Airtightness of a multi-family passive residential building in the Czech Republic

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ABSTRACT

During the construction of a multi-family residential building the developer decided that the building must comply with the airtightness requirements for passive houses. Based on inspection work and preliminary testing, the original design was revised. The execution of the new air barrier system was supervised. Selected flats were repeatedly tested during the construction process. The whole building was tested once before the completion of the construction. After the completion of the building, all the flats, the whole building and the staircase were tested again. In order to evaluate the effectiveness of the designed air barrier system, a very similar “standard” building of the same development was tested under the same conditions. The airtightness deteriorated during the building process, which proves the need of control until the completion of the building. The test results of particular flats were worse than the whole building test results due to the internal leakage (it points out the limits of sampling methods). The estimation of the airtightness of different envelope sections allowed the major leakages to be identified, despite a significant uncertainty. The experience proved that the major problems can be avoided in the early stages of the design process.

KEYWORDS

airtightness, passive houses, design methods, quality control, sampling methods

SITUATION

During the construction of a low-energy multi-family residential building, the developer decided to improve the target energy performance and finalize the building as a passive house. The load bearing structure was already erected as well as external walls and internal partitions. The external windows and doors were already fastened to the building envelope. Since the building was originally designed as a low-energy building, thermal parameters of the building envelope as well as the heating system and ventilation system with heat recovery were designed in order to meet this target energy performance. Nevertheless, no special attention was paid to the building airtightness until this moment.

The building has 4 residential floors (with 14 flats) above the ground level and a parking in the underground. The load bearing structure consists of concrete walls and columns in the underground, hollow brick masonry walls above the ground level and concrete floor slabs. The external walls are erected of the hollow brick masonry with an external thermal insulation layer. Both external and internal surfaces are plastered. The staircase includes an elevator shaft, which is a tube of prefabricated concrete segments, partly integrated into the external wall. This tube is completely separated from the building structure (noise protection). Hence, the continuity of the envelope is interrupted with a system of expansion joints (figure 1).

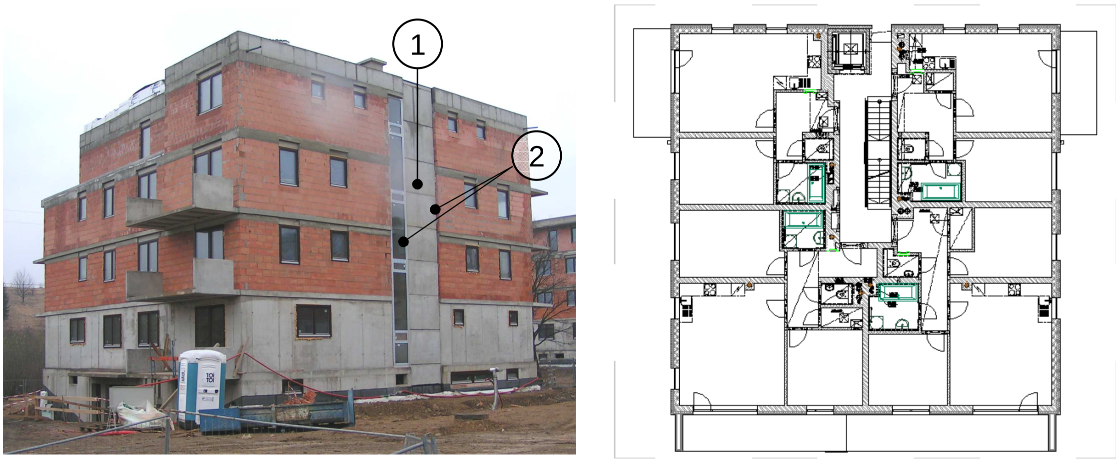

Figure 1: The studied building. Left hand side: initial state, 1 - elevator shaft, 2 – expansion joint. Right hand side: typical residential floor plan

OBJECTIVES OF THE WORK

The developer demanded that the building matches the specifications of the passive house label, including the corresponding airtightness requirements ($n_{50} \leq 0.6\ h^{-1}$). The compliance with the requirement had to be justified by means of an airtightness test after completion of construction works. The relevant aspects of the original design had to be revised (thickness of thermal insulation layers, construction details, airtightness). In this contribution, only the airtightness issues are addressed. Moreover, this work presented the following opportunities:

- monitoring the evolution of the building envelope airtightness throughout the construction process
- comparison of the final airtightness of buildings designed and constructed with opposite approaches to the airtightness related issues – one without any special care, the other with a respect to these issues
- comparison of different airtightness measurement methods

APPROACH

The task was resolved in the following successive steps:

- Inspection of the design project and the building (identification of problems and obstacles which could threaten the achievement of the target airtightness level)
- Preliminary airtightness testing (verification of the previous step outcomes)
- Design of a new air barrier system
- Control of the air barrier system execution
- Final airtightness testing (declaration of the result, compliance check)

- Airtightness test of a reference building (effectiveness evaluation of the new air barrier system)
- Additional measurements (comparison of different testing methods, evaluation of the air leakage distribution over the building envelope)

RESULTS

Inspection of the design project and the state of the building

Firstly, the original design project was examined in the following steps:

- definition of the airtight boundary delimiting the heated and ventilated space
- identification of building structures and building elements on this boundary
- control of the presence of an air barrier layer in each of these structures
- control of the airtightness specifications of building elements on the airtight boundary
- identification of critical, potentially leaky details (interfaces of building elements, penetrations, etc.)

The outcomes of the previous steps were verified in situ. This inspection work revealed namely the following potential problems:

- natural ventilation opening of the elevator shaft (simple grille, not adjustable)
- expansion joint around the elevator shaft
- joints between the prefabricated concrete elements of the elevator shaft (the surfaces of the elevator shaft, both internal and external, were not intended to be coated with plaster)
- surfaces of the external wall with no internal plaster coating inside the installation shafts
- roof hatch, and its interface to the roof structure
- penetrations of installations through the ceiling above the underground parking and penetrations through the roof
- electrical boxes in the external walls

Preliminary airtightness tests

In order to estimate better the significance of some of the problems listed above a series of preliminary tests was performed before the modifications of the original design were proposed.

The results of airtightness test of the elevator shaft proved that the joints between the concrete segments are sufficiently airtight and therefore will not affect the overall building airtightness.

A simple qualitative test using the fog and overpressure in sanitary rooms showed a poor airtightness of penetrations of building services installations through the floor slabs. It proved that the fireproof sealing of the penetrations was not sufficiently airtight and the airtightness must be ensured by other means.

The airtightness of a selected flat in a similar building was examined experimentally. This reference building was built in the same development using the same technologies as the studied building, but without special attention paid to the airtightness. A series of tests pointed out that probably the most significant leakage is situated in the installation shafts (internal air leakage) whilst the external walls were found more airtight, despite the presence of some common leakage paths (electrical boxes, window interface, joint of the floor slab and external wall). These results indicated the possibility to achieve the target n_{50} value even in case of particular flats, after some improvements of the original design solutions as well as the quality of workmanship. It was assumed that if the target airtightness seems to be achievable in case of particular flats, it would be achievable in case of the whole building envelope as well. Moreover, the preliminary testing helped the building site managers to understand better the issues they were facing.

Design of the air barrier system

Based on the results of inspection works and the feedback from the preliminary airtightness tests, a new air barrier system was designed and documented, including detailed drawings and airtightness requirements for the potentially leaky building elements. Design of airtightening measures for the expansion joint around the elevator shaft represented the most complicated task (use of special airtight polyurethan foam was necessary despite the reliability of such solution is questionable). After agreement with the elevator technology supplier the natural ventilation opening in the external wall of the elevator shaft was sealed and substituted by another opening to the staircase.

Control of the air barrier system execution

Besides a visual control of construction works related to the air barrier system, 4 flats were tested at different stages of construction process. This approach allowed several defects of the air barrier system to be detected and repaired in time. The measured n_{50} values were included between 0.6 and 2.4 h^{-1}, the q_{50} (air permeability related to the external surfaces) between 2.2 and 7.4 $m^3/(h \cdot m^2)$. Measurements of each particular flat repeated later, in the subsequent stages of the construction process, produced very similar results. It means that after application of the internal plaster layer the airtightness did not change significantly and the successive construction processes had little impact on the airtightness of these flats.

The later whole building test results revealed that all the 4 tested flats had a significantly higher air permeability than the whole building envelope. This discrepancy was assumed to be a consequence of a significant air leakage through the internal partitions.

Due to the coincidence with construction process, it was complicated to measure the whole building envelope airtightness before completion of the construction works.

Hence, the whole building airtightness was tested only once before the completion of the building. The test was carried out with the opening for the entrance door temporarily filled by means of a gypsum board structure. The measured n_{50} and q_{50} values were 0,26 h^{-1} and 0.47 $m^3/(h{\cdot}m^2)$ respectively. After obtaining this satisfactory result, the quality of the air barrier system had no longer been supervised during the subsequent construction works until the final airtightness testing.

Final airtightness testing

The whole building envelope airtightness test was repeated after completion of the building. The measured n_{50} value of 0.48 h^{-1} significantly exceeded the result of the 1st test carried out during the construction process (n_{50} = 0.26 h^{-1}). The entrance door represented the most important leakage path due to unsuitable choice of product and installation method (the specifications of the air barrier system design project were not respected). The building was re-tested again with the curtain wall temporarily sealed (during the 1st test, it was sealed as well). Then, the measured n_{50} value was 0,37 h^{-1}. It is still significantly higher than the whole building n_{50} value measured during the construction process with the entrance door opening sealed. This discrepancy may be a consequence of:

- a deterioration of the air barrier system that occurred between the two tests
- different building preparation before the tests

The building preparation before the 1st and the 2nd test differed from each other in the following aspects:

- Before the 1st test, the wings of several staircase windows were fastened with a tape because the window frames were not still equipped with the locking mechanism. This taping also sealed the openable window gap. During the 2nd test (after completion of the building), these windows were closed in a normal way, the gaps were leaky.
- After completion of the building, the envelope was tested together with a portion of ventilation system ducts in the underground parking, which was not installed at the moment of the 1st test

The air permeability of the window gaps and the ductwork was estimated and the contribution of the ductwork and window gaps to the measured envelope air leakage was calculated. A simplified sensitivity analysis showed that this air leakage can not explain by itself the discrepancy between the two test results. It means that the airtightness of the building envelope deteriorated between these two tests. The air barrier system was probably damaged during the final construction works after the first whole building test (the defects remained undisclosed).

The contribution of these defects to the n_{50} value was roughly estimated to be 0.09 h^{-1} which represents approximately 36% of the n_{50} value from the 1st test. This decrease of the airtightness is relatively significant. Since it occurred during a period with no supervision, the importance of a systematic quality control until the end of all construction works is evident.

The estimated difference in air leakage corresponding to the different building preparation represented a non negligible portion of the measured envelope air leakage. The building preparation is clearly a limiting factor of reproducibility of the airtightness test results. In this case, the way of the ventilation ductwork temporary sealing appeared as a significant aspect. Since no exact rules set e.g. in the technical standards, the details concerning the building preparation should always be carefully reported.

Measurement of the reference building

A nearly identical building of the same development built by means of the same technology, but without the respect to airtightness, was tested after its completion. This reference building was prepared for the test in the same way as the studied building (2nd test). The measured n_{50} value was higher than the test result of the studied passive building (0.71 h^{-1} against 0.48 h^{-1}) and higher than the passive house requirement as well.

So far, the effectiveness of the design methods, technical solutions and the quality control procedures used in this project seem to be justified. The statement that the strict airtightness requirements for passive houses can not be achieved accidentally, seems to be proved as well. However, the airtightness of the reference building achieved without any special care is very good and approaches closely the passive house requirement. On one hand such a good result achieved with minimal effort shows a certain robustness of the air barrier system used (massive structures with internal plaster as the air barrier layer). On the other hand, this surprisingly good result is casting doubts upon the adequacy of several technical solutions used in case of the passive house air barrier system (e.g. careful sealing of electrical boxes).

ADDITIONAL MEASUREMENTS

Besides the whole building tests mentioned above, the airtightness of all the 14 flats and the staircase was tested in order to evaluate the distribution of the air leakage over the building envelope and verify the possibility to estimate the building envelope airtightness from the test results of a sample of flats. Table 1 summarizes the results of all the tests performed after completion of the building.

Table 1 Results of tests performed after completion of building (lower index – means depressurisation test, + means pressuristion, -/+ means average of both)

test ID	zone (part of the building) tested	V_{50-} [m^3/h]	V_{50+} [m^3/h]	$V_{50-/+}$ [m^3/h]	n_{50-} [h^{-1}]	n_{50+} [h^{-1}]	$n_{50-/+}$ [h^{-1}]
BE 01	whole building	1216	1300	1258	0.46	0.49	0.48
BE 02	whole building, entrance door sealed	---	961	---	---	0.37	---
BE 03	staircase, entrance door sealed	---	701	---	---	0.27	---
	flats - total	3260	3358	3309	---	---	---
BE 101	flat 101	462	407	435	3.47	3.05	3.26
BE 102	flat 102	235	254	244	1.71	1.84	1.77
BE 103	flat 103	117	106	111	1.33	1.20	1.27
BE 104	flat 104	115	158	136	0.65	0.90	0.78

BE 201	flat 201	178	193	186	1.37	1.48	1.43
BE 202	flat 202	228	253	241	1.31	1.46	1.38
BE 203	flat 203	212	235	224	1.20	1.33	1.27
BE 204	flat 204	112	136	124	0.86	1.05	0.96
BE 301	flat 301	156	172	164	1.18	1.30	1.24
BE 302	flat 302	237	254	246	1.36	1.46	1.41
BE 303	flat 303	266	297	281	1.50	1.68	1.59
BE 304	flat 304	207	227	217	1.58	1.74	1.66
BE 401	flat 401	233	206	220	0.91	0.80	0.86
BE 402	flat 402	503	459	481	1.97	1.80	1.89

Distribution of the air leakage

For the estimation of the air leakage distribution, the method proposed in (Moujalled 2011) was used. The building envelope was divided into segments (envelope of flats, envelope of staircase and entrance door). Then the following balance equations of air flow rates were established for each measured zone (figure 2).

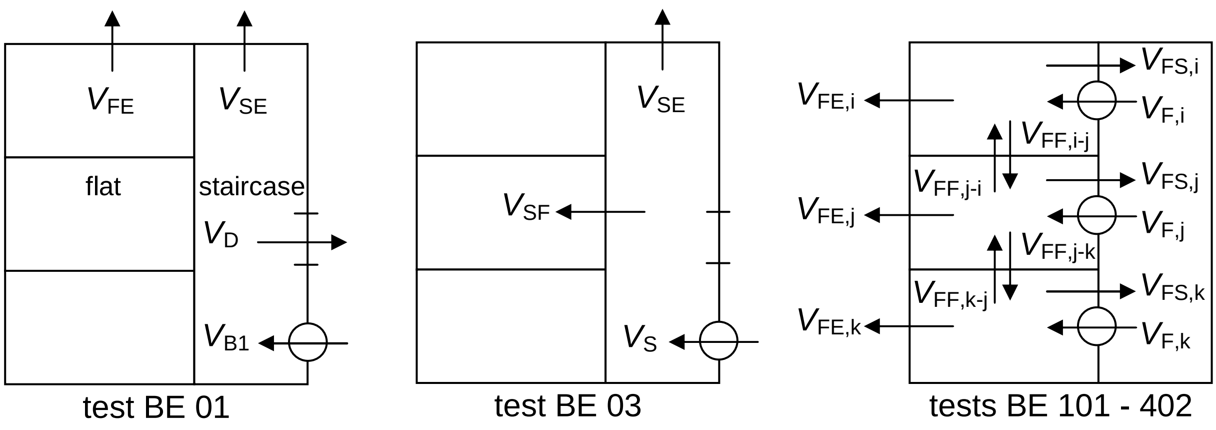

Figure 2: Air flow rates and balances for tested zones

$$\dot{V}_{B1} = \dot{V}_{FE} + \dot{V}_{SE} + \dot{V}_{D} \quad (1)$$

$$\dot{V}_{B2} = \dot{V}_{FE} + \dot{V}_{SE} \quad (2)$$

$$\dot{V}_{S} = \dot{V}_{SE} + \dot{V}_{SF} \quad (3)$$

$$\sum \dot{V}_{F,i} = \sum \dot{V}_{FE,i} + \sum \dot{V}_{FS,i} + \sum \dot{V}_{FF,i\text{-}j} + \sum \dot{V}_{FF,j\text{-}i} \Rightarrow \sum \dot{V}_{F,i} = \dot{V}_{FE} + \dot{V}_{SF} + 2 \cdot \sum \dot{V}_{FF,i\text{-}j} \quad (4)$$

$\dot{V}_{B1}$ is the whole building air leakage – result of the test BE 01

$\dot{V}_{FE}$ is the total air leakage from flats to the exterior (through the envelope of flats), unknown

$\dot{V}_{SE}$ is the air leakage from staircase to the exterior (through the envelope of staircase)), unknown

$\dot{V}_{D}$ is the air leakage through the entrance door), unknown

$\dot{V}_{B2}$ is the whole building air leakage – result of the test BE 02

$\dot{V}_{S}$ is the total staircase air leakage – result of the test BE 03

$\dot{V}_{SF}$ is the air leakage from staircase to the flats, unknown

$\dot{V}_{F,i}$ is the air leakage of the flat i – particular flat test result
$\dot{V}_{FE,i}$ is the air leakage from the flat i to the exterior (through the envelope of the flat), unknown
$\dot{V}_{FS,i}$ is the air leakage from the flat i to the staircase, unknown
$\dot{V}_{FF,i\text{-}j}$ is the air leakage from the flat i to the adjacent flat j, unknown

After some rearrangements and simplifications (e.g. $\dot{V}_{FF,i\text{-}j} = \dot{V}_{FF,j\text{-}i}$) the equations can be rewritten as follows:

$$\dot{V}_D = \dot{V}_{B1} - \dot{V}_{B2} \quad (5)$$

$$\dot{V}_{SE} = \dot{V}_S - \dot{V}_{SF} \quad (6)$$

$$\dot{V}_{FE} = \sum \dot{V}_{F,i} + \dot{V}_{SF} - 2 \cdot \sum \dot{V}_{FF,i\text{-}j} \quad (7)$$

$$\dot{V}_{SF} + \sum \dot{V}_{FF,i-j} = \frac{1}{2} \cdot (\sum \dot{V}_{F,i} + \dot{V}_S + \dot{V}_{B2}) \quad (8)$$

Since the depressurisation test results are not available for tests BE 02 and BE 03, the air flow rates at 50 Pa, $\dot{V}_{50+}$ resulting from the pressurisation tests, were introduced into these equations in order to quantify the air leakages through the segments of the building envelope ($\dot{V}_D$, $\dot{V}_{FE}$, $\dot{V}_{SE}$). It was assumed that calculation with either the depressurisation test results or averages of pressurisation and depressurisation test results would lead to a similar pattern of the leakage distribution.
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The air leakage through the entrance door $\dot{V}_D$ can be calculated directly from equation (5). In order to calculate the airflows through the other segments of the building envelope, one of the 4 unknown variables in the system of equations (6,7,8) has to be estimated. Based on the observation from the test BE 03, it was assumed that the air leakage to flats might vary from 10% to 67 % of the total air leakage from staircase $\dot{V}_S$. Taking this interval as an estimate of the uncertainty in the air flow rate $\dot{V}_{SF}$ with best estimate of $\dot{V}_{SF}$ in the middle of the interval, the remaining air flow rates from equations (5) to (8) can be calculated with their uncertainties by means of the error propagation. The calculated air flow rates and the corresponding air permeabilities are presented in table 2. The uncertainties in measured airflow rates $\dot{V}_{B1}$, $\dot{V}_{B2}$, $\dot{V}_S$ and $\dot{V}_{F,i}$ were estimated according to (Zeller 2002), since the results of this method seems to correspond with the experience from the round-robin tests (Novák 2011).

Despite the large uncertainty the results give at least a rough estimation of the air leakage distribution. The air leakage through the envelope of flats represents approximately one half of the total building envelope leakage. However, due to its large surface, the air permeability of this part of building envelope is very good (comparable to values achieved in case of single-family passive houses). On the opposite, the air leakage through the entrance door is excessively high (as mentioned above, the specification for the product and installation method were not respected). The air permeability of the staircase envelope is poor. This is probably caused by the presence of some leaky elements (roof hatch, glazed curtain wall) which were already installed at the moment of the air barrier system revision. The expansion joint around the elevator shaft was probably also a significant air leakage path. These problems illustrates that the airtightness should be considered from the early stages of the design process – e.g. placing the elevator shaft completely inside or outside the external wall would allow effectively overcome the problems related with the complicated expansion joint.

Table 2 Calculated air flow rates with uncertainties

		air flow rate V_{50} [m³/h]	air permeability q_{50} [m³/(m².h)]
measured	whole building envelope	1300 ±100	0.9 ±0.1
	whole building envelope - ent. door sealed	1000 ±100	0.66 ±0.09
	staircase - entrance door sealed	700 ±90	
	particular flats - total	3360 ±70	1.04 ±0.04
calculated	entrance door	300 ±200	60 ±30
	staircase to flats	300 ±200	
	staircase envelope	400 ±200	2 ±1
	envelope of flats	500 ±300	0.4 ±0.2
	internal partitions between flats	1300 ±200	

Limits of the sampling methods

The so called sampling methods allows the whole building envelope airtightness to be estimated from the test results of a sample of smaller zones inside the building, e.g. a sample of flats.

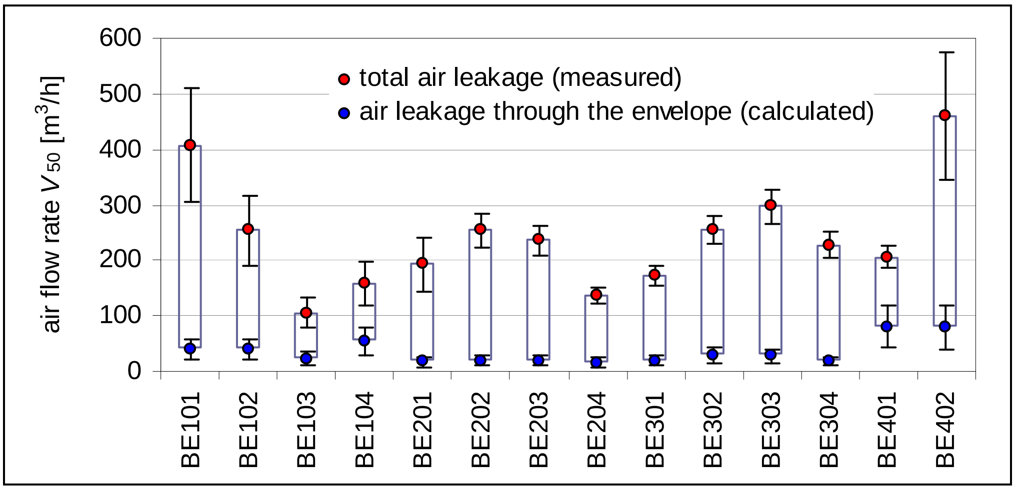

Figure 3: Comparison of the total air leakage and the air leakage through the surfaces facing exterior. The rectangles between these values are the estimates of the internal air leakage

In the case of the studied building the air leakage rates resulting from the tests of particular flats were always surprisingly high, despite a low global air permeability of the building envelope. Figure 3 compares for each flat the measured air flow rate with the air leakage through the external surfaces. This air leakage was calculated from the estimated air permeability of the envelope of flats (table 2). The difference between the two figures points out the magnitude of the internal leakage. In case of all flats it is significantly higher than the air leakage through the envelope. Obviously, it is not possible to deduce correctly the airtightness of the building envelope from the particular flats test results influenced by the internal leakage in such extent. Regardless the approach and the sampling rules the use of a sampling method would lead to erroneous results.

The use of the sampling methods seems to be limited to the buildings with airtight internal partitions. I this context several practical issues arise, namely how to decide before starting the measurements if the internal partitions are sufficiently airtight and the use of the sampling method would be meaningful.

CONCLUSIONS

The objective set by the developer (n_{50} ≤ 0,6 h^{-1}) was fulfilled. The comparison with "standard" reference building showed that it is rather unlikely to achieve this result without a special care to the building airtightness during the design and construction process, despite the results achieved accidentally may be good.

The good result achieved justify the effectiveness of approach and methods used for the air barrier design which can be recommended in such cases. The preliminary testing provided valuable background information for the design and can be recommended namely in refurbishment projects. The practical experience points out that the major problems should be avoided in the early stages of the design process (e.g. it was possible to overcome the complications due to the leaky expansion joint by changing the position of the elevator shaft).
It was shown that the airtightness may change in the course of the building process. In this case, it deteriorated during the final construction phase, which proves the need of careful control until the completion of the building.

The significant internal air leakage was found to be a limiting factor for the use of so called sampling methods (estimation of the whole building airtightness from the test results of a sample of building parts, e.g. particular flats).

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