Measuring airtightness of 100-meter high-rise buildings (lessons learned)

Stefanie Rolfsmeier[1], Emanuel Mairinger[2], Johannes Neubig[3], Thomas Gayer[3]

1 BlowerDoor GmbH
Zum Energie- und Umweltzentrum 1,
31832 Springe, Germany
rolfsmeier@blowerdoor.de

2 Dr. Ronald Mischek ZT GmbH
Donau-City-Straße 1, A-1220 Vienna, Austria
e.mairinger@mischek.at

3 Stadt Wien
Magistratsabteilung 39
Rinnböckstraße 15/2, A-1110 Vienna, Austria
johannes.neubig@wien.gv.at and
thomas.gayer@wien.gv.at

ABSTRACT

Worldwide, the demand for airtightness tests of tall buildings with a height of approximately 100 m is increasing. This report provides information on the planning and measurement concept for testing the entire building as a "single-zone" and presents the results and findings of the airtightness tests. The test set-up and the tests as such are based on the Passive House Institute's Guide to Measuring Tall Buildings [5] which includes recommendations that go beyond the ISO 9972 standard. The team conducted and recorded additional tests to learn more about the process when testing tall buildings for airtightness.
The team focussed on the following points:

- High buildings require a measurement concept for the test set-up as well as for preparing the building. Sufficient time - in some situations 2 to 3 days - should be allotted for these first steps.
- Installing the measuring fans throughout the entire building height is necessary if the building envelope exhibits a very high air permeability and / or if the building has very small airflow paths, i.e. "bottlenecks". These preparations ensure that the building pressure does not drop below 10%.
- Additional Differential pressure gauges were installed on the ground floor and the top standard floor to see the impact of stack effect and wind on the building pressure difference.
- Based on the building pressure differences on the first and top floor, the data points of the multipoint tests can be adjusted in such a way that the entire building is fully depressurized or fully pressurized.
- Boundary conditions for the weather during the tests are a maximum of 1000 - 1250 mK and a wind force equal to or less than 3 Beaufort.

Based on the findings, the test set-up and procedure can improved to achieve reliable and repeatable measurement results when testing tall buildings for airtightness in future.

KEYWORDS

Airtightness test, tall buildings, pressure drop in tall buildings, air permeability, airflow paths

1 INTRODUCTION

In the last decades airtightness of buildings has become a necessary step to minimize energy consumption, increase living comfort and to protect the building envelope from moisture damage. The ISO 9972 [4] test standard gives precise definitions for air permeability tests in small buildings, such as single-family homes and larger buildings, e.g. office buildings, schools, vestibules and foyers.

Meanwhile, demand for measuring high-rise buildings of approximately 100 m is increasing. Hardly any experience, however, has been gathered so far in that field and the test standard does not fully provide for these kinds of tests ([2], [3], [5], [7]), the reason being that there isn't much information on the impact that wind and stack effects have on air permeability tests in tall buildings and as to which action has to be taken to produce a uniform pressure distribution in all floors and rooms while capturing the results at each data point – one of the prerequisites for reliable and repeatable test results.

In 2021 an international test team took up the task of testing high-rise buildings with a height of more than 100 meters and up to 38 floors [6]. One of the major challenges was to ensure that the building envelope pressure which had been artificially induced with BlowerDoor fans was evenly distributed throughout the entire height of the building (maximum pressure drop ≤ 10%) while dealing with the high and fluctuating natural pressure differentials along the building envelope caused by stack effect and wind.

The "Airtightness Measurement of High-Rise Buildings Guidelines" of the Passive House Institute Darmstadt [5] served as starting point to develop a measuring plan for tall buildings. Additional test points were set up measure the pressure difference at the building envelope and to analyze how it changes throughout the height of the building before and during a test. Valuable insights were gained for European and national standardization work.

This article describes the planning process, the approach used, the measuring process as well as the results and findings of these tests.

2 SPECIMEN AND MEASURING TASK

Specimen

The three Triiiple Towers in Vienna, Austria with heights ranging from 108 m to 125 m served as test specimens (Figure 1).Figure 1 Towers 1 and 2 house 500 apartments and Tower 3 houses 670 dormitories (Table 1). Table 1 lists additional building data such as reference values, building heights and the number of floors and apartments.Table 1
Each building has a staircase in its center and several elevators with access to the floors.

Figure 1: The three Triiiple Tower (Towers 3, 2 and 1) in Vienna, Austria (Source: DiePresse.com)

Table 1 Building Parameters

Name	Tower 3 Student dormitories	Tower 2 Apartments	Tower 1 Apartments
Height	125 m	108 m	115 m
Volume	76,844 m³	68,779 m³	71,280 m³
Envelope Area	15,652 m²	17,933 m²	16,079 m²x
Floors plus Basements	36 + 2 Subbasements	32 + 2 Subbasements	35 + 2 Subbasements
Rooms / Apartments	ca. 670	ca. 260	ca. 240
Moisture-controlled supply air vents in external walls	ca. 670	ca. 370	ca. 340

Special features
The apartments' external walls are fitted with moisture-controlled supply air vents which can cause an additional airflow of 28 m^3/h to 40 m^3/h per unit during the tests as indoor humidity changes. This is an element of uncertainty when planning for the required measuring equipment [8], as are the numerous fire dampers. Most of them were installed underground in the partitions between heated and unheated building sections and tend to suddenly open up at certain pressure differentials while the tests are ongoing.

Measuring Task
All three buildings may not exceed the specified air change rate of $n_{50} \leq 1.5\ h^{-1}$ at 50 Pa induced envelope pressure difference. When converting this rate to the air permeability of the building envelope at 50 Pa it corresponds to $q_{E50} \leq 6{,}6\ m^3/hm^2$. The building was prepared according to method 1 of ISO 9972:2015.

3 COORDINATION, PRE-TEST INSPECTIONS, ON-SITE-VISITS

Coordination
Measuring the air permeability of buildings of this size is a highly sophisticated process. Unfortunately, only a tiny time window is made available while construction is ongoing. In the case of these high-rise buildings every tower was allotted one weekend for the tests: Tower 3 in February, Tower 2 in July, and Tower 1 in September. First of all, the building has to be in a condition that allows for such tests. This means, for instance, that the airtight layer has to be finished. Testing does not make any sense as long as windows and doors are still missing or cannot be closed. Also, only the contractors conducting the tests should be in the building to avoid situations where construction workers who don't belong to the test team accidentally open exterior doors or windows. These criteria and prerequisites have to be coordinated beforehand with the site manager.

Pre-test inspection
Selected sample rooms of the first tower (Tower 3) were inspected months prior to the air permeability test in order to assess air leakage paths of moisture-controlled supply air units in exterior walls etc. and to account for them when calculating the required number of BlowerDoor fans [7].

Wind speeds, indoor and outdoor temperatures and building envelope pressure differentials were measured during additional on-site visits, thus allowing us to assess the impact of wind and stack effects on the building's baseline pressure at an early stage. In the case of Tower 3, for instance, the request was made to reduce the building temperature (and thus the stack effect), because the outdoor temperature was expected to be 5° C or less during the test date. After matching the pressure readings with the theoretical calculations of envelope pressure differentials based on building height and temperature difference [Zeller2012], we found that it is extremely useful to account for this estimate while planning the test date [5].

On-site visits
Additional on-site visits were necessary in order to plan the airflow paths and openings for air leaks flowing from the building envelope to the measuring devices (e.g. via the staircase, elevator shafts and fire protection ducts). All parts of the building have to be set up as one open zone. Only then can the building be treated and tested as a "single zone" [4]. In order to connect, for instance, the stairwell to the floors and the rooms, 1200 wooden wedges were used in Tower 3 to keep the self-closing doors open. All three Triiiple Towers needed an elevator shaft to serve as an additional flow path throughout the entire height. It was also

important to secure the open lift doors leading into the 130-meter high shaft prior to testing and to define roles and responsibilities.
Locations for installing the BlowerDoor fans (ground floor, top floor, mezzanine floors) were inspected in order to plan for any auxiliary constructions that might be required during set-up.

4 TEST CONCEPT

A test concept was defined for each building by using the information obtained and the floor plans. The concept specified the following items: determine the required flow rate to demonstrate that the building meets the specified airtightness, define the envelope boundaries and plan for air leakage paths, plan the required number of test fans and where to locate them and the data points in the building in order to measure the envelope pressure inside to outside as well as indoors.

4.1 Required airflow rate

The required air change rate is multiplied with the volume of each building to determine the airflow that the testing equipment has to supply to meet the specified $n_{50} \leq 1.5\ h^{-1}$ [8].
The required airflow rates q_{50} are set at ca. 107.000 m³/h for Tower 1, ca. 103.000 m³/h for Tower 2, and ca. 115.000 m³/h for Tower 3.

4.2 Envelope boundaries and air leakage paths while testing

Envelope boundaries
The air barrier was highlighted in floor plans and sectional drawings in order to delineate the parts and rooms of the building within the envelope boundaries. The building is prepared according to these boundaries, e.g. the team decides which doors of the building stay open and which doors leading to unheated parts of the building stay closed.

Airflow paths
It was quite a challenge to plan the paths that the building envelope's air leaks would take to the measuring devices. A building envelope with many air leaks produces higher air leakage rates and thus requires larger sections for air leakage paths in order to limit the indoor pressure drop to a maximum of 10%. As the measuring team expected high airflow rates of approximately 115,000 m³/h (Tower 3), it was too risky to use only the narrow stairwell and just the three doors leading to each floor as airflow paths. For that reason an elevator shaft running through the entire height of each tower was added as flow path (Figure 2). During the tests the elevator doors were opened only partially for safety reasons.

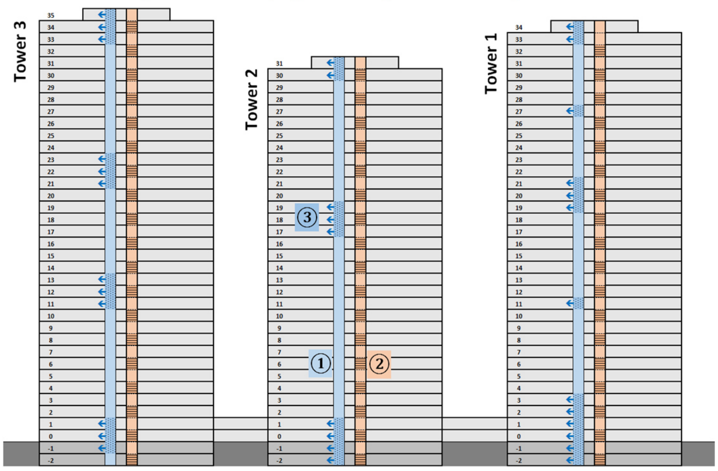

Figure 2 Airflow paths through the staircase ① and elevator shaft ②. ③ Open elevator doors

4.3 Number and location of BlowerDoor fans in the buildings

Test set-up with high air permeability and airflow bottlenecks
The expected airflow rates (q_{E50} at around 6.6 m³/hm²) are high and the plan was to set up 18 BlowerDoor fans in every building [5]. All three towers have just a few doors on their ground floors leading into the staircase plus the open elevator shaft (three doors in Towers 2 and 3, two doors in Tower 1). The measuring team decided that these doorways were too small to distribute the entire airflow volume through the rest of the building. The risk that there would be a pressure drop already in this bottleneck was too high. For that reason the higher-level floors were also equipped with BlowerDoor fans. (Figure 3).

Figure 3: Installation sites of BlowerDoor fans in Towers 3, 2 and 1.

The fans were installed in external / balcony doors in the building envelope. The operators were then able to individually adjust each BlowerDoor fan to ensure a uniform distribution of the induced envelope pressure.

Alternative test set-up with low air permeability and wide airflow paths

Buildings with a significantly lower air permeability, such as passive houses with a $q_{E50} \leq 0{,}6$ m³/hm², only need fans on the ground floor, provided that the air flow paths are wide enough. The readings of a different measuring team in a tall building in Luxembourg in 2021 that was easily 100 meters high confirmed this finding. The q_{E50} was 0.9 m³/hm² and the building had two staircases which were used to distribute the air leak flows throughout the entire height of the building.

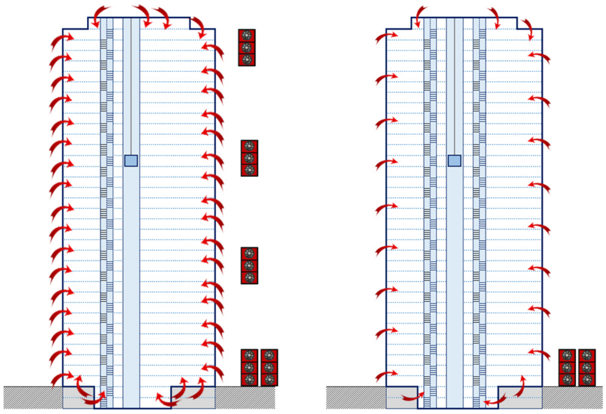

Figure 4: Left: Building with high air permeability and small airflow paths - BlowerDoor fans are located throughout the height of the building. Right: Building with low air permeability and wide airflow paths - BlowerDoor fans placed on the ground floor

4.4 Gauges to measure envelope pressures and pressure drops

Where possible, gauges were installed at various building heights and sides to measure wind and stack effects on envelope pressure differentials inside to outside. The gauges located in the top standard floor and on the ground floor are needed to capture and verify the test sequence (Figure 5Figure 5

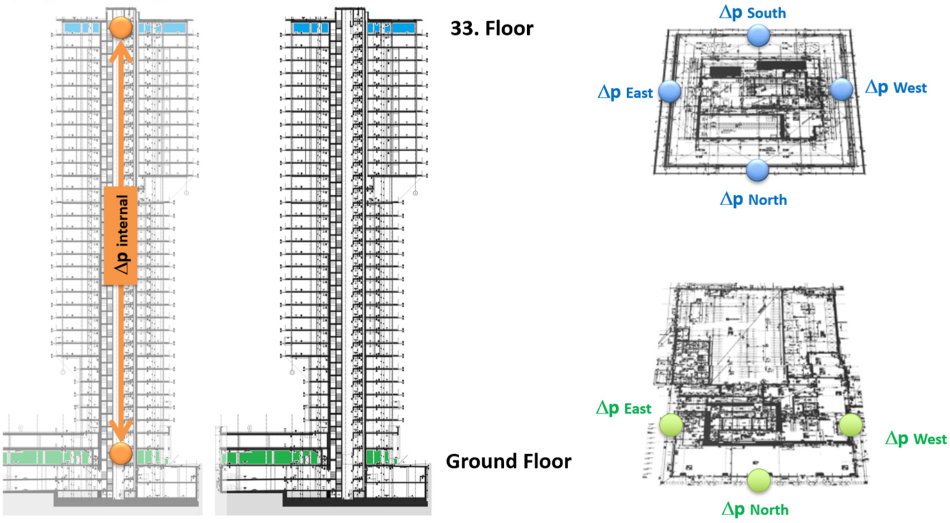

Figure 5 Gauges for interior pressure differential (left) and building envelope pressure differentials (right) in the top standard floor and on the ground floor - illustrated with Tower 1.

Based on the pressure differences measured at the building envelope, the team was then able to adjust the BlowerDoor fans to achieve a negative building pressure throughout the entire building during depressurization tests and a positive building pressure during pressurization tests.
Multiple data points captured interior building pressure differentials to verify whether the building pressure was evenly distributed throughout all floors. Figure 5 illustrates the set-up for measuring the pressure difference between top and ground floor [5], [7], [9].

4.5 „Base Camp“ on the ground floor

In each tower the base camp was set up in the largest room on the ground floor, usually in the foyer. This area was easily accessible and ideal for distributing the measuring equipment, because it was close to the elevator. Most of the fans were installed on the ground floor. The ground floor also served as control center to operate all BlowerDoor fans and to monitor the building pressure difference inside to outside and indoors. TECLOG 4, a specialized software, was installed on a laptop to control and track measurements. The data cables and tubes of the measuring equipment on the higher-level floors were routed through the open elevator shaft and then connected to the control center. Rope access technicians ran the cable bunches and tubing through the shaft because the fall height of 130 meters posed too great a risk.

5 AIRTIGHNESS TEST AND TEST RESULTS

5.1 Time required for tests

Taking into account the installation and removal of the measuring equipment, the building preparation, and the test sequences, the entire test with 5 persons took roundabout 25 hours for each building. 4 of them are experts for testing large buildings. Capturing the test sequences at negative and positive pressure only took approximately 2.5 hours. Preparing the building took up a lot of time. For instance, one person in Tower 1 needed 7 hours just to prop open the doors in the staircase and to the apartments. The rope access technicians needed about 3 hours to rout and haul the cable bunches and tubing through the elevator shaft.

5.2 Performing the test

In each building, one test sequence was performed at negative and one at positive pressure with approx. 8 data points per test and then evaluated according to ISO 9972 [4]. Both test sequences were used to derive the mean air leakage value at 50 Pa q_{50} which is then used to determine the air change rate for each tower in order to set off the irregular air flow through the envelope leaks throughout the height of the building due to stack effect and wind [5], [7].

The data points for the depressurization test sequence were adjusted to ensure that the indoor-outdoor pressure difference on the top and ground floor were negative at each pressure stage. This is the only time where the air flows through the leaks of the building envelope from the outside [5]. The pressurization test yielded positive building pressure differentials with the air flowing through the leaks from the inside to the outside.

The building leakage curve illustrates the airflow as a function of the induced pressure difference. The leakage curves for the Triiiple Towers were drafted with the mean values of three indoor-outdoor pressure differences on the ground floor. The building envelope pressure differentials from the higher-level floors only had the purpose to ensure that the pressure was either negative or positive throughout the entire height of each tower.

The BlowerDoor fans installed in the higher-level floors ensured that the induced envelope pressure was uniformly distributed throughout the entire height of the building. As soon as a building zone showed a pressure drop larger than 10% the fans' flow rate was readjusted.

5.3 Test results

The air change rates of all Triiiple Towers met the specified airtightness target of $n_{50} \leq 1.5\ h^{-1}$ (Table 2). Average air permeability q_{E50} is approximately 4.1 m^3/hm^2.

Table 2: Results of the Airtightness Measurements

	Tower 3	Tower 2	Tower 1
q_{50} depressurization	52,700 m³/h	75,970 m³/h	69,937 m³/h
q_{50} pressurization	66,800 m³/h	75,760 m³/h	69,222 m³/h
q_{50} average	**59,750 m³/h**	**75,865 m³/h**	**69,580 m³/h**
n_{50} air change rate	**0.78 h^{-1}**	**1.10 h^{-1}**	**0.98 h^{-1}**
q_{E50} air permeability	3.8 m³/hm²	4.2 m³/hm²	4.3m³/hm²

6 LESSONS LEANRED

6.1 Test according to ISO 9972 versus the Triiiple measuring concept

The test team had the opportunity to perform a single-point test in Tower 1 based on the test set-up according to ISO 9972. For this purpose reference for the building pressure differential was captured in some distance from the building and the air flow was induced solely by the 6 BlowerDoor fans on the ground floor. The team did not verify whether the pressure was distributed uniformly throughout the building nor whether the entire building was under negative pressure.
Air permeability q_{E50} according to ISO 9972 was 52,872 m³/h and thus 22 % lower than the air permeability yielded with the "Triiiple Concept" at 67,802 m³/h.

Lessons learned
Tests according to ISO 9972 requirements entail the risk that the resulting air permeability is too low for high-rise buildings.

6.2 Installation sites of BlowerDoor fans as a function of air permeability

The three Triiiple Towers have an average air permeability q_{E50} of ca. 4.1 m³/hm². The measuring team had to make do with a narrow staircase and an elevator shaft with a few connecting doors to each floor to distribute the air flow throughout the entire building height during the air permeability test. BlowerDoor fans had to be installed also on higher-level floors to avoid excessive pressure drops in the building.

Another test in a tall building of more than 100 meters in Luxembourg yielded an air permeability q_{E50} of 0.9 m³/hm². The air flow rate was significantly lower and was routed through two large staircases. As the data points didn't show any pressure drops throughout the height of the building, the team only needed to set up the 6 BlowerDoor fans on the ground floor.

Lessons learned
If the envelope's air permeability is high and the paths to distribute the air flow during testing have bottlenecks, the fans should be located throughout the height of the building.
While testing buildings with low air permeability, such as passive houses, it is fine to install the fans only on the ground floor, provided that the air flow can easily reach all floors.

6.3 Stack effect

The impact of stack and wind effects on the pressure differences at the building envelope was clearly exemplified while testing Tower 3 in February 2021. Compared to that experience the tests in Tower 2 (July 2021) and Tower 1 (September 2021) were relatively easy.

Due to its height and a "large" temperature difference of 17 K at the building envelope, Tower 3 exhibited a very high baseline pressure: Nearly +70 Pa positive pressure on the top standard floor and -10Pa negative pressure on the ground floor (Figure 6).

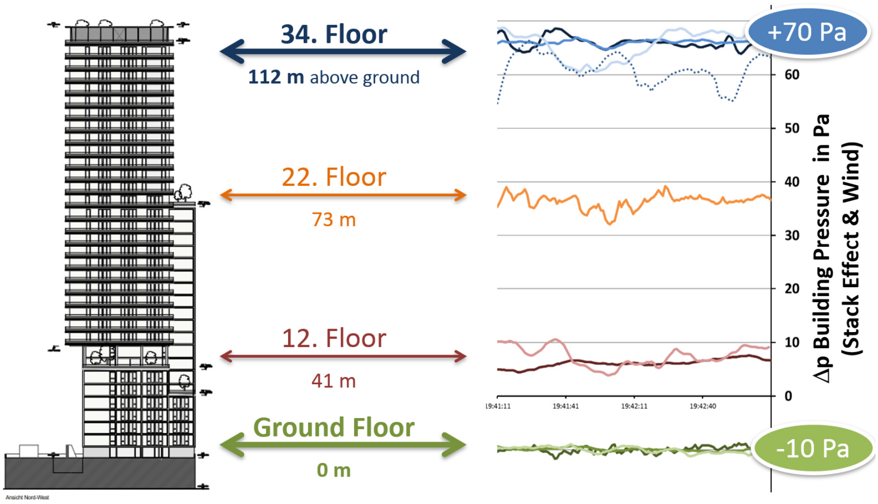

Figure 6 Baseline pressure difference due to stack effect and wind

These boundary conditions were taken into account while capturing the individual data points. During depressurization, for instance, -80 Pa were needed as lowest building pressure in order to achieve a negative pressure in the entire building.

Lesson learned:
When testing tall buildings you not only have to measure the building envelope pressure differential on the ground floor but also on the top floor in order to be able to respond to the stack effect. The data points for depressurization test sequences can be set according to these readings to ensure that the entire building is under negative pressure during depressurization and under positive pressure during pressurization test sequences [5].

We recommend for future tests that a temperature difference from 8 K - 10 K should not be exceeded for buildings with a height of up to 125 meters - this corresponds to 1000 mK - 1250 mK. With leaks distributed uniformly throughout the entire height of the building the readings would yield approx. -25 Pa on the ground floor and +25 Pa on the top floor [10]. When using those target values, the measuring range from the smallest to the highest value of 100 Pa should be sufficiently large for one test sequence. Even in the event of an irregular distribution of air leaks - as in Tower 3 - there would still be enough scope to generate reliable test sequences covering a sufficiently large range from the smallest to the highest data point.

6.4 Wind pressure

Figures 6 and 7 show the impact of wind at wind force 3.Figure 6Figure 7 The three building sides (East, North and West) on the ground floor exhibit significantly lower fluctuations in building pressure (green graphs) than the 4 building sides on the top floor (blue graphs for the 34th floor, North, East, South and West). The values for the windward and leeward side on the 34th floor also deviate significantly.

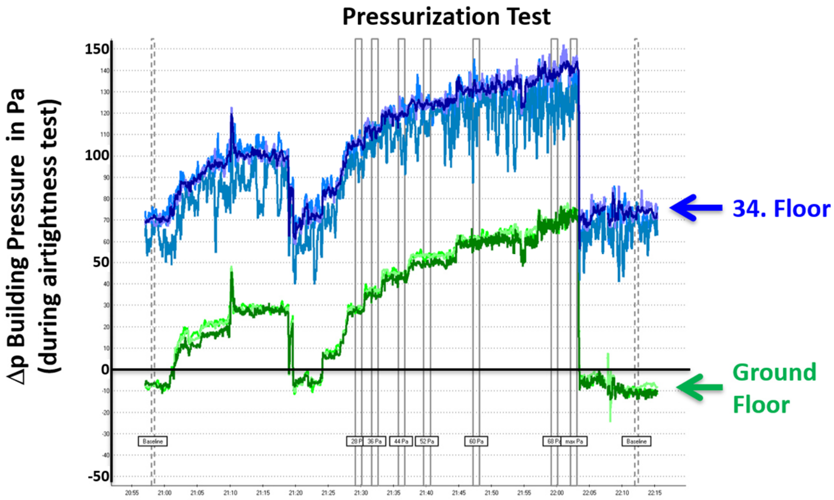

Figure 7Fluctuating pressures due to wind during a pressurization test in Tower 3

Lessons learned
During windy weather it makes sense to measure the building pressure differential on more than one side of the building to capture the wind impact on the windward and leeward side. As soon as the wind force is greater than 3 Beaufort, the test results are no longer reliable, because pressure fluctuations are very high and increase from floor to floor.

Since building pressure fluctuations are markedly lower on the ground floor versus the top floor, they provide a solid basis to adjust the BlowerDoor fans and to derive the leakage curves from the ground floor values.

6.5 Neutral pressure plane

The distribution of natural pressure differentials can also be used to locate the neutral pressure plane. In theory it is in the middle of the building. This would mean that the leaks are uniformly distributed throughout the height of the building. The pressure distribution in Tower 3 shows clearly (Figure 8) that in reality the plane is somewhere else.Figure 8 Here, the neutral pressure plane is more or less on the 5th floor. This indicates that significantly more leaks or larger leaks were located in the lower part of the building.

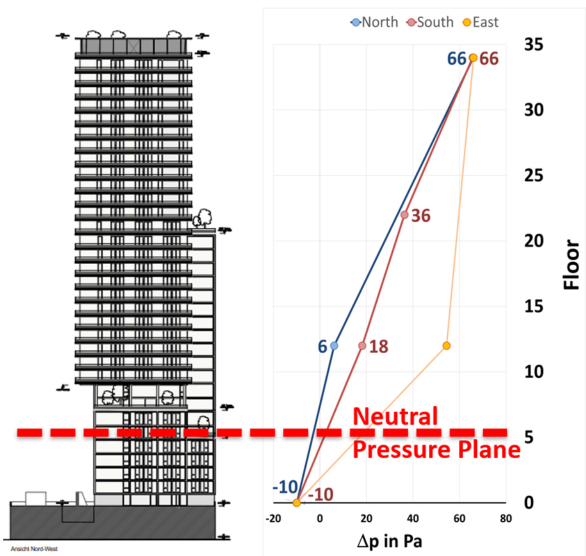

Figure 8Neural Pressure Plane in Tower 3

Lessons learned
The location of the neutral pressure plane can provide information on leakage distribution in the building or on large openings (e.g. windows) that still need to be closed for testing.

7 SUMMARY

The “Airtightness Measurement of High-Rise Buildings Guidelines” of the Passive House Institute Darmstadt, Germany [5] is a reliable starting point when testing tall buildings for air permeability. This was confirmed while testing the Triiiple Towers in Vienna with a height of up to 125 m.

Performing tests in approx. 100-meter high buildings is time-consuming and complex. Experience has shown that is makes sense to thoroughly plan the test and to establish a test concept.
Measurement points need to be installed on the ground floor and on the top standard floor to capture the building envelope pressure difference, since they can be very high due to the stack effect.
Measurement points on each of the four building sides on the ground floor and on the top floor provide insights on the wind impact, that can cause significant fluctuations.

To ensure a uniform distribution of the induced building pressure (≤ 10%) during testing, BlowerDoor fans are set up in the building based on the following two factors: Air permeability of the building envelope q_{E50} and the airflow paths (staircases, elevator shafts etc.) to distribute the airflows from the leaks to the fans. The higher the air permeability and the more bottlenecks are in the building, the higher the probability that the BlowerDoor fans will also have to be set up on higher-level floors.

The Triiiple Towers with a mean q_{E50} of 4.1 m^3/hm^2 had nothing but bottlenecks and thus left no choice but to install the fans throughout the height of the building.
A comparative test according to ISO 9972 excluding pressure drops in the building and without verifying whether all leakages exhibited airflows in the same direction yielded an airflow that was 22 % lower.

Another 100-meter high building in Luxembourg with a q_{E50} of 0.9 m^3/hm^2 and two large staircases needed BlowerDoor fans only on the ground floor in order to achieve a uniform pressure distribution.

Thanks to the building pressure differentials captured at the very top and bottom of the building during the air permeability tests, the team was able to readjust the data points during the test sequences to ensure that negative pressure was induced throughout the height of the building during depressurization and positive pressure during pressurization. The mean air leakage value q_{50} derived at negative and positive pressure was then used for subsequent analyses. To a certain extent, this sets off irregular air flows through the leakages which are caused by stack effect and wind.

We recommend for future tests that a temperature difference from 8°K-10 K should not be exceeded for buildings with a height of up to 125 meters - this corresponds to 1000 mK to 1250 mK.
While testing, the wind speed should be equal or below 3 on the Beaufort scale.

It is considered to be good practice to set up a base camp on the ground floor. The measuring equipment can be installed, removed and distributed with the least effort because the elevators and staircases are nearby.
Usually the rooms are very large (e.g. near the foyer) and have exterior doors which are ideal to install the fans. They also offer large airflow paths to other parts of the building / floors via the staircases and elevator shafts.
Furthermore, the team can adjust all of the BlowerDoor fans, monitor the building envelope pressure inside to outside and the induced pressure differentials inside of the building.

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