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DESIGN PRINCIPLES FOR PRESSURE MODERATED WINDOW FRAMES

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ABSTRACT

High performance window frames that are widely used in Europe rely on pressure moderation to achieve a good weathertightness. By separating the airtightness plane from the water shedding surface a drained cavity can be pressure moderated. As wind pressure is the main driving force for water to infiltrate into the frame, a pressure equalized system is able to achieve higher performance levels. In this paper the performance of window frames is analyzed in two separate ways: first of all experimental research was conducted on a single frame to analyze the way it functions and fails, secondly a database of the university window testing facility was used to perform a parametric analysis.

High frequency measurements on window frames provide for the information to model the pressure in the cavity and render information on prevalent parameters. The influence of different elements (section, joggles, gaskets, fittings) is examined in both dry as well as rainy conditions during static and dynamic pressure differences. The airtightness of the outer plane divided by the airtightness of the inner plane is the main parameter that will determine the watertightness potential of window frames.

Based on the research carried out within the framework of that program and the analysis of the test reports in the database design principles have been determined requisite to achieve adequate pressure moderation in window frames.

RÉSUMÉ

Les cadres de fenêtres à haute performance utilisés couramment en Europe comptent sur la modération des pressions pour atteindre une bonne étanchéité. En séparant le plan étanche à l’air de la surface drainant l’eau, la pression d’air dans une cavité peut être modérée. Comme la pression due au vent est la cause principale d’une force sur l’eau menant à l’infiltration dans le cadre, un système permettant l’équilibre des pressions est capable d’atteindre de hauts niveaux de rendement. Dans cet article, le rendement des cadres de fenêtres est analysé de deux façons : un cadre de fenêtre a été étudié expérimentalement pour analyser son fonctionnement et son mode de défaillance, puis la banque de données du centre universitaire d’essai sur les fenêtres a servi de base à une analyse paramétrique.

Des mesures à haute fréquence effectués sur des cadres de fenêtre fournissent les données requises pour modéliser la pression d’air dans la cavité et documenter des paramètres-clé. L’influence des différentes composantes (profilés, fixations, garnitures d’étanchéité, quincaillerie) est examinée sous conditions sèches et mouillées et des différences de pression d’air en régimes stationnaire et transitoire. L’étanchéité de l’air du plan extérieur divisée par celle du plan intérieur est identifiée comme le paramètre principal déterminant le potentiel d’étanchéité à l’eau de cadres de fenêtre.

Se basant sur la recherche effectuée et l’analyse des rapports d’essai de la banque de donnée, des lignes directrices de conception sont proposées pour atteindre une modération des pressions d’air dans les cadres de fenêtres.

1) INTRODUCTION

In order to shield the indoor environment from the exterior most building components are assembled out of several layers of materials to meet different performance requirements (watertightness, airtightness, thermal resistance, structural stability etc). In that regard windows and doors are usually the weak spot of the building: it is a transition from the building component to the insulated glass unit where all the different materials and functions are literally forced together. On top we want them to open and close, so that interface becomes even more crucial and difficult to design and construct.

Pressure equalization is the basic principle where windows and doors derive their performance from, but how can this be realized, and what are the main parameters that influence it? As in walls and roofs we can distinguish different elements in the window casement that will fulfill those needs and influence the performance: the section, joggles, gaskets and fittings (handle, gearbox, locking bar, corner pivot, stay, hinges…). Using high frequency measuring equipment the influence of the different elements is examined in both dry as well as rainy conditions during static and dynamic pressure differences.

The most common design strategy for watertight windows is pressure equalization, although pressure moderation might be a more appropriate name (Straube J.F. 1998). The performance of different types of cladding that use pressure equalization has well been studied over the last 40 years: an extensive literature review can be found in (Suresh Kumar K. 2000). The Pressure Equalized Percentage (PEP) is a specific value between 0 and 100% which measures the rapidity and degree to which the internal air pressure within the cavity can equalize with the external air pressure (Burgess J.C., 2000). A PEP value of 100% implies a perfect pressure equalization of the cavity with the same amplitude and in phase with the external air pressure. As window frames only have a small cavity volume, we expect the phase shift of the pressure to be relatively small because the major determinant of response speed is the compressibility of the air (Straube J.C., 2001). The PEP can be calculated with following formula (1):

$$PEP = 100\left(1 - \frac{1}{2PT}\int_0^T \left|P_e(t) - P_c(t)\right|\right) \tag{1}$$

PEP: Pressure Equalization Percentage [%]

P: Amplitude of external air gauge pressure [Pa]

T: Period [s]

Pe(t): Gauge air pressure outside at time t [Pa]

Pc(t): Gauge air pressure in cavity [Pa]

However, the figure 2 in the denominator suggests that a PEP of 0% would occur at the moment the pressure in the cavity is in antiphase with the outside pressure throughout the whole period. The measured phase shift caused by the pressure moderation in the cavity is about 0.05 up to 0.25 seconds, so the period of the outside pressure in which the pressure should rise from a negative to a positive pressure should lie somewhere between 0.02 and 0.15 seconds. Looking at climatic data measured with high frequency equipment this is not the case, certainly not for amplitudes above 10

Pa. Hence we suggest deleting the figure 2 in formula (1). This way the pressure equalization percentage gives a more intuitive approach to relate to the pressure in the cavity. In static conditions where the pressure in the cavity is half the outside pressure, the PEP equals 50%. According to formula (1) the PEP would be 75%. Further in this paper formula (2) will be used to calculate the PEP.

$$PEP = 100\left(1 - \frac{1}{PT}\int_{0}^{T}\left|P_e(t) - P_c(t)\right|\right) \qquad (2)$$

Due to the complex geometry of windows (caused by thermal and mechanical characteristics) and the fact that they have to open and close, it is practically impossible to create a face-sealed watertight window that is impervious to water and air through time under all circumstances. As a result we take for granted that failure will occur: the window should be designed as a drained construction with a water barrier, an air barrier, and drainage paths as separated functions. The water barrier is in fact just a shedding device to prevent water from entering in the cavity of the window frame, like the exterior facing of a masonry brick wall. The air barrier is utterly important for the performance of the window because it must withstand high pressure loads to enable pressure equalization at all times. Any penetration of the airtight barrier by hinges, joggles or fittings may be crucial to the overall performance. Any water that penetrates into the cavity should be drained to the exterior by weep holes at the bottom, and in order to prevent negative pressure effects in the cavity by static watercolums in the weep holes, vents are located at the top of the window.

The pressure equalization is just one principle of water management. If we also take the buffering effect into account and realistic weather data, it becomes clear that some windows may perform quite well under high pressure loads, without obtaining real good pressure equalization (See also: Rousseau J., 1999). The effect of external pressure gradients is strongest along the vertical edges of buildings for wind angles between 30 and 60 degrees, but usually this does not coincide with the greatest wetting intensities (those occur during perpendicular winds). In this paper only windows of relatively small dimensions are discussed, so external pressure gradients are not taken into account. The biggest mean pressure difference as well as the biggest peak pressure differences do in fact coincide with the greatest wetting intensities (Suresh Kumar K., 2003) The outer 5 to 10% of the building width and the top 5 to 10% of the building height experience the largest gradients and normal compartmentalization should be adjusted to that (Inculet D., 1997).

There are reservations concerning all of the current watertightness tests available, and research is needed on the principles and requirements of dynamic testing (Kerr D., 1997). In order to design a new standard test, there should be a good agreement between the performance under real conditions, and the performance according to the lab test. The different damage initiation phenomena need to be closely examined to develop the test conditions for dynamic testing. On one hand there is a difficult balance between the conditions and performance of a window during its total service time, and the conditions and performance in the test facility (Cornick S.M., 2004) On the other hand there is also a balance between creating a test method that comes close to reality and a test method that is economically realistic and viable.

2) PRESSURE EQUALIZATION OF THE WINDOW CAVITY

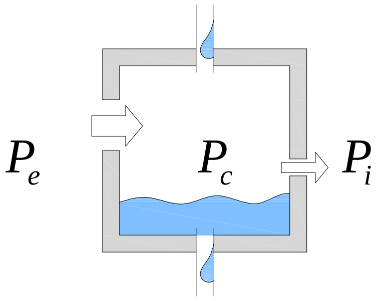
2.1) Theoretical background

The mass balance of the cavity can be visualized by figure 1:

$$\Delta p_1 + \Delta p_2 = \Delta p_{total} \qquad (3)$$

$$Q_1 = C_1 \Delta p_1^{n_1} \quad (4)$$

$$\Delta p_1 = \left| P_e - P_c \right| \quad (6)$$



$$Q_2 = C_2 \Delta p_2^{n_2} \quad (5)$$

$$\Delta p_2 = \left| P_c - P_i \right| \quad (7)$$

Figure 1: mass balance of the window frame cavity

Q:	Air flow rate	[m³/h]
C:	Flow coefficient	[m³.h^{-1}.Pa^{-n}]
n:	Flow exponent	[-]
Δp:	Pressure difference	[Pa]

If only static conditions are taken into account, formula (1) can be simplified:

$$PEP = 100\left(1 - \frac{\left|P_e - P_c\right|}{\Delta p_{total}}\right) = 100\left(1 - \frac{\Delta p_1}{\Delta p_{total}}\right) \qquad (8)$$

We can assume that the flow exponents of both openings are the same and equal to 2/3. Furthermore, the air flows through the openings at the top and bottom of the drawing (vents and weep holes) are comprised within the air flow rate in front. Therefore:

$$Q_1 = Q_2 \quad \Leftrightarrow \quad C_1 \Delta p_1^{2/3} = C_2 \Delta p_2^{2/3} \qquad (9)$$

After substituting equation (3) in (9) we get:

$$PEP = 100\left(1 - \left[1 + \left[\frac{C_1}{C_2}\right]^{3/2}\right]^{-1}\right) \qquad (10)$$

If the pressure equalization is plotted against the ratio of the flow coefficients (of the outer water shedding surface and the inner airtightness plane) of the window frame it is possible to estimate the minimum ratio of the flow coefficients if a certain level of pressure equalization is required (figure 2).

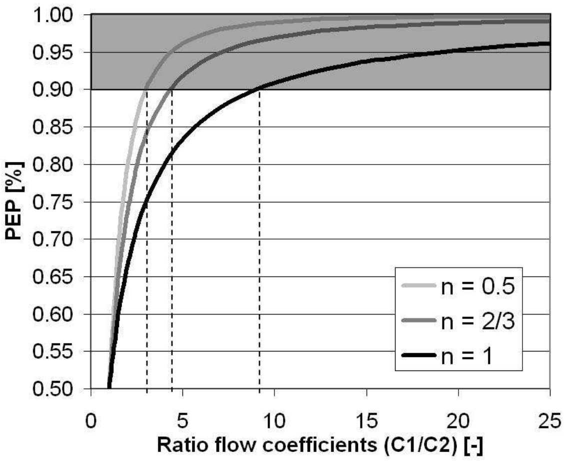


Figure 2: PEP - ratio flow coefficients

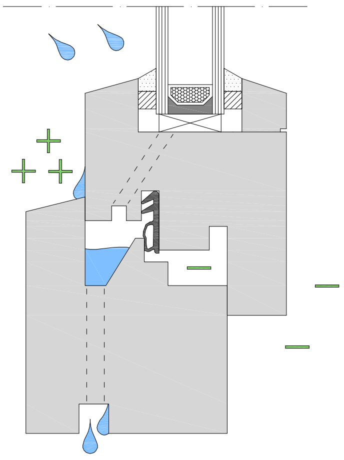


Figure 3: equalization in a wooden window frame

The flow exponent has a significant influence on the pressure equalisation, but measurements point out the variability of the flow exponent is quite small. On the other hand, the power-law equation (4,5) is only valid for a rigid opening, whereas windows do not fulfil that requirement: at high pressure differences the sash tends to move a little bit away from the sash allowing higher air flow rates passing through cracks and joints. However, this is only a theoretical approach to explain some phenomena in the following sections.

2.2) Experiments

In order to analyze the effect of different parameters on pressure equalization in windows experiments are conducted at our certified test facility on a vinyl window (1.44m high by 1.22m wide, see figure 4). The window has 3 drainage openings (a slot of 5mm wide and 30mm long) at the bottom and 2 vents of the same size at the top. It is a turn and tilt window and it uses an inner- and outer gasket for respective water- and airtightness. Including the hinges there is a total of 11 closing points for a contour of 5.04m. The sash is well dimensioned in accordance to the frame, the hardware is adjusted correctly, and the glass is also placed as it should be.

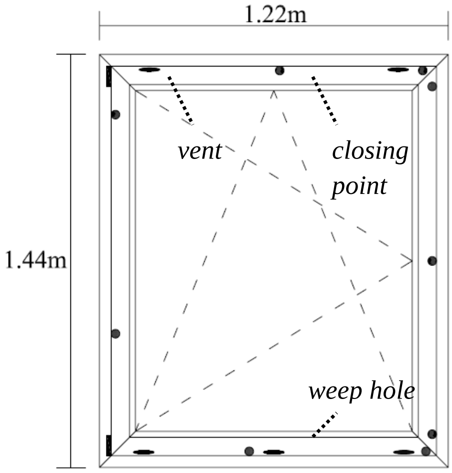


Figure 4: schematic drawing of window

Figure 5: window mounted at test facility

Three pressure taps are used: one to measure the pressure on the exterior of the frame, and two to measure the pressure in the cavity of the window. These are placed in the left and right jamb of the frame to see if there is a difference caused by the place of the tilting hardware that is situated in the upper left corner. The pressure taps are calibrated very low range differential pressure transmitters with a full scale error of less than 1.0 % (GEMS 5266 transmitter). The output of the taps is transmitted to a data acquisition module with a full scale error of 0.1% (Dataq DI-158) into the computer for direct processing with the software WinDaq.

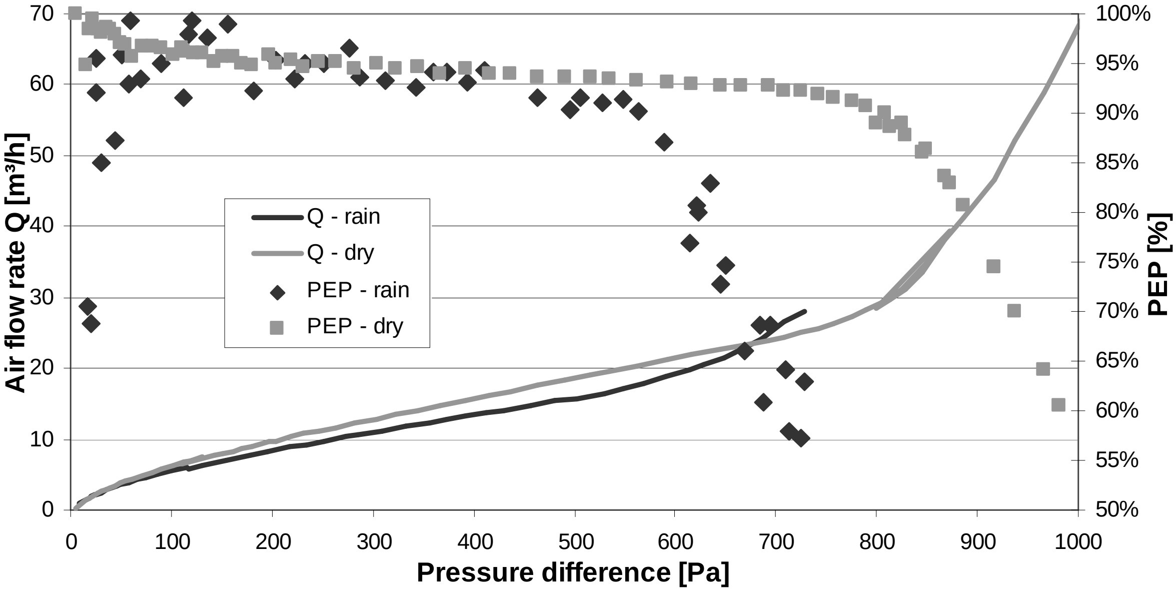
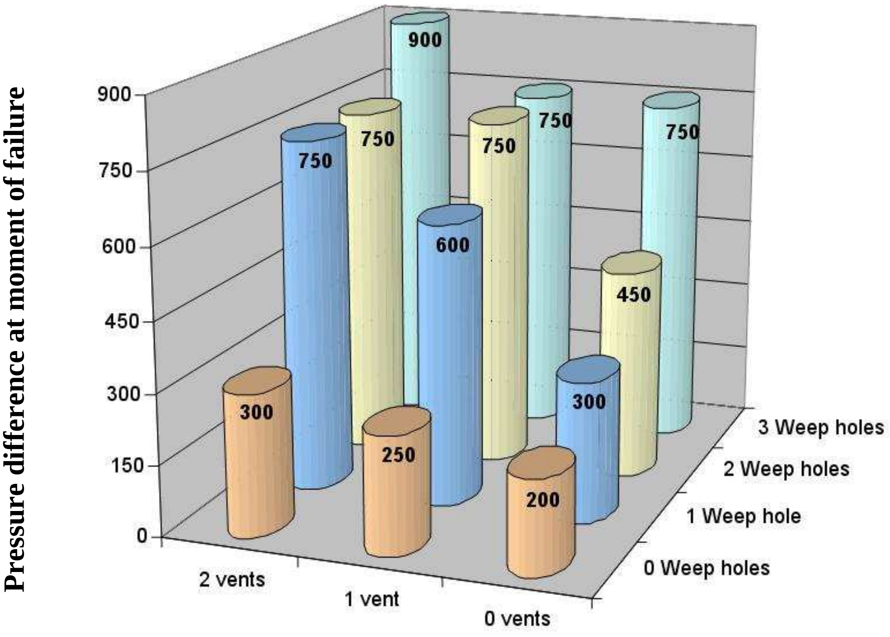


Figure 6: Air flow rate and PEP plotted against the total pressure difference over the window

Figure 6 shows the air flow rate of the window as a function of the pressure difference across it, both in dry as well as in rainy conditions. On the second Y-axis the PEP is plotted for the two situations. The measurement for the rainy conditions does not go beyond 730 Pa because water infiltration occurred at that stage (raising the pressure difference beyond that point would distort the measurements). During a shower of rain the film of water will partially close the vents and weep holes, thus reducing the airflow but also reducing the pressure equalization of the cavity. The amount of water that is entering the cavity depends mainly on the pressure difference and the geometry and deformation of the window frame and sash.

When the pressure rises above a certain level all of a sudden the water cannot be drained quickly enough by the weep holes any more and static water columns in the weep holes partially block the pressure equalization (for this particular window that phenomenon started at 620 Pa). This causes the pressure in the cavity to fluctuate with an amplitude of 20 up to 50 Pa and a period of 0.1 to 0.2. seconds. From that moment on the average pressure in the cavity drops while the total pressure difference across the window is raised. The amplitude of the fluctuation on the other hand rises up to 100 Pa at the point of failure (730 Pa). If the total pressure difference is decreased, the fluctuating of the pressure in the cavity will not cease until all the water has drained. The amplitude of the fluctuation seems to be a measure to predict the failure of the window in different circumstances, however more research is needed to confirm these preliminary conclusions. One could think that the deformation of the window is the most critical factor for the balance between the airtightness of the outer and inner plane, but apparently for this window the water film and imbalance of the water drainage system causes the pressure equalization to fail preliminary and water will infiltrate into the interior.



	2 vents	1 vent	0 vents
□ 0 Weep holes	300	250	200
□ 1 Weep hole	750	600	300
□ 2 Weep holes	750	750	450
□ 3 Weep holes	900	750	750

Figure 7: watertightness failure related to number of vents and weep holes

The normal test procedure according to EN1027:2000 contains a wetting period of 15 minutes followed by a number of pressure steps of 5 minutes each (0 – 50 – 100 – 150 – 200 – 250 – 300 – 450 – 600 – 750 – 900 – 1050 – 1200 Pa). During the test 2 liters of water are sprayed per minute per square meter on the window. Every window in Europe is tested that way to measure its performance regarding watertightness. It is up to member states to define which level of performance is required and obliged in a certain situation, based on a correlation between the test conditions and the conditions of the window in situ. Figure 7 shows the results of different tests on the same window, while only the number of vents and weep holes are changed. First of all, it is clear that there should be at least one weep hole: adding more vents will only lower the amount of water entering the cavity, thus postponing the moment of failure. Secondly, if there is at least one weep hole, high pressure differences can be obtained without failure if there are enough vents. Adding an extra weep hole does not seem to matter that much, which could be an indication that the amount of water that needs to be drained is not determining the failure mode (also see 3.3). Once there are three weep holes the number of vents has little influence on the performance: it is most likely that at certain moments in time one of the weep holes functions as a vent while the other weep holes drain water.

3) PARAMETRIC ANALYSIS

3.1) Introduction

The test centre for façade elements of Ghent University was founded in 1952 in order to conduct research on watertightness of windows. Between 1952 and 2008 the test facility has tested a lot of windows including their performance regarding watertightness, airtightness and resistance to wind loads, but unfortunately the results of the tests are only stored in archives during a limited period of time. We were able to retrieve 207 test reports, containing tests of 136 aluminum windows (66%), 52 vinyl windows (25%) and 19 wooden windows (9%). These experiments where all done according to current European standards. For more information on watertightness testing see (Van Den Bossche et al. 2008). The large number of tests on different samples gives the opportunity to analyze the influence of the type of materials, gaskets and hardware on the overall performance of the window.

3.2) Frame materials, gaskets

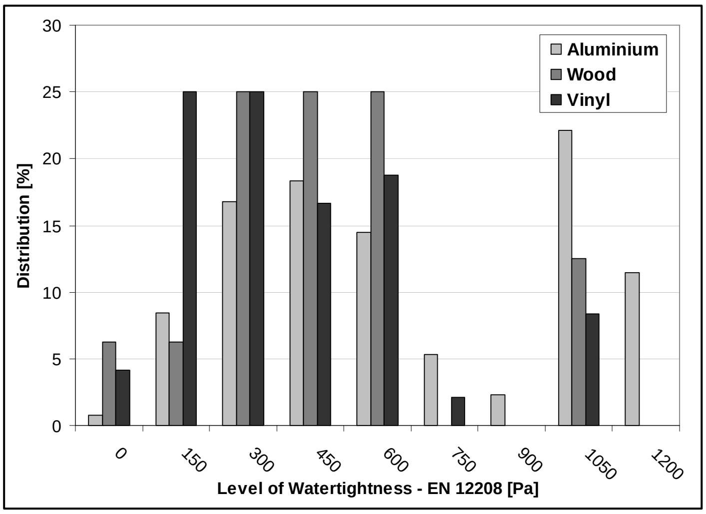


Figure 8. Watertightness of window frames - materials

While the aluminum windows achieve high levels of watertightness more frequently than the other materials, many wooden windows seem to fail at very low pressure differences. However, the difference in performance between the three types of windows may have little to do with material properties. Every material has it own specific construction methods and technology to achieve watertight windows, in that way every material generates other advantages and potential problems. The type of material is also correlated with the scale of the production process. The investment in order to produce wooden window frames is relatively low and the necessary training is available at most schools where courses of carpentry are given. Therefore most of the manufacturers of wooden windows are rather small workshops with only a few employees in Belgium. Vinyl and aluminum window frames require more advanced technology and much higher investments. Those enterprises are bigger and the technology transfer is primarily located in the company itself. While big companies rely on subdividing the construction process into little and easy steps in an assembly line and use quality control systems, small workshops rely on craftsmanship and may have a larger risk for errors to occur.

Looking at the results of experiments on aluminium windows during the last 15 years there is no clear evolution in the average performance. The average performance fluctuates very strongly throughout that period, and this is not caused by statistical flaws (e.g. too small sample group). Vinyl windows have improved significantly especially since 2001, going from an average watertightness of 300 Pa between 1997 and 2001 to somewhere between 500 and 650 Pa in the last 5 years. Aluminium on the other hands slightly shows a downwards trend regarding average watertightness (from 800 Pa in 1994 to 600 Pa in 2007). Before 2001 there was a clear difference in performance between the two types of material, but since 2001 this difference has declined significantly and has practically vanished. The total sample group of wooden windows is too small to carry out a reliable analysis.

3.3) Airtightness

Airtightness does not give the same result as watertightness: aluminium windows achieve the highest airtightness levels, followed by wooden and vinyl windows respectively. The airtightness of the windows is specified by a level according to EN 12207 ranging from 1 to 4, level 4 being the most airtight windows.

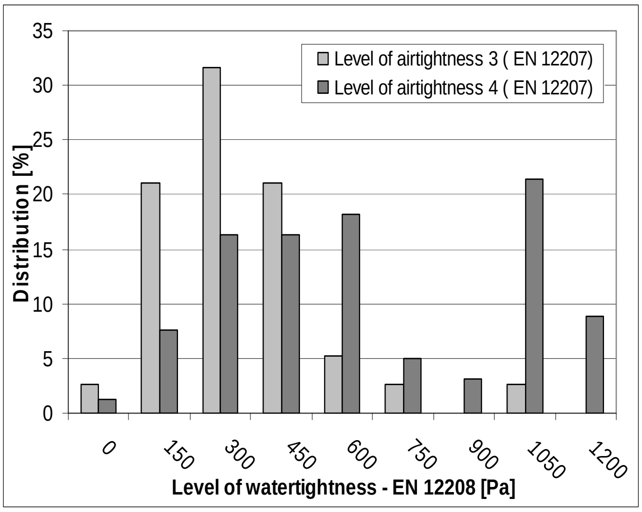


Figure 9. Watertightness vs airtightness level

Figure 9 shows the correlation between airtightness and watertightness of windows: it may be clear that the level of airtightness is a stipulation for good watertightness because only 6% of the windows of level 3 achieve a watertightness level above 600 Pa (for windows with airtightness level 4 that percentage is 38). A close examination of those results shows that at least airtightness level 3 is required for watertightness levels above 150 Pa, level 4 is required for watertightness above 450 Pa, and all the windows with a watertightness of 1200 Pa have an air leakage per meter joint length that is about half of the permissible leakage to reach level 4. Figure 10 shows the air leakage per meter of joint length in function of the air pressure across the window for 29 windows. 14 windows remained watertight up to 150 Pa (light grey lines), the other 15 windows reached a watertightness level of 1200 Pa (black lines). This clearly indicates that airtightness is a condition to reach a certain level of watertightness. The theoretical analysis already pointed out the influence of the ratio between the inner and outer plane of the window frame. As already mentioned, the airtightness of those planes is not constant, and the flow coefficient and flow exponent vary with the pressure difference. The airtightness of the outer plane is small (there are vents and weep holes) and will be primarily changed by raindrops blocking the weep holes, and to a lesser extent the vents and joints. The airtightness of the inner plane is changed by the deformation of the sash and failure of the gaskets. That way the airtightness of the outer plane is higher, whereas the inner plane becomes less airtight, thus changing the ratio in a way that has a negative effect on the pressure equalisation. The pressure across the outer plane will determine the amount of water entering the cavity, whereas the pressure difference across the inner plane will primarily determine the airtightness ratio. The pressure difference across the outer plane also determines the water level in the window cavity. When the outside pressure is 50 Pa higher than the pressure in the cavity, a water column of 5mm is built up in the cavity to obtain a balanced situation. The moment the window fails and water infiltrates, the pressure across the outer plane has raised up to 300 Pa. Hence there is an imbalance that is compensated with a water column of 30mm. It may be clear that these water heights can cause infiltration.

As the pressure difference rises, the airflow rate across the window rises accordingly (figure 6). As the air speed inside the cavity also rises, more water drops are carried along onto the airtightness gasket. Measurements show the pressure in the cavity is very unstable (fluctuations with an amplitude up to 50 Pa) which is caused by air gusts coming into the cavity through the weep holes and water columns draining out of the cavity simultaneously.

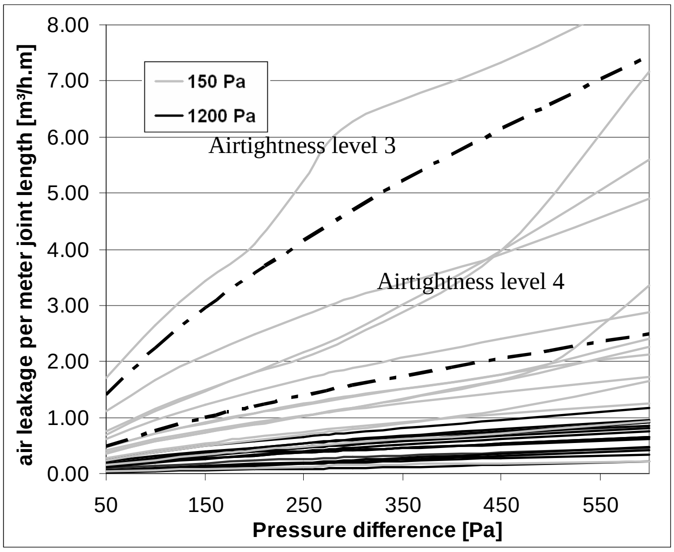


Figure 10. Measured airtightness of two categories of windows: windows watertight up to 150Pa (grey lines) and windows which are watertight up to 1200Pa.

3.4) Structural stability

The correlation between mechanical resistance to wind loads (the deformation when submitted to a certain pressure difference) and watertightness is slightly less explicit, but more rigid frames do tend to achieve a better watertightness performance, whereas slack windows (relative sag under a 1000 Pa load is bigger than 1/350) apparently do not reach a watertightness level above 600 Pa. Good pressure equalisation and watertightness depend on the collaboration between the frame, hardware and gaskets. Apparently the gaskets in the less rigid frames are not able to follow the bigger deformation: either this is a physical limitation, or none of those windows had gaskets adjusted to the type of frame. The mechanical resistance is a combination of the stiffness of the frame and sash, the fine tuning of operating hardware and the number of hinges, stays and other elements that connect the sash to the frame. More information on relaxation of the gasket and its influence on pressure equalisation, particularly during gust effects, can be found in (Van Den Bossche et al., 2008).

In order to analyse the influence of the positioning of the gaskets in the profile (inside, central or outside) the results of the aluminium windows were analyzed. Some results were excluded from the statistical analysis to avoid distortion due to infiltration problems which are not related to the gaskets. Most aluminium windows have at least two gaskets, and the most common systems are: inside-central, inside-outside, inside-central-outside, central-outside. The window frames with an inside-outside gasket configuration clearly perform less then the other systems, as only 25% of all windows achieve a watertightness level higher than 600 Pa. On the other hand 43% of the windows with gaskets central-outside reach that level, and 41% of the inside-central types. Windows with three gaskets apparently perform slightly less well than the types above. This is probably caused by tolerance problems to position the sash correctly with regards to the frame. The overall conclusion for aluminium windows is clear: two gaskets will do, of which one is located centrally in the cavity between the sash and frame.

3.5) Operating hardware

During 2006 Ghent University did a series of tests on the interchangeability of hardware in collaboration with the BCCA. For the tests 7 identical vinyl windows were manufactured, with identical size, section, reinforcements, gaskets, glazing type, etc. Only the hardware was altered: 7 different types of hardware (4 brands) were installed in the turn-tilt windows. This also meant that not every window had the same amount of closing points: this varied from 9 to 12. However, every single window was constructed by a different manufacturer. Each window was handled with kid gloves and brought to the testing facility. Out of 7 windows no less than 5 did not reach the watertightness level that was achieved during initial type testing (1200 Pa). Two windows initially did not even reach the required level for windows in low-rise buildings (<10m height) in coastal area's (450 Pa).

Most failures were traced back to construction errors of the manufacturers. With some guidance and a number of follow-up experiments eventually all windows (one sash had to be replaced) were able to reach a satisfactory level (600 Pa), but eventually only 3 windows achieved the same watertightness level as during initial type testing. Further analysis points out that the resistance to water infiltration is slightly correlated with the airtightness of the window, but no correlation with the type of hardware, number of closing points or brand could be made. Why does one window perform better than another? Although only one parameter was changed that was probably not the dominant influence on the system. This clearly underlines that initial type testing is only an indication of the potential performance of a certain window type.

Another example of the influence of craftsmanship was obtained during other tests on interchangeability of hardware: two different brands were installed in identical double side-hung casement windows. Initially the results were not that good (both windows failed at 600Pa), but when just one closing tap was adjusted 1mm, the windows achieved watertightness levels of 750Pa and 1200Pa. These kinds of differences can hardly be traced, because even the required force to bolt the gearbox did not change after the adjustment of the closing tap.

4) CONCLUSIONS

A survey on 207 tests according to current EN standards shows there is a clear connection between airtightness and watertightness: apparently a certain level of airtightness is required to realize a corresponding level of watertightness. On top the window needs to be rigid enough to enable the gaskets to follow any movement of the sash to avoid premature failure. The operating hardware needs to be well adjusted in order to obtain the right pressure on the gaskets. Practical experiments on pressure equalisation confirm these findings.

At least 13.7% of all windows (incomplete dataset, probably higher) does not pass the watertightness test for the pressure level stated by the manufacturer of the window. Without passing a judgement on that number, it should be clear that this is only true for those windows, especially prepared with kid gloves to be put to the test. In order to get any idea on the performance of windows in real buildings, one should test them in situ, or arbitrarily choose windows that are produced in the factory.

Theoretical analysis and experiments in the lab pointed out that the proportion of the airtightness of the outer plane to the airtightness of the inner plane is crucial to the pressure equalisation in the cavity of the window. Once the Pressure Equalisation Percentage drops below 90% the window will fail shortly after. During rain events a water management imbalance originates at a certain pressure difference causing pressure fluctuations in the cavity. The pressure across the outer plane determines the amount of water that enters the cavity, and the level of the static water column inside the cavity compensates the pressure imbalance.

5) ACKNOWLEDGEMENTS

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