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Procedure for a detailed territorial assessment of wind-driven rain and driving-rain wind pressure and its implementation to three Spanish regions

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ABSTRACT

Wind-driven rain and the simultaneous action of wind pressure contribute to water penetration into building façades. Therefore, both climatic parameters must be considered in the design of building enclosures to manage the effects of water intrusion. This article presents a procedure for determining both parameters in a geographic area, by combining various data sources. The procedure was implemented in three Spanish regions with different climates (Galicia, Catalonia and Andalusia), by combining precipitation and wind velocity records compiled at 393 weather stations distributed across these regions, using wind maps, and fitting relationships between exposure indices. In comparison to other studies, this procedure allows for data from a relatively large number of locations to be included in the exposure assessment, which can produce a more detailed characterisation across the territory and facilitate the creation of isopleth exposure maps. A risk index of water penetration, which combines the influence of both exposures, was also calculated. The results showed that the exposure of building façades to water penetration was driven by the climate of each zone. Galicia is the most exposed region. Moreover, the Strait of Gibraltar and Gulf of Cadiz in Andalusia and the Cape of Creus in Catalonia are also zones of high exposure.

1. Introduction

The simultaneous action of precipitation and wind pressure on building façades leads to wetting of construction materials and penetration of atmospheric water into building enclosures (Blocken and Carmeliet, 2004; Blocken et al., 2013). Wind action on raindrops imparts a horizontal component to their fall velocity, causing them to impinge the exterior surface of building walls (wind-driven rain or WDR). Simultaneously, wind pressure acting on a building façade (driving rain wind pressure or DRWP) facilitates water penetration through the pores and cracks present in the building façade.

Therefore, exposure to the combined action of WDR and DRWP is considered to be the primary cause for problems associated with water penetration into building components above ground (Sahal and Lacasse, 2004; Cornick and Lacasse, 2005; Kerr, 2004), including reduced thermal performance and subsequent increases in energy consumption (Del Coz et al., 2013; Sanders, 1996), increased maintenance costs (Franke et al., 1998; Waldum, 1993; Tang et al., 2004), and even health problems for building residents (Haverinen-Shaughnessy, 2007; WHO, 2011). Characterising the exposure to both climatic parameters for a given location is therefore a primary goal when designing building enclosures that minimise these problems (Carll, 2001; Kvande and Lisø, 2009; Straube and Burnett, 1999).

Many studies in different countries have focused on the analysis of WDR exposure (Blocken and Carmeliet, 2004). These studies analysed this exposure for a discrete number of locations distributed throughout a particular geographic area, e.g., 1 location per 26000 km^2 in Chile and Nigeria (Pérez et al., 2013a; Akingbade, 2004); 1 location per 9400 km^2 in India (Chand and Bhargava, 2002); 1 location per 4250 km^2 in Greece (Giarma and Aravantinos, 2011); or 1 location per 3300 km^2 in Turkey (Sahal, 2006).

However, the representativeness of these exposure results is limited in areas that are distant from the locations for which the exposure was determined. According to the international standard ISO 15927–32009 (ISO, 2009), the validity of exposure results can be extended to locations within a maximum radius of 100 km around the location for which WDR exposure is known (for flat regions with differences in height less than 100 m). In mountainous or hilly regions or in coastal and lakeside areas, the validity radius is likely considerably smaller. These limitations mean that the results of the analyses

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typically performed to extract WDR conditions are only reliable close to the analysed locations, leaving extensive areas without a valid estimate of WDR exposure.

In most countries, estimating this exposure at additional locations is limited by the number of available weather stations that have concurrent records of rain and wind of sufficient age and precision. To the best of the authors' knowledge, only the United Kingdom has attempted to estimate WDR exposure in a detailed way throughout its entire territory using wind patterns and precipitation records to interpolate the values of WDR exposure in areas located far from the analysed sites (BSI, 1992; Prior, 1985).

This study proposes an alternative procedure that permits analysing a large number of additional locations by combining rainfall records and wind velocity data, gathered at weather stations, with information from regional wind maps and fitting relationships between different exposure indices. As a demonstration, the procedure was applied to generate a detailed estimate of the WDR and DRWP exposures in three regions of Spain: Galicia (1 location per 370 km^2), Catalonia (1 location per 218 km^2) and Andalusia (1 location per 525 km^2). This allowed for the characterisation of the entire territory encompassing these regions through the creation of different isopleths exposure maps. The WDR and DRWP exposure values obtained in these regions also allowed for the calculation of a detailed risk index of water penetration, or RIWP (Pérez et al., 2013b), that characterises the combined effect of both exposures on building façades.

2. Background

The characterisation of the two exposures (WDR and DRWP) is necessary to adequately determine the risk of water penetration through a building façade. A number of investigations have shown that driving rain is capable of penetrating deteriorated façades (walls with pores and cracks larger than 5 mm) even in the absence of significant wind pressure (Cornick and Lacasse, 2005; Sahal and Lacasse, 2004). Likewise, a relatively small quantity of driving rain can penetrate building enclosures without defects or pores greater than 1 mm if elevated wind pressure occurs simultaneously with rain deposition on the building façade. Due to the variety of surface finishes and different states of building maintenance, both climatic parameters must be considered to develop a comprehensive characterisation of water penetration risk in building façades.

Although there are currently different procedures that can be used to quantify each parameter with great precision, it is preferable to use simple and functional calculation methods to determine these exposures at many locations using a reasonable effort. Therefore, the majority of studies on WDR have used semi-empirical calculation methods based on the “WDR relationship” (Hoppestad, 1955; Lacy, 1965).

Compared to more precise CFD methods, which require extensive datasets to define each situation (Blocken et al., 2011a, 2011b; Hensen and Lamberts, 2011; Kubilay et al., 2013), the WDR relationship can be used to approximately determine the WDR exposure based on climatic data that are generally recorded at a majority of weather stations irrespective of the country of interest. Thus, the WDR value (l/m^2) may be estimated based on records of precipitation intensity R_h (l/m^2) for each precipitation event at a given location and wind velocity U (m/s) occurring simultaneously at the same location by applying the empirically fitted coefficient k (s/m) of Eq. (1):

$$WDR = k \times U \times R_h \tag{1}$$

The fitted coefficient k (physically related to the terminal falling velocity of raindrops) is affected by the characteristic size of water droplets for each precipitation event and, therefore, also influenced by the rainfall intensity. Various studies have proposed mean values for this coefficient, which may range between 0.20 and 0.25 s/m (Lacy, 1977; Straube and Burnett, 2000).

However, the simplest and most widespread application of the WDR relationship does not use a fitted coefficient. Instead, it considers a driving rain index (DRI), which is used to qualitatively characterize WDR exposure independent of location-specific storm events (Lacy and Shellard, 1962). This scalar index (m^2/s), which is typically averaged over an annual period (*aDRI*), can be calculated using average annual records (*aaDRI*) for precipitation R_h (mm/year) and wind velocity U (m/s) gathered over N years at each sampling location (Eq. (2)). The velocity records are usually taken under reference conditions, i.e., at a height of 10 m over clear and obstacle-free terrain (WMO, 2008).

$$aaDRI = \frac{\sum_{i=1}^{N} U \times \left(\frac{R_h}{1000}\right)}{N} \tag{2}$$

The use of monthly or daily averaged values (*maDRI* and *daDRI*, respectively) reduces data averaging and co-occurrence errors (Blocken and Carmeliet, 2007, 2008). While this scalar index does not quantify the volume of driving rain or its distribution along different building wall orientations, it does provide an exposure estimate, and it has been shown by Henriques (1992) that an empirical fit can be used to relate the index value with a WDR estimation (l/m^2).

Moreover, a scalar calculation based on climatic records gathered at each site can be used to determine the DRWP exposure value (Cornick and Lacasse, 2005). Therefore, the mean driving rain wind pressure $DRWP_a$ (Pa) value may be obtained using the Bernoulli equation (Eq. (3)), where C_p represents a pressure coefficient (usually equal to 1), ρ_{air} (kg/m^3) represents air density and U (m/s) represents wind velocity at the time of a significant precipitation event (>0.05 mm). To determine the mean wind pressure, m records of simultaneous wind and rain events gathered over multiple years can be averaged.

$$DRWP_a = \frac{\sum_{i=1}^{m} C_p \times \frac{1}{2} \times \rho_{air\ i} \times U_i^2}{m} \tag{3}$$

Similar to the *aDRI* index, the wind velocity records typically refer to reference conditions, i.e., DRWP exposure is calculated at a height of 10 m over clear and obstacle-free terrain. Moreover, the use of wind records collected over shorter time intervals allows for consideration of only those wind velocity records that occur simultaneously with rainfall, thereby reducing co-occurrence errors in the calculation of DRWP exposure.

As discussed above, the precision of both indices (*aDRI* and $DRWP_a$) depends on the quality of available climatic records. In contrast, the level of detail for the WDR and DRWP exposure analysis performed for a geographic area depends on the distance between sampling locations for the data used in the calculation (i.e., the number of points analysed).

2.1. Previous studies conducted in Spain

Several studies have been conducted to generally characterise WDR and DRWP exposures in Spain by analysing climatic data gathered over 30 years at 80 locations (Pérez et al., 2012, 2013b, 2013c). These studies have provided a level of precision higher than typically attained in other countries because they used daily climatic records of precipitation and wind velocity rather than monthly or annual records often used in other countries (Akingbade, 2004; Chand and Bhargava, 2002; Giarma and Aravantinos, 2011; Sahal, 2006).

Nevertheless, at the scale of 1 result per 6300 km^2, these studies are not sufficient to obtain a representative characterisation of the entire Spanish territory, especially for areas far from urban centres.