

Improvement alternatives for determining water tightness performance of building façades

J.M. Pérez-Bella¹, J. Domínguez-Hernández^{1,*}, E. Cano-Suñén¹, J.J. del Coz-Díaz², F.P. Álvarez Rabanal²

¹ Department of Construction Engineering, Engineering and Architecture School, University of Zaragoza, María de Luna s/n, 50018, Zaragoza, Spain.

E-mails: jmpb@unizar.es, javdom@unizar.es and ecs@unizar.es

² Department of Construction Engineering, University of Oviedo, Edificio Departamental Viesques nº 7, 33204 Gijón, Spain.

E-mails: juanjo@constru.uniovi.es and felipe@constru.uniovi.es

* **Corresponding author:** Dr. Javier Domínguez-Hernández.

Department of Construction Engineering, University of Zaragoza,

Campus Río Ebro, Edificio Betancourt, María de Luna s/n, 50018, Zaragoza, Spain.

Tel.Fax: +34 976 76 21 00. E-mail: javdom@unizar.es

1

2 Acknowledgements

3 These results were obtained from data provided by the Spanish Meteorological Agency, Ministry of
4 Environment, Rural and Marine Affairs (AEMET). This work was partially financed by the Spanish Ministry
5 of Science and Innovation co-financed with FEDER funds under the Research Project BIA2012-31609.

Improvement alternatives for determining water tightness performance of building façades

Abstract

Accurately determining the water tightness performance of façades in of climatic conditions that cause water penetration is important for optimising design. The recently developed Bayesian method allows this performance to be estimated for any operating condition and location based on the results of standardised water tightness tests. Thus, this performance-based method uses semi-empirical calculations for wind-driven rain, estimates of wind velocity based on the wind profile power law and analyses of the annual maximum climatic data. Thus, this method determines the return period of climatic conditions that each façade system can withstand. In this work, alternative approximations are studied that may be implemented using the Bayesian method to obtain more precise or functional estimations: improved friction coefficients, peaks-over-threshold analyses or catch ratios from computational fluid dynamics (CFD), among others. The effects of these alternatives on the results of the Bayesian method were evaluated by analysing different case studies in two cities in Spain. This analysis suggests that the original formulation of the method underestimates water tightness performance and highlights the fundamental importance of wind velocity for accurately estimating the performance of any façade.

Keywords

Water tightness; Façade design; Climate loads; Performance assessment; Power law; POT method

Total number of words in the manuscript: 5,098

1. Introduction

The penetration of rainwater through building façades negatively affects building conservation and maintenance (Erkal, D'Ayala, & Sequeira, 2012; Etyemezian *et al.*, 2000; Tang, Davidson, Finger, & Vance, 2004) by producing aesthetic issues, corrosion, chemical degradation, frost damage, adherence loss, deformation or cracking. Similarly, increasing humidity in construction materials reduces thermal insulation (del Coz *et al.*, 2013; Hens, 2010; Sandberg, 2009) and may lead to biological growth or provoke disease outbreak (Hardin, Kelman, & Saxon, 2003; Koskinen, Husman, Meklin, & Nevalainen, 1999; World Health Organisation, 2011). However, these negative impacts can be prevented by limiting penetration of atmospheric water through building façades.

The combined action of wind and rain is responsible for wetting and water penetration through vertical construction elements (Blocken & Carmeliet, 2004; Blocken, Derome, & Carmeliet, 2013). Thus, the amount of rain that is diverted by wind impacting the façade (wind-driven rain or WDR) provides the required water supply for allowing the simultaneous wind pressure (driving rain wind pressure or DRWP) to cause penetration through the materials (Cornick & Lacasse, 2005; Sahal & Lacasse, 2004).

Consequently, current water tightness tests attempt to simulate both exposures (WDR and DRWP) by exposing real-scale façade samples to constant water supply (water spray rate) with an increasing pressure difference (ΔP) between the exterior and interior surfaces of the sample (American Architectural Manufacturers Association, 2005; American Society for Testing and Materials, 2009a, 2009b; Australian and New Zealand Standards Institution, 2008; European Committee for Standardisation, 2001). However, the standardised parameters set by these tests do not represent all possible façade exposure conditions that can occur under different operating conditions and at different locations (Sahal & Lacasse, 2008; Van der Bossche, Lacasse & Janssens, 2013a). Therefore, the results of these tests, which are characterised by the maximum ΔP before losing water tightness, do not characterise the precise performance that is expected under real conditions. In turn, the different standardised values for water spray rates, ΔP and test

durations in each test produce incomparable results. Thus, trials must be repeated for every regulatory framework (Pérez *et al.*, 2013c).

To remedy this situation, various procedures have attempted to relate water tightness test parameters (i.e., water spray rate and ΔP) with the climatic conditions of the façade (WDR, DRWP) associated with certain return period (Choi, 1998; Cornick & Lacasse, 2005; Sahal & Lacasse, 2008; Van der Bossche, Lacasse & Janssens, 2013b). The Bayesian Performance-Based method (BPB) is particularly adequate for this purpose due to its functional approach (Pérez, Domínguez, Rodríguez, del Coz & Cano, 2013a). In addition, the BPB method is precise compared to similar methods (Pérez, Domínguez, Cano, del Coz & Suárez, 2014) and its results allow to compare results from different water tightness tests (Pérez *et al.*, 2013c).

This method establishes an equation that allows associating the standardised parameters of a water tightness test (water spray rate, exposure duration and withstood ΔP value) with the real exposure conditions. For this, a semi-empiric approximation of the real WDR exposure, a DRWP estimate for different heights and surroundings based on the wind profile power law and the calculation of the return period associated with these conditions (through the annual maximum series and the Gumbel distribution) were used.

Recently, multiple studies have shown various alternatives for more accurately calculating every equation parameter (WDR, DRWP and return period). For example, improved semi-empirical approximations or peak catch ratios that are derived from computational fluid dynamics (CFD) simulations can be used to calculate the WDR. In addition, a friction coefficient that considers the atmospheric instability can be used in the wind profile power law to estimate the DRWP exposure. Furthermore, the Peak over Threshold (POT) method can determine the return period without an extensive climatic data series. These alternatives are analysed here and are implemented in the BPB method to compare their impacts on the water tightness performance test results.

The water tightness performance is analysed for various façades from two Spanish cities, Jerez de la Frontera and Bilbao. These case studies allow us to propose an improved formulation for the method that can be used to estimate the expected façade performance with greater precision at any location and under any operating condition.

2. Background

The random nature of wind and rain, together with other factors, make it difficult to estimate the WDR and DRWP on a specific façade (see figure 1).

Figure 1. Factors that determine the WDR and DRWP exposures and their return period (grey). Test parameters considered in the BPB method for the water tightness performance calculation (black).

Wind velocity that diverts raindrops towards the façades and varies with height above the ground, surrounding roughness and atmospheric stability is one of the most important factors (Touma, 1977). In addition, several studies have identified the uppermost corners of buildings as the most exposed areas to the wind, so that the geometry of the façade should also be considered (Straube & Burnett, 2000). Wind direction is another relevant factor because the WDR and DRWP are maximised when the wind direction is perpendicular to the façade (Blocken & Carmeliet, 2006). In turn, the intensity of each precipitation event determines the number and size of raindrops that can be deviated by the wind (Best, 1950) and thus affect the WDR value.

Another relevant aspect for calculating the WDR and DRWP is the time interval associated with both exposures. The maximum WDR and DRWP values that can be sustained over long intervals are always

lower than the WDR and DRWP values produced over shorter time intervals (Pérez *et al.*, 2013c).

Exposures associated with a shorter return period (i.e., more frequent and less severe exposures) are also characterised by lower WDR and DRWP values than those associated with longer return periods (Cornick & Lacasse, 2009). Given the above information and the random character of climatic events, statistical approaches must be used to estimate the WDR and DRWP values.

In water tightness tests, all of these factors are simplified, and standardised water spray rates, ΔP and exposure duration are used to assess the façade systems. However, given this simplification, these tests do not simulate all possible expected WDR and DRWP values for each façade. Therefore, these tests do not accurately characterise the water tightness performance expected for a façade under actual operating conditions (Van der Bossche *et al.*, 2013a).

Thus, the constant water spray rate is fixed to guarantee a continuous flow of runoff water over the outer surface of the test sample (usually 2 to 4 l/m² min). Regarding façades without relevant superficial defects (such as the test samples), the supply of water (i.e., WDR) does not significantly influence water tightness (Sacré, 1984). For these façades, the amount of water supplied only defines the infiltration rate once infiltration has been established (Mayo, 1998; Selvarajah & Johnston, 1995). It follows, therefore, the secondary relevance of the water spray rate in these tests.

In contrast, the wind pressure applied over the enclosure must exceed the pressure threshold that is generated by the capillary pressure and surface tension of water in the façade deficiencies to allow for filtration into the material (Lacasse, O'Connor, Nunes & Beaulieu, 2003; Van der Bossche, Lacasse, Moore & Janssens, 2012). Thus, the ΔP is the main test parameter for façades without major defects where the pressure threshold is very high. By progressively incrementing the pressure during the test (in different magnitude ranges) the water tightness of the façade system is characterised by the maximum ΔP value before filtration into the inner surface of the test sample.

Finally, the exposure interval used in different tests may significantly vary (usually between 5 to 20 min). A very short exposure interval could be insufficient for exceeding the pressure threshold required to breach the menisci on the interior of the deficiencies and for establishing the filtration. However, long exposure intervals may simulate infrequent exposures that are unrealistic under certain operating conditions. Thus, although no consensus exists for establishing the exposure duration, this parameter decisively influences the return period associated with the WDR and DRWP that are simulated and thus also determines the severity of the test (Pérez *et al.*, 2013c).

Currently, two approaches are proposed to improve the characterisation results from water tightness tests. The first approach is to fix water spray rates and the ΔP values equal to the expected WDR and DRWP values over the façade for a particular design return period (forcing the user to modify test parameters and equipment for each trial) (Choi, 1998; Cornick & Lacasse, 2005; Sahal & Lacasse, 2008; Van der Bossche *et al.*, 2013b). The second approach is to estimate the return period associated with the standardised water spray rate and the ΔP value withstood in the test, for the real operating conditions of the façade (thereby maintaining the test configuration, allowing to compare results of different water tightness test and taking advantage of available results for multiple façade systems).

The BPB method belongs to the second approach, which characterises the water tightness performance of any façade by calculating this return period (Pérez *et al.*, 2013a, 2013c). Alternatively, this method can also be used to calculate the ΔP value that must be withstood in a standardised test to guarantee the water tightness of the façade under the climatic conditions associated with a certain return period.

2.1 Approaches used by the Bayesian method and possible alternatives

To apply this method, the actual WDR and DRWP values that may be exerted over the façade during the test exposure interval and for the design return period must be accurately determined. For this, a system

of three equations with five unknowns was established in which various improvement alternatives are identified that may improve the accuracy and functionality of the determined parameters (see table 1).

Table 1. Scheme of the proposed alternatives for their implementation in the BPB method.

2.1.1 DRWP estimation

The first equation determines the DRWP value over a façade by combining the Bernoulli relationship and the wind profile power law (which extrapolates wind velocity U_z at any height from the available wind velocity records). For this purpose, wind velocity records U_{10} (m/s) that are simultaneous to precipitation and have been collected near the façade are used. These records must have similar time intervals to the test exposure intervals (5-20 min) and must be obtained under reference conditions (i.e., at a height of 10 m above the ground and on flat terrain without obstacles) (World Meteorological Organisation, 2008). Thus, the $DRWP_z$ (Pa) can be estimated based on the height z (m) and literature values for a generic friction coefficient α (-) of the surroundings (Ray, Rogers, & McGowan, 2006). In addition, a pressure coefficient C_p of 1, a wind direction perpendicular to the façade ($\cos \theta = 1$) and a constant air density ρ of 1.2 kg/m³ can be used as conservative estimates (equation 1).

$$DRWP_z = C_p \cdot \frac{1}{2} \cdot \rho \cdot (U_z)^2 \cdot \cos \theta \approx 0.6 \cdot (U_{10})^2 \cdot \left(\frac{z}{10}\right)^{2\alpha} \quad (1)$$

This friction coefficient may range from 0.1 in smooth or rough ground to 0.4 in urban areas. However, these tabulated values do not consider the roughness length of the area around the façade or the atmospheric stability (a neutral condition of atmospheric stability is assumed). Therefore, the precision of this coefficient may be questionable. In turn, other possible wind profiles, such as the log-linear law, have

shown poor functionality for general application in engineering (Bañuelos, Ángeles & Ríos-Marcuello, 2010).

Most cloud formation mechanisms that can produce WDR and DRWP events (e.g., free convection due to surface heating, forced convection due to low pressure systems, rising air due to an orographic barrier or warm air passing over cold fronts) are associated with unstable atmospheric conditions (Jacobson, 2005; Queralt, Hernández, Gallego & Iturrioz, 2007). To incorporate the roughness length z_0 and the influence of atmospheric instability into the friction coefficient α , Smedman-Högström & Högström (1978) developed an empirical formula using measurements from Southern Sweden. In addition, this formula obtained more precise results relative to the log-linear law for locations with different climates than Sweden, especially under unstable atmospheric conditions (Gualteri & Secci, 2011). By incorporating this formula into equation (1), the $DRWP_z$ can be accurately estimated (equation 1a) as a function of roughness length z_0 [m], which has been frequently tabulated in the literature (Bañuelos *et al.*, 2010; Jacobson, 2005).

$$DRWP_z \approx 0.6 \cdot (U_{10})^2 \cdot \left(\frac{z}{10}\right)^{2 \cdot [0.18 + 0.13 \cdot \log z_0 + 0.03 \cdot (\log z_0)^2]} \quad (1a)$$

2.1.2 WDR estimation

The second equation uses the semi-empirical relationship proposed by Straube & Burnett (2000) to determine WDR exposure on the façade (equation 2). A rain admittance factor (RAF) of 0.9 and a wind direction perpendicular to the façade ($\cos \theta = 1$) are adopted conservatively. The driving rain factor (DRF) is determined by using the terminal falling velocity of raindrops, which varies according to raindrop diameter (Dingle & Lee, 1972). For simplification, the predominant raindrop diameter may be estimated from rainfall intensity as described by Cornick *et al.* (2002).

$$WDR_z = RAF \cdot DRF \cdot U_z \cdot R_h \cdot \cos \theta \approx \frac{U_{10} \cdot \left(\frac{z}{10}\right)^\alpha}{-0.184478 \cdot (R_h)^{-1} + 5.471534 \cdot (R_h)^{-0.768} - 0.988909 \cdot (R_h)^{-0.536} + 0.061193 \cdot (R_h)^{-0.304}} \quad (2)$$

This equation characterises the WDR_z (l/m^2) value from simultaneous wind velocity U_{10} (m/s) and rainfall intensity R_h (mm) records, estimating the wind velocity for different conditions of z (m) and α (-) by applying the wind profile power law. As for the equation (1), the Smedman-Högström & Högström formula may be applied to accurately characterise the wind velocity U_z for any point on the façade (see equation 2a).

$$WDR_z \approx \frac{U_{10} \cdot \left(\frac{z}{10}\right)^{\left[0.18+0.13 \cdot \log z_0 + 0.03(\log z_0)^2\right]}}{-0.184478 \cdot (R_h)^{-1} + 5.471534 \cdot (R_h)^{-0.768} - 0.988909 \cdot (R_h)^{-0.536} + 0.061193 \cdot (R_h)^{-0.304}} \quad (2a)$$

In addition, the adopted raindrop diameter may be optimised to improve the precision of this estimation. Van der Bossche *et al.* (2013b) showed that WDR is underestimated by 14% when using the predominant drop diameter rather than the numeric solutions, which are based on integrating an array of raindrop diameters according to a raindrop distribution spectrum. By including a correction factor of 1.14 in equation (2), this error may be minimised to obtain more realistic exposure estimates (equation 2b).

$$WDR_z \approx 1.14 \cdot RAF \cdot DRF_{\phi_{pred}} \cdot U_z \cdot R_h \cdot \cos \theta \quad (2b)$$

Finally, various CFD simulations for buildings have shown that a peak catch ratio of 1.3 may be used to approximate the WDR for a wind speed of 10 m/s and a rainfall intensity of 1 mm (Blocken & Carmeliet, 2006). Consequently, Van der Bossche *et al.* (2013b) proposed equation (2c) as a possible functional alternative to the semi-empirical relationships determined by Straube & Burnett.

$$WDR_z \approx 0.13 \cdot U_z \cdot R_h \quad (2c)$$

2.1.3 Return period estimation

The last equation used in the BPB method can determine the return period associated with any two simultaneous values of WDR_{Z_i} and $DRWP_{Z_i}$ by applying the Bayesian probability approach and a Gumbel distribution (equation 3). The mode u and dispersion β that are required for defining the Gumbel distribution (Gumbel, 1958) are obtained from the maximum annual rainfall and wind velocity records that were collected at each location. U_{10i} represents the wind velocity value that produces the $DRWP_{Z_i}$ value over the façade and R_{hi} is the rainfall intensity that produces the WDR_{Z_i} value when the wind velocity U_{10i} simultaneously acts.

$$\frac{1}{\text{Return period } (WDR_{Z_i} \cap DRWP_{Z_i})} \approx \left(1 - \exp^{-\exp \frac{-(U_{10i} - u(U_{10}))}{\beta(U_{10})}} \right) \cdot \left(1 - \exp^{-\exp \frac{-(R_{hi} - u(R_h))}{\beta(R_h)}} \right) \quad (3)$$

Nevertheless, other accepted alternatives are available for analysing extreme values (Balkema & Haan, 1974; Pickands, 1975). For example, the POT method can be used to determine the return period associated with each U_{10i} and R_{hi} parameter by only using climatic records that are above a sufficiently high exposure threshold T . This method may be used for sites with limited climatic data, where the available annual maximum series is insufficient for determining representative values for mode u and dispersion β (Bezak, Brilly & Šraj, 2013; Pérez, Domínguez, Cano, del Coz & Suárez, 2014; Rasmussen, Ashkar, Rosbjerg & Bobee, 1994; Simiu, Heckert, Filliben & Johnson, 2001; Tanaka & Takara, 2002).

To apply this method, the empirical cumulative distribution function (CDF) of the values above the threshold T must be obtained for each climatic variable (U_{10} and R_h). By adjusting a Generalised Pareto Distribution (GPD) with γ and σ parameters to this empirical CDF, the return period associated with any value may be obtained by considering the number of years with records n_{year} and the number of values N above the optimal threshold (equation 3d).

$$\frac{1}{\text{Return period } (WDR_{Z_i} \cap DRWP_{Z_i})} \approx \left(\frac{N_{U_{10i}}}{n_{\text{year}}} \left(1 + \frac{\gamma_{U_{10i}}}{\sigma_{U_{10i}}} (U_{10i} - T_{U_{10i}}) \right)^{-\frac{1}{\gamma_{U_{10i}}}} \right) \cdot \left(\frac{N_{R_{hi}}}{n_{\text{year}}} \left(1 + \frac{\gamma_{R_{hi}}}{\sigma_{R_{hi}}} (R_{hi} - T_{R_{hi}}) \right)^{-\frac{1}{\gamma_{R_{hi}}}} \right) \quad (3d)$$

2.2. Solving the equation system

The system formed by equations 1, 2 and 3 (or their respective proposed alternatives), presents five unknown variables, *Return period*, WDR_{Z_i} , $DRWP_{Z_i}$, U_{10i} and R_{hi} . Other factors, such as the height of the façade, its surroundings and parameters that define the Gumbel Distribution or POT analysis are known for each case study (review table 1). To solve the system analytically and relate it to a water tightness test, its standardised parameters (water spray rate and ΔP) are set as two of the unknown variables (Pérez *et al.*, 2013a).

Thus, the water spray rate is set as the WDR_{Z_i} value and the ΔP value withstood by the test sample is set as the $DRWP_{Z_i}$ value. The solution to the equation system will determine the *return period* that is associated with the test exposures under the façade operating conditions (i.e., the verified water tightness performance of the analysed façade under its real operating conditions). Alternatively, a certain design performance (years) can be set as the design return period and the water spray rate can be adopted as the WDR_{Z_i} value. Thus, the $DRWP_{Z_i}$ (i.e., ΔP) value that must be withstood during the test to verify this specified design performance may be obtained. The following section examines the effects of each calculation alternative that was proposed according to the results of the BPB method. For this, different case studies are analysed.

3. Implementing improvement alternatives for the Bayesian method: Water tightness performance in two Spanish cities

The BPB method and the alternatives proposed in the previous section were applied to assess the water tightness conditions of three generic case studies (A, B and C). The façades represented by these operating conditions reflect common situations in European cities, such as single-family urbanisations of up to 10 m tall (case A), residential block buildings of more than 25 m in suburban areas (case B) or tall buildings of up to 40 m that are used as apartments or offices in urban centres (case C). Available climatic records for two Spanish cities were used for this analysis (Bilbao and Jerez de la Frontera).

Jerez de la Frontera, which is located southwest of the Iberian Peninsula and near the Strait of Gibraltar, is subject to strong Atlantic winds that are responsible for high DRWP exposure (see figure 3). However, moderate rainfall at this location reduces the WDR exposure. In turn, Bilbao is located on the northern coast of Spain and is exposed to Atlantic winds with low intensity but also to a high annual rainfall. Consequently, the WDR exposure of Bilbao is slightly higher than the WDR exposure of Jerez (Pérez, Domínguez, Rodríguez, del Coz & Cano, 2012, 2013b, 2014).

Figure 2. Map of the Iberian Peninsula that illustrates the exposure characteristics and locations of the analysed weather stations.

Both cities have 10-min records of rainfall and wind velocity that were recorded simultaneously by the Spanish Meteorological Agency (AEMET in Spanish) over 14 years in Bilbao and 18 years in Jerez. Altogether, 41155 10-min intervals of WDR-DRWP events were recorded in Bilbao, while Jerez only had 15213 intervals due to its lower rainfall.

The calculation parameters that were used for the three case studies are shown in table 2. The friction coefficient α and roughness length z_0 were obtained from tabulated values for suburban areas and urban centres (Ray *et al.*, 2006). The parameters that define the Gumbel distribution (u and β) and GPD for the

POT analysis (γ , σ , T and n_{year}) were calculated for each climatic variable from the 10-min records that were available for both sites. The Method of Moments was used to adjust the GDP to the empirical CDF of the values above the threshold T , verifying the minimum Mean Squared Error between both distributions.

Table 2. Calculation parameters associated with each case study (operating condition) and location.

For simplicity, the water spray rates and ΔP values used as references for the analysis were adopted from the water tightness test EN 12865:2001 (European Committee for Standardisation, 2001). This test sets the exposure interval to 10 min (i.e., equal to the recording interval of the available data). Regarding the use of tests with other exposure intervals, the available climatic records could be extrapolated to other intervals using a previous procedure (Pérez *et al.*, 2013c). This procedure reduces the degree of uncertainty that is associated with general climatic extrapolations, such as the extrapolations of Durst (1960), Linsley, Kohler & Paulus (1975) or Choi (1998).

By adopting a WDR_{zi} value of 2 l/m² min (water spray rate for the EN 12865 test) and a $DRWP_{zi}$ values of 150, 300, 450 or 600 Pa (ΔP ranges for the same test), the equations system was resolved for the proposed case studies. Thus, by using these test conditions and the parameters shown in table 2, the original BPB method (equations 1, 2 and 3) yields the results that are shown in table 3.

Table 3. Return periods that were calculated by the original BPB method (equations 1, 2 and 3) for the ΔP ranges established in the EN 12865:2001 test (in years).

3.1 Implementing the improved friction coefficient for the wind profile power law

To consider the roughness length of the surrounding surfaces and the atmospheric instability during storm events, the original equations were replaced with the equations (1a) and (2a). The new return periods obtained for each case study and for each ΔP range established in the EN 12865:2001 test are shown in table 4.

This improved friction coefficient estimation significantly reduces the wind velocity that is calculated with the wind profile power law. In addition, this estimation results in greater return periods relative to those resulting from the original BPB method, especially for greater heights of the façades and higher ΔP values.

Table 4. Implementation of the improved friction coefficient (equations 1a, 2a and 3) for the return period calculation (in years) and the percentage differences from the original results.

These important differences suggest the need to accurately analyse the wind profile around each façade. Only a precise characterisation of the wind velocity will reduce the uncertainty of the calculated water tightness performance. Therefore, the simplified formula that was used by the original method overestimates the WDR and DRWP conditions that may be produced on the façades. Thus, a lower design performance is considered relative to the actual values.

3.2 Implementing the correcting factor due to predominant raindrop diameter

The error that results from a simplified use of a predominant drop diameter may be reduced by substituting equation (2) with its alternative (2b), which introduces a correction factor for WDR. Table 5 shows the return periods that resulted from solving this new system of equations. This correction produces variations that are hardly significant when calculating the design performances.

Table 5. Implementation of the correcting factor (equations 1, 2b and 3) for the return period calculation (in years) and the percentage difference from the original results.

Using the predominant drop diameter slightly underestimates the expected WDR exposure on the façade. Therefore, the calculated values are slightly optimistic for the enclosure design performance. In addition, the percentage differences are reduced by increasing the ΔP values (lower than 10% for a ΔP of more than 300 Pa) and reached zero for Bilbao. All of these results indicate the secondary relevance of raindrop diameter when calculating the water tightness performance of building façades.

3.3 Implementing the peak catch ratio for estimating the WDR

Table 6 shows the return periods obtained by simplifying the WDR calculation using the peak catch ratio derived from the CFD simulations. For this, the initial system of equations was solved by substituting equation (2) by the alternative equation (2c). The new results were more optimistic regarding water tightness performance relative to the original BPB performance. In addition, the divergences are similar for all analysed operating conditions. In general, Jerez presents greater differences than Bilbao.

Although the theoretical simplification introduced by equation (2c) is important, these results present differences of less than 20% (with respect to the original method) for ΔP values of more than 300 Pa.

Such divergence is reduced by increasing the ΔP , reaching less than 5% at Bilbao. Thus, a peak catch ratio of 1.3 could be adopted to approximate the water tightness performance with less mathematical complexity.

Table 6. Implementation of the peak catch ratio (equations 1, 2c and 3) for the return period calculation (in years) and the percentage difference from the original results.

3.4 Implementing the POT method for estimating the return period

To implement the POT method in BPB method calculation, equation (3d) is used rather than equation (3). The results obtained for each case study are presented in Table 7 and cover the same ΔP ranges that were used in the previous sections.

Table 7. Implementation of the POT method (equations 1, 2 and 3d) for the return period calculation (in years) and the percentage difference from the original results.

Given the different natures of both statistical estimates and the distinct treatment of the necessary data for their definition (annual maximum series or climatic records over a threshold), the obtained results are different from the original results. Regarding Bilbao, the differences are greater under the more adverse operating conditions (B and C) and generally produced lower return periods relative to those of the original method. However, for operating condition A, the return period estimate was greater than the initial estimate. Jerez de la Frontera presented results that were similar to the original results obtained

under operating condition B. However, greater differences occurred for operating conditions A and C that were higher or lower than the original results.

The observed differences are lower than the differences identified for other aspects that are subject to improvement in the original method, such as ignoring atmospheric instability and roughness length in the wind profile (compare tables 4 and 7). Therefore, both statistic estimates can resolve the BPB method without distinction, by calculating the return period associated with the exposure conditions used in the tests. Thus, the type of statistical approximation that should be used for the extreme value analysis will only depend on the availability of climatic records at each location. Thus, the POT method (equation 3d) can be considered an adequate alternative when these data do not provide a representative annual maximum series for applying equation (3).

Nevertheless, the application of the POT method is more laborious than the original procedure because the climatic records generated by the same storm event would be associated with the same return period and must be identified. In addition, the election of the optimal threshold T is a delicate task. For this, diverse mathematical methods that are not exempt from uncertainty must be used. Thus the management of the climatic data and adopted parameters for the adjusted GDP may give way to significant differences when estimating the design return periods.

4. Discussion

Two effective improvements have been identified for the BPB method that can be used to incorporate atmospheric instability during WDR and DRWP events and the roughness length of the façade's surroundings (equations 1a and 2a) or to correct the WDR value associated with using the predominant raindrop diameter (equation 2b).

Both alternatives may be jointly implemented to propose an improved BPB method that assesses the exposure conditions of a façade with greater precision. For this, the Smedman-Högström & Högström friction coefficient and the correcting factor 1.14 must be included in the original system of equations. The results obtained from this improved method are shown in Table 8.

Table 8. Combined implementation of the improved friction coefficient and the correcting factor for raindrop diameter (equations 1a, 2a, 2b and 3) for the return period calculation (in years) and the percentage difference from the original results.

In turn, two functional alternatives have been analysed to reduce the mathematical complexity of the method (equation 2c) and to allow applying the BPB method in sites with limited climatic records (equation 3d). While using a peak catch ratio equal to 1.3 slightly increases the design return period relative to the initial method, the application of the POT method for the statistical calculations provides greater variation around the initially calculated return periods (by increasing or reducing their value).

These alternatives are limited to the internal mathematical formulation of the method and do not modify its structure or calculation procedure (Pérez *et al.*, 2013c). Therefore, every one of these alternatives allows applying the method in water tightness tests with an exposure duration that is different from the available climatic records. Figures 3 and 4 are used to compare the results from each alternative and the corresponding original and improved methods. For clarity, only the ΔP values associated with return periods of less than 150 years were shown.

Figure 3. Comparing the different calculation alternatives for the BPB method in Bilbao (operating conditions A, B and C).

Figure 4. Comparing the different calculation alternatives for the BPB method in Jerez de la Frontera (operating conditions A, B and C).

In general, the original formulation determines lower water tightness performances relative to the various proposed alternatives and results in a more demanding accreditation. The use of POT provides results that vary around the original values due to the different natures of the statistical approaches. These variable results may lead to lower design return periods relative to the initial values. Meanwhile, the improved BPB method increases the expected water tightness performance, resulting in a greater difference from the original method as the exposure produced by the operating conditions increases.

Although both cities have similar exposure indicators (review figure 3), differences occurred in the calculated design return periods for each city. These differences suggest that tools that are more elaborate are necessary for optimising building façade design (e.g., the BPB method) even when indicators, such as the driving rain index or the average WDR and DRWP exposures, may qualitatively characterise the location. In addition, similar differences were observed among the evaluated operating conditions, which demonstrated that real operating condition should be considered for each façade. To homologate a façade system only through the ΔP value withstood in water tightness tests (as it is done currently) is an incomplete task if particular operating conditions of the façade are not considered. Thus, the BPB method and its improvements proposed in this work allow researchers and test labs for a more detailed and individualised analyses for each case. For this, only the general result obtained by the façade system in a single standardised water tightness test is needed. These improvements can be used by standardisation

bodies to provide better building regulations and design criteria for façade systems manufacturers and designers.

5. Conclusions

In this study, various improvements were analysed that are capable of providing greater accuracy or functionality when estimating the water tightness performance of building façades with the BPB method. Thus, the atmospheric instability during storm events, the error derived from the WDR estimates based on the predominant raindrop diameter, the usage of a peak catch ratio from CFD simulations, and the implementation of a POT method for calculating exposure values associated with different return periods were considered. The results indicated the significant influence of the wind profile that was used to calculate the water tightness performance and suggested that this profile should be rigorously determined in each situation. Conversely, the proposed changes in the WDR exposure calculations did not significantly affect these results. The application of a statistical estimate based on the POT method provided reasonably similar results to those that were obtained from the analysis of annual maximum series.

Two of the analysed alternatives were implemented in the Improved BPB method (IBPB). This method is capable of estimating the performance of any façade with greater precision for any operating conditions and location. In general, this improved method determines greater water tightness performance than the original method. The remaining alternatives are adequate for estimating the performance with lower mathematical complexity or in the absence of ample climatic data series.

These advances indicate the feasibility of establishing performance-based codes that determine the water tightness performance that is necessary for façades (i.e., its required design return period). This requirement may be justified by using the IBPB method and the ΔP value withstood by the façade system

in any of the current water tightness tests. Thus, the building solutions currently accepted by national regulations could be expanded and the real operating conditions could be considered for the design of each specific façade.

References

- American Architectural Manufacturers Association. (2005). *AAMA 501.1. Standard test method for water penetration of exterior windows, curtain walls and doors using dynamic pressure*. Schaumburg, IL: American Architectural Manufacturers Association (AAMA).
- American Society for Testing and Materials. (2009a). *ASTM E331-00. Standard test method for water penetration of exterior windows, skylights, doors, and curtain walls by uniform static air pressure difference*. West Conshohocken, PA: American Society for Testing and Materials (ASTM).
- American Society for Testing and Materials. (2009b). *ASTM E547-00. Standard test method for water penetration of exterior windows, skylights, doors, and curtain walls by cyclic static air pressure difference*. West Conshohocken, PA: American Society for Testing and Materials (ASTM).
- Australian and New Zealand Standards Institution. (2008). *AS/NZS 4284. Testing of building façades*. Sydney: Australian and New Zealand Standards Institution (AS/NZS).
- Balkema, A. & de Haan, L. (1974). Residual life time at great age. *The Annals of Probability*, 2, 792–04.
- Bañuelos, F., Ángeles, C. & Ríos-Marcuello, S. (2010). Analysis and validation of the methodology used in the extrapolation of wind speed data at different heights. *Renewable and Sustainable Energy Reviews*, 14, 2383-2391. doi: 10.1016/j.rser.2010.05.001
- Best, A.C. (1950). The size distribution of raindrops. *Quarterly Journal of the Royal Meteorological Society*, 76, 16–36. doi:10.1002/qj.49707632704

- Bezák, N, Brilly, M. & Šraj, M. (2013). Comparison between the peaks over threshold method and the annual maximum method for flood frequency analyses. *Hydrological Sciences Journal, Published online 05 Aug 2013*. doi: 10.1080/02626667.2013.831174
- Blocken, B. & Carmeliet, J. (2004). A review of wind-driven rain research in building science. *Journal of Wind Engineering and Industrial Aerodynamics, 92(13)*, 1079–1130. doi:10.1016/j.jweia.2004.06.003
- Blocken, B. & Carmeliet, J. (2006). On the validity of the cosine projection in wind-driven rain calculations on buildings. *Building and Environment, 41(9)*, 1182-1189. doi:10.1016/j.buildenv.2005.05.002
- Blocken, B., Derome, J. & Carmeliet, J. (2013). Rainwater runoff from building facades: A review. *Building and Environment, 60*, 339-361. doi:10.1016/j.buildenv.2012.10.008
- Choi, E. C. C. (1998). Criteria for water penetration testing. In R. Kudder J. & J. Erdly L. (Eds.), *Water leakage through building facades* (pp. 3–16), ASTM STP 1314. West Conshohocken, PA: American Society for Testing and Materials.
- Cornick, S.M., Dalglish, A., Said, N., Djebbar, R., Tariku, F. & Kumaran, M.K. (2002). *Report from Task 4 of MEWS Project: Task 4 – Environmental conditions final report* (Research Report No. 113). Ottawa: National Research Council Canada.
- Cornick, S.M. & Lacasse, M.A. (2005). A review of climate loads relevant to assessing the watertightness performance of walls, windows, and wall-window interfaces. *Journal of ASTM International, 2(10)*, 1-16. doi:10.1520/jai12505
- Cornick, S.M. & Lacasse, M.A. (2009). An investigation of climate loads on building façades for selected locations in the US. *Journal of ASTM International, 6(2)*, 1–17. doi:10.1520/jai101210
- Del Coz, J. J., Rabanal, F. P., García, P. J., Domínguez, J., Rodríguez, B. & Pérez, J. M. (2013). Hygrothermal properties of lightweight concrete: Experiments and numerical fitting study. *Construction and Building Materials, 40*, 543–555. doi: 10.1016/j.conbuildmat.2012.11.045

- Dingle, A. N. & Lee, Y. (1972). Terminal fall speeds of raindrops. *Journal of Applied Meteorology*, 11, 877–879.
- Durst, C.S. (1960). Wind speeds over short periods of time. *The Meteorological Magazine*, 89, 181-7.
- Erkal, A., D' Ayala, D. & Sequeira, L. (2012). Assessment of wind-driven rain impact, related surface erosion and surface strength reduction of historic building materials. *Building and Environment*, 57, 336-348.
doi:10.1016/j.buildenv.2012.05.004
- Etyemezian, V., Davidson, C.I., Zufall, M., Dai, W., Finger, S. & Striegel, M. (2000). Impingement of rain drops on a tall building. *Atmospheric Environment*, 34, 2399-2412.
- European Committee for Standardization. (2001). *EN 12865. Hygrothermal performance of building components and building elements. Determination of the resistance of external wall systems to driving rain under pulsating air pressure*. Brussels: European Committee for Standardization (CEN).
- Gualteri, G. & Secci, S. (2011). Comparing methods to calculate atmospheric stability-dependent wind speed profiles: A case study on coastal location. *Renewable Energy*, 36, 2189-2204. doi:
10.1016/j.renene.2011.01.023
- Gumbel, E.J. (1958). *Statistics of extremes*. New York: Columbia University Press.
- Hardin, B.D., Kelman, B.J. & Saxon, A. (2003). Adverse human health effects associated with molds in the indoor environment. *Journal of Occupational and Environmental Medicine*, 45(5), 470-478.
- Hens, H. (2010). Wind-driven rain: from theory to reality, In Proceedings *Thermal performance of the exterior envelopes of whole buildings XI*. Clearwater, FL.
- Jacobson, M.Z. (2005). *Fundamentals of atmospheric modeling* (2nd. Ed.). New York: Cambridge University Press.
- Koskinen, O.M., Husman, T.M., Meklin, T.M. & Nevalainen, A.I. (1999). The relationship between moisture or mould observations in houses and the state of health of their occupants. *European Respiratory Journal*, 14(6), 1363-1367.

- Lacasse, M. A., O'Connor, T., Nunes, S. C. & Beaulieu, P. (2003). *Report from Task 6 of MEWS Project: Experimental assessment of water penetration and entry into wood-frame wall specimens – Final report* (Research Report No. 133). Ottawa: Institute for Research in Construction, National Research Council Canada.
- Linsley, R.K., Kohler, M.A. & Paulhus, J.L.H. (1975). *Hydrology for engineers* (2nd ed.). New York: McGraw-Hill.
- Mayo, A. P. (1998). To develop a European standard dynamic watertightness test for curtain walling. Task 5. Develop the methodology for the standard dynamic watertightness test. Watford: Building Research Establishment (BRE).
- Pérez, J.M., Domínguez, J., Rodríguez, B., del Coz, J.J. & Cano, E. (2012). Estimation of the exposure to moisture in Spain from daily wind and rain data. *Building and Environment*, 57, 259–270.
doi:10.1016/j.buildenv.2012.05.010
- Pérez, J. M., Domínguez, J., Rodríguez, B., del Coz, J. J., & Cano, E. (2013a). A new method for determining the water tightness of building facades. *Building Research & Information*, 41(4), 401–414.
doi:10.1080/09613218.2013.774936
- Pérez, J.M., Domínguez, J., Rodríguez, B., del Coz, J.J., & Cano, E. (2013b). Combined use of wind-driven rain and wind pressure to define water penetration risk into building façades: the Spanish case. *Building and Environment*, 64, 46–56. doi: 10.1016/j.buildenv.2013.03.004
- Pérez J.M., Domínguez, J., Rodríguez, B., del Coz, J.J., Cano, E. & Navarro, A. (2013c). An extended method for comparing watertightness tests for facades. *Building Research & Information*, 41(6), 706-721.
doi:10.1080/09613218.2013.823538
- Pérez, J.M., Domínguez, J., Rodríguez, B., del Coz, J.J., & Cano, E. (2014). Review and improvement of the water tightness degree required by the CTE DB-HS1 for building façades. *Informes de la Construcción* (In press, accepted manuscript).

- Pérez J.M., Domínguez, J., Cano, E., del Coz, J.J. & Suárez, F.J. (2014). A comparison of methods for determining watertightness test parameters of building façades. *Building and Environment*, 78, 145-154. doi: 10.1016/j.buildenv.2014.04.027
- Pickands, J. (1975). Statistical inference using extreme order statistics. *The Annals of Statistics*, 3(1), 119–31.
- Queralt, S., Hernández, E., Gallego, D. & Iturrioz, I. (2007). Atmospheric instability analysis and its relationship to precipitation patterns over the western Iberian Peninsula. *Advances in Geosciences*, 10, 39-44.
- Rasmussen, P.F., Ashkar, F., Rosbjerg, D. & Bobee, B. (1994). The POT method for flood estimation: a review. In K. Hipel (Ed.), *Extreme values: floods and droughts* (pp. 15-26), Water Science and Technology Library 10/1. Dordrecht, NL: Kluwer Academic Publishers.
- Ray, M., Rogers, A.L. & McGowan, J.G. (2006). Analysis of wind shear models and trends in different terrains, *American Wind Energy Association Windpower 2005 Conference*. Pittsburgh.
- Sacré, C. (1984). Concomitance de la pluie et du vent en France: approche statistique. In Proceedings *Colloque de Centre Scientifique et Technique du bâtiment: étanchéité à l'eau des couvertures et petits éléments sous l'effet de la concomitance vent-plui*, p.18-21. Paris.
- Sahal, A.N. & Lacasse, M.A. (2004). *Experimental assessment of water penetration and entry into siding-clad wall specimen* (Internal Report No. 862). Ottawa: Institute for Research in Construction, National Research Council Canada. doi: irc_id:16429
- Sahal, N. & Lacasse, M. A. (2008). Proposed method for calculating water penetration test parameters of wall assemblies as applied to Istanbul, Turkey. *Building and Environment*, 43, 1250–1260. doi:10.1016/j.buildenv.2007.03.009
- Sandberg, I. (2009). Effects of moisture on the thermal performance of insulating materials. In H.R. Treschek & M.T. Bomberg (Eds.), *Moisture control in buildings: the key factor in mold prevention* (2nd Ed.). New York.

- Selvarajah, S. & Johnston, A.J. (1995). Water permeation through cracked single skin masonry. *Building and Environment*, 30(1), 19-28. doi: 10.1016/0360-1323(94)E0033-N
- Simiu, E., Heckert, N.A., Filliben J.J. & Johnson S.K. (2001). Extreme wind load estimates based on Gumbel distribution of dynamic pressures: an assessment. *Structural Safety*, 23, 221-229. doi: 10.1016/S0167-4730(01)00016-9
- Smedman-Högström, A.S. & Högström, U. (1978). A practical method for determining wind frequency distributions for the lowest 200 m from routine meteorological data. *Journal of applied Meteorology*, 17, 942-954. doi: 0021-8952/0942-0954\$06.50
- Straube, J. F., & Burnett, E. F. P. (2000). Simplified prediction of driving rain on buildings. In Proceedings *International Building Physics Conference* (pp. 375–382). Eindhoven.
- Tanaka, S. & Takara, K. (2002). A study on threshold selection in POT analysis of extreme floods. In A. Snorrason, H.P. Finnsdóttir & M.E. Moss (Eds.), *The Extremes of the Extremes: Extraordinary Floods* (pp. 299-304). Wallingford, UK: International Association of Hydrological Sciences
- Tang, W., Davidson, C. I., Finger, S. & Vance, K. (2004). Erosion of limestone building surfaces caused by winddriven rain. 1. Field measurements. *Atmospheric Environment*, 38, 5589–5599.
doi:10.1016/j.atmosenv.2004.06.030
- Touma, J.S. (1977). Dependence of the wind profile power law on stability for various locations. *Journal of the Air Pollution Control Association*. 27(9), 863-866. doi: 10.1080/00022470.1977.10470503
- Van der Bossche, N., Lacasse, M.A. & Janssens, A. (2013a). A uniform methodology to establish test parameters for watertightness testing. Part I: A critical review. *Building and Environment*, 63, 145-156.
doi:10.1016/j.buildenv.2012.12.003
- Van der Bossche, N., Lacasse, M.A. & Janssens, A. (2013b). A uniform methodology to establish test parameters for watertightness testing. Part I: Pareto front analysis on co-occurring rain and wind. *Building and Environment*, 63, 157-167. doi:10.1016/j.buildenv.2012.12.019

Van der Bossche, N., Lacasse, M.A. Moore, T. & Janssens, A. (2012). Water infiltration through openings in a vertical plane under static boundary conditions. In Proceedings *5th International building physics conference*. Kyoto.

World Health Organisation (2011). Environmental burden of disease associated with inadequate housing. Methods for quantifying health impacts of selected housing risks in the WHO European Region. Copenhagen: World Health Organisation (WHO).

World Meteorological Organisation (2008). Guide to meteorological instruments and methods of observation (WMO No. 8). Geneva: World Meteorological Organisation (WMO).

List of tables

Table 1. Scheme of the proposed alternatives for their implementation in the BPB method.

Table 2. Calculation parameters associated with each case study (operating condition) and location.

Table 3. Return periods that were calculated by the original BPB method (equations 1, 2 and 3) for the ΔP ranges established in the EN 12865:2001 test (in years).

Table 4. Implementation of the improved friction coefficient (equations 1a, 2a and 3) for the return period calculation (in years) and the percentage difference from the original results.

Table 5. Implementation of the correcting factor (equations 1, 2b and 3) for the return period calculation (in years) and the percentage difference from the original results.

Table 6. Implementation of the peak catch ratio (equations 1, 2c and 3) for the return period calculation (in years) and the percentage difference from the original results.

Table 7. Implementation of the POT method (equations 1, 2 and 3d) for the return period calculation (in years) and the percentage difference from the original results.

Table 8. Combined implementation of the improved friction coefficient and the correcting factor for raindrop diameter (equations 1a, 2a, 2b and 3) for the return period calculation (in years) and the percentage difference from the original results.

Figure captions

Figure 1. Factors that determine the WDR and DRWP exposures and their return period (grey). Test parameters considered in the BPB method for the water tightness performance calculation (black).

Figure 2. Map of the Iberian Peninsula that illustrates the exposure characteristics and location of the analysed weather stations.

Figure 3. Comparing the different calculation alternatives for the BPB method in Bilbao (operating conditions A, B and C).

Figure 4. Comparing the different calculation alternatives for the BPB method in Jerez de la Frontera (operating conditions A, B and C).