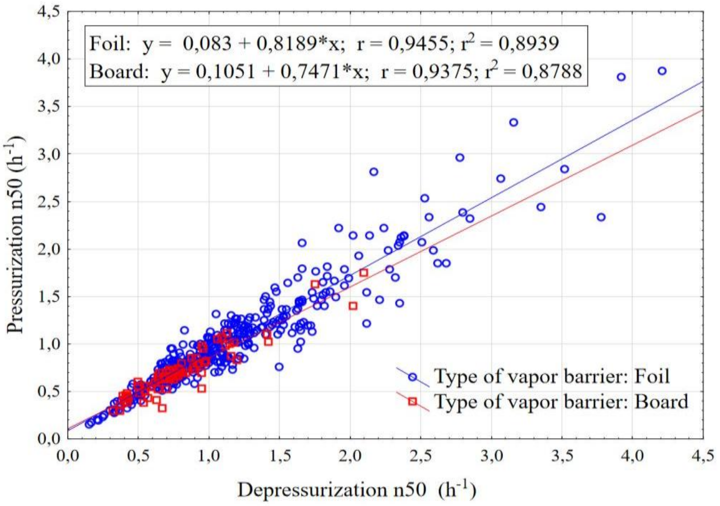

Fig. 3 Relationship between ACH50 values measured during pressurization and depressurization for foil-based and board-based airtightness systems.

Figure 3 shows that the differences between pressurization and depressurization are similar for houses with foil-based and board-based airtightness systems. The maximum ACH50 values of board-based houses remained below 2 h^{-1} in both measurement modes, while foil-based houses reached values of up to approximately 4 h^{-1}. These higher values were mainly recorded in older measurements conducted before 2013.

The data also demonstrate that the relationship between pressurization and depressurization is highly consistent for both airtightness systems. The coefficients of determination were 89% for foil-based houses and 88% for board-based houses, indicating a stable, predictable response to positive and negative pressure regardless of the absolute ACH50 level.

In recent years, ACH50 values have decreased in both groups, reflecting the impact of subsidy programs, stricter national requirements, and improvements in airtightness materials (Böhm *et al.*, 2021). Since 2018, all board-based houses in the dataset achieved ACH50 values below 1 h^{-1}, and for foil-based houses, only a single measurement exceeded 2 h^{-1} after 2016.

Influence of Construction Details on Airtightness:

Construction details play a decisive role in ensuring the long-term airtightness of lightweight timber buildings. Even when high-quality materials are used, inadequate execution of joints, penetrations or junctions between structural components can create significant air-leakage paths. These areas require precise workmanship and careful substrate preparation to prevent detachment, tearing or incomplete adhesion of the airtight layer during pressure fluctuations.

In foil-based airtightness systems, execution errors occur most frequently at locations where the membrane must be bonded to adjacent components or wrapped around complex geometric transitions. Typical problems include insufficient adhesion due to dust or moisture on the substrate, incomplete bonding of tape at corners and edges and local tearing or detachment caused by mechanical stress during installation. Examples of such defects are shown in Figure 4. These issues often create extended and continuous leakage paths, as flexible membranes are prone to movement and deformation under pressure differences during blower-door testing.

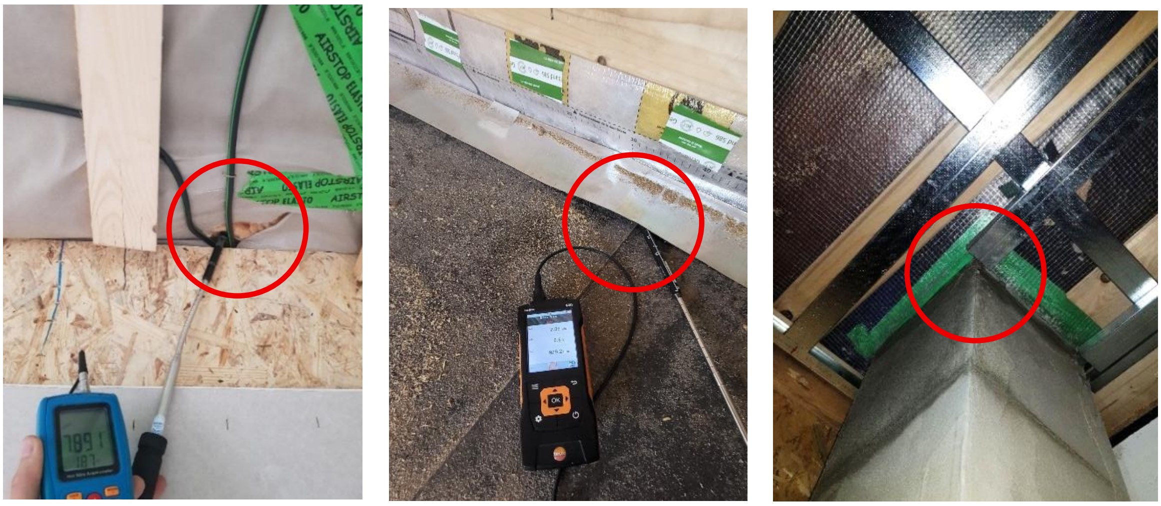

Fig. 4 Examples of incorrectly executed airtightness details in foil-based systems: (a) insufficient sealing of an electrical penetration, (b) inadequate adhesion of the foil to a dusty base, (c) improper chimney penetration where the foil is applied directly to the chimney casing, leading to detachment (this configuration is also unsuitable from a fire-safety perspective).

Correctly executed foil-based airtightness details are illustrated in Figure 5. In these examples, the foil adheres uniformly to a clean substrate, the tape is properly pressed along the entire joint and the membrane remains flat without folds or localized tension. Such execution minimizes the likelihood of detachment during blower-door testing and ensures that the airtight layer performs as intended. Photographic examples for board-based systems are not included, as their defect patterns are more effectively represented by the statistical distribution shown in Figures 6 and 7.

Fig. 5 Examples of correctly executed airtightness details in foil-based systems: (a) properly bonded polyethylene foil; (b) aluminum foil securely fixed and well sealed.

The behavior of board-based airtightness systems differs fundamentally from that of foil-based membranes. Due to their rigidity and dimensional stability, boards do not deform under pressure and are less prone to sudden detachment or the formation of extended leakage paths. Defects in board-based systems typically occur at joints between boards or at geometrically complex locations. However, these leaks tend to remain localized and therefore have a smaller impact on the final ACH50 value. The frequency and distribution of these defect types are illustrated in Figures 6 and 7.

Frequency and Impact of Airtightness Defects:

To complement the qualitative assessment of construction details, Figures 6 and 7 present the relative frequency of individual airtightness defects identified during blower-door diagnostics. These categories reflect the most common leakage mechanisms in lightweight timber buildings and were classified consistently across all 450 tested houses.

It is important to note that the frequency of a defect does not necessarily indicate its overall influence on airtightness, as the impact of an individual leakage path depends primarily on its geometry, continuity, and the pressure-driven airflow it enables. Even a relatively rare defect may dominate the resulting ACH50 value if it forms a continuous or pressure-sensitive flow path. Conversely, multiple localized discontinuities may have only a limited influence if they remain spatially confined and mechanically stable. This observation is consistent with large-scale analyses showing that airtightness performance is determined by the continuity and sensitivity of leakage paths rather than by their mere presence (Mélois *et al.*, 2019).

The defect distribution further shows that the dominant leakage mechanisms are less governed by their occurrence and more by their ability to form continuous or pressure-sensitive flow paths, which explains the higher resulting ACH50 in foil-based systems.

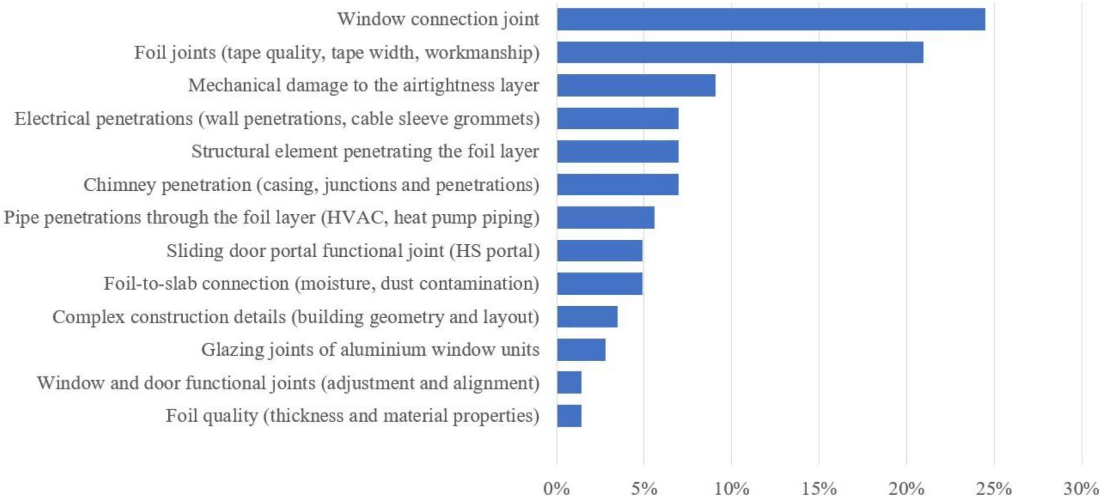

Fig. 6 Relative frequency of airtightness defects in foil-based systems. The most frequent leakage categories were window connection joints and foil joints, which together accounted for nearly half of all recorded defects.

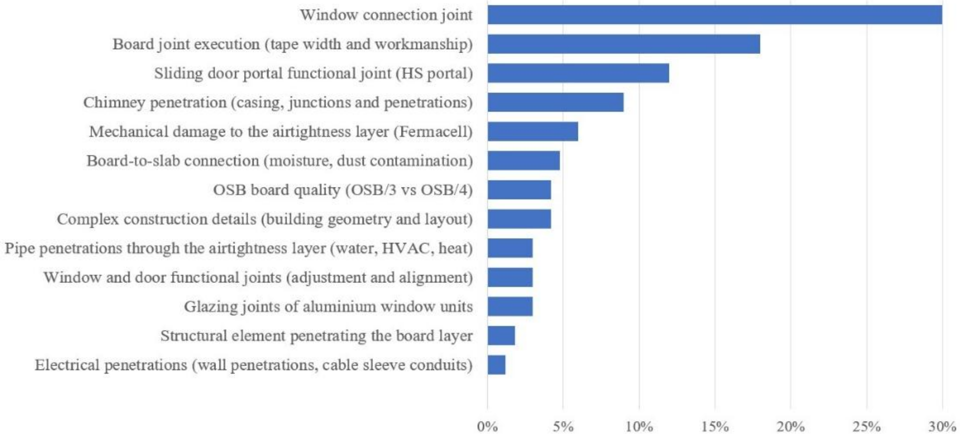

Fig. 7 Relative frequency of airtightness defects in board-based systems. Defects were dominated by window connection joints and board joint execution, while most other categories occurred at consistently low frequencies.

In foil-based systems (Figure 6), leakage occurrences were dominated by window connection joints and taped foil joints, which together accounted for nearly half of all identified defects. These details depend strongly on the proper application of adhesive tapes and surface preparation, making them highly sensitive to workmanship and on-site conditions. Foil-based systems also exhibited a wider variety of defect types, including several categories that were completely absent in board-based constructions.

The influence of window connection joints was more difficult to quantify precisely because part of the airflow may occur through secondary or concealed cavities that are not directly accessible during sealing. In several cases, the measured impact of these defects was smaller than expected despite their high occurrence.

Other leakage categories, such as penetrations for electrical wiring or HVAC systems, showed similar levels of influence. These defects typically produced small, localized leakage paths that can be effectively controlled by using system-manufactured grommets or flexible sealing compounds. Large sliding HS doors represented a specific case in which the functional gap geometry limited the achievable airtightness. These systems rely on brush seals rather than continuous compression seals, which inherently limit the maximum airtightness achievable, even when installation is correct.

In board-based systems (Figure 7), the most frequent defects were similarly associated with window junctions and board joints. However, most other defect categories occurred at consistently low frequencies. Although board materials exhibit higher intrinsic material permeability than foil membranes, the joints between boards were consistently tighter and less prone to forming continuous leakage paths. As a result, the overall impact of board-joint defects on ACH50 was lower than that of the corresponding defects in foil-based systems.

Field diagnostics showed that although taped foil joints were not the most frequent defect category, they had the strongest influence on the resulting ACH50. During progressive sealing of identified leakages, the largest reductions in ACH50 occurred after repairing detached or insufficiently pressed tape joints. This confirms that continuous leakage paths formed along foil joints represent the dominant mechanism affecting air permeability.

Foil-based airtightness layers require careful handling during installation. The membranes may deform when tensioned, lose adhesion on dusty or cold substrates, and cannot be reliably pressed into tight or geometrically complex junctions. Connections relying solely on sealants were particularly sensitive to aging and moisture, reducing their long-term reliability.

In contrast, defects in board-based systems typically affected only the joints between individual boards and did not compromise larger areas of the airtight layer. The rigidity and dimensional stability of the boards limited the potential size of leakage paths and reduced the likelihood of sudden detachment or deformation under pressure.

These findings are consistent with previous diagnostic work conducted by the authors, which identified similar defect patterns and emphasized the greater impact of foil-related failures on airtightness (Beránková, 2021; Brich, 2023). Comparable results have also been reported in peer-reviewed studies showing that flexible foil-based systems exhibit greater sensitivity to workmanship, climatic variability, and long-term deformation than rigid board-based layers (Prignon and Van Moeseke, 2017; Kysela *et al*., 2023).

Taken together, the present findings indicate that airtightness performance at the building scale is primarily a function of system continuity and mechanical robustness rather than nominal material properties alone. The ability of an airtight layer to maintain stable geometry and limit the formation of continuous leakage paths is more decisive than its intrinsic vapor diffusion resistance

CONCLUSION

Airtightness performance of 450 low-energy timber houses was evaluated in the study, and a clear difference between the two airtightness systems examined was confirmed. Houses with board-based airtight and vapor-tight layers achieved significantly lower ACH50 values than houses with foil-based layers.

Analysis of construction details demonstrated that the most frequent defects in foil-based systems occurred at window connection joints and taped foil joints, which also represented the most influential leakage paths. These defects often formed extended airflow channels due to the membrane's flexible nature and its sensitivity to substrate conditions.

In contrast, defects in board-based systems were confined to relatively small junction areas, so their impact on the resulting ACH50 remained limited despite occurring in similar functional locations and despite the higher intrinsic permeability of rigid boards compared to high-Sd foils.

The results indicate that envelope airtightness at the building scale is primarily governed by the continuity and robustness of the airtight system rather than by nominal material diffusion resistance alone.

Overall, the findings show that the quality and configuration of construction details play a decisive role in the airtightness of timber buildings, and that rigid board materials provide a more robust, fault-tolerant airtight layer under real construction conditions. The results highlight the need for precise execution of junctions, especially in foil-based systems, and support the growing practical adoption of board materials for achieving reliable long-term airtightness performance.

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