In Situ Methodology to Assess the Action of Water-Wind on Building Windows

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Abstract The chapter describes a new methodology for the evaluation of the in situ water tightness in window openings located in the building envelope, as well as the development process carried out for its real application. It is an innovative non-destructive testing procedure that reproduces the effects of rain combined with wind, which is applicable both during the building construction process and in buildings in use. It is a useful tool for tightness analysis in quality control of elements and constructive pathologies that offers verifiable results in the field of habitability evaluation in buildings.

Keywords Window · Water tightness · Blowerdoor · Buildings

1 Introduction

Infiltration and moisture are amongst the main pathologies that affect building envelopes [1, 2] and in some cases, such as in Spain, constitute the greatest percentage of lawsuits in relation to this type of construction unit [3]. This fact also affects the thermal behaviour of walls [4], thus influencing the energy demand of heating, ventilation, and air conditioning systems.

Window cavities in envelopes are critical points for moistures [5], where rain and wind are the determinant factors regarding water solicitation [6]. Thus, testing the parameters of water tightness and wind pressure in windows is important, so the respective regulation usually includes verification points for the assessment and quality control of windows. For instance, this issue is widely included in the European standard, and there are standards on water tightness tests for both external windows

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D. Bienvenido-Huertas and J. Moyano-Campos (eds.), *New Technologies in Building and Construction*, Lecture Notes in Civil Engineering 258,
https://doi.org/10.1007/978-981-19-1894-0_6

and doors (EN 1027:2016) and resistance to wind (EN 12211:2016). According to the results obtained by the tests mentioned, this European standard also establishes classification criteria for both water tightness (EN 12208:1999) and resistance to wind (EN-12210:2016). However, this powerful standard on window control is subject to laboratory tests focussed on carpentry samples, in which the ensemble set of the window to the cavity or its construction perimeter (lintels, sills, etc.) cannot be tested. Laboratory results provide the features of the insulated element, dividing their values into various typologies, which is very useful to choose and validate typologies and construction project acceptance, however, these tests cannot prove the construction features of the several units of the building as each has their own factors, such as tolerances and execution failures, adjustment to other elements, and termination accessories. Consequently, in situ tests are considered an essential part to assess windows and their cavities appropriately, but performing a test outside a laboratory and in different locations implies another technical complexity that should be borne in mind as the tools, systems, and procedures used should be adapted to the various spaces and designs. For this reason, there are important limitations to achieve the utilization requests regarding the elements tested.

Aware of this problem, the TEP 970 research group (technological innovation, 3D modelling systems, and energy diagnosis in heritage and building), which is related to the field of production technologies, belongs to the Research Andalusian Plan of the Regional Government of Andalusia (PAIDI) and is made up by a multidisciplinary group of coordinated researchers from the University of Seville, included this issue in the ongoing works, aiming at looking for a transversal solution based on the knowledge acquired. Building façades are continuously subjected to pressure variations because of atmospheric conditions, with the wind pressure being the variable magnitude load that generally affects the exterior surfaces of architectural constructions. Studies on envelope air permeability are amongst the important areas studied by this research group, so the progress in this issue was considered to make a feasible proposal: the combination of wind pressure with rainfall, two meteorological phenomena that usually takes place together. This combination is very interesting to be studied given its impact on envelope elements and its direct influence on pathologies related to moisture and water infiltration, with window cavities being critical points. Thus, window features should be tested in situ against simultaneous water-wind solicitations, so the behaviour of the elements actually executed could be specified, thus solving existing failures and being a learning bank for future performances.

After the contribution of a particular team within the research group responsible for both this aspect and the development of many works and studies for that purpose, a theoretical proposal was obtained in the first stage of works for a testing system that gave response to these issues [7].

In the second stage of the research, the theoretical solution was implemented in many actual cases, in which the method was improved and adapted to be used in building quality control. This chapter describes the final result obtained after that empirical stage applied to existing buildings. Consequently, the current proposal is a new technique, but with proven tests, to assess in situ water and air permeability in the envelope cavities of any building by simulating in situ various water conditions and wind pressure.

This procedure is based on putting an interior room of a building under variable pressure conditions; at the same time, an artificial rain is caused in the exterior surface of the existing façade cavities. Thus, meteorological conditions caused by driving rain are simulated in an actual building, i.e. the water driven by wind when acting on the envelope, thus testing the behaviour of the construction elements when these actions take place. It has been empirically tested that this system that assesses in situ permeability in façade cavities is fully versatile and universal to be used as its equipment is easy to be adapted and similar to other widely used diagnostic techniques.

2 State of the Art

There is no antecedent with these characteristics in the existing techniques. The study of sources to know the current state of the technique in this area reveals the existence of methods focussed only on theoretical and calculation models related to the various physical effects that the phenomenon of water driven by wind causes on façades [8, 9]. In this regard, there is a standard proposal in ISO 15927-3: 2009 called "*hygrothermal performance of buildings. Calculation and presentation of climatic data. Part 3: Calculation of a driving rain index for vertical surfaces from hourly wind and rain data*". In other cases, measurements have been conducted in buildings to quantify in façades the typical values of these atmospheric phenomena in natural episodes [10, 11]. However, few references have assessed the phenomenon through actual reproduction techniques in view of such environmental conditions. In this regard, José María Pérez Bella's doctoral thesis should be stressed [12]. His works conclude that the assessment tests included in the current international standards (and therefore marketed) correspond to sample patterns of laboratory tests whose principle, according to the author in page V.1 of the reference work, is: "*someter a la acción de un determinado caudal de agua sobre su superficie y a la acción simultánea de una determinada presión externa… determinando la presión máxima que el cerramiento es capaz de superar para un aporte de agua constante, sin presentar fugas de agua*" [12]. This author, together with other researchers, has studied this issue in several research studies [13–16] and although the method proposed focusses on the numeric calculation to characterize exposure parameters and payback periods, a correlation with the tests used in various international standards is also made. Nevertheless, in all the cases referenced, assessment techniques, together with the reproduction of actual conditions of water and wind pressure, are always limited to samples or graduated cylinders, expressly made for tests in laboratories or specialized facilities, such as those included in UNE-EN 12865: 2012 to determine water permeability in external walls under pulsating air pressure. There is no procedure for in situ (in the actual building) determinations by using air pressure variations.

On the other hand, some texts within the Spanish standard define tests to prove in situ water permeability, usually used to control quality in building works. This is the UNE 85247:2011 standard, called "*Windows. Water tightness. Site test*", which describes a simple projection test of a constant water volume for 30 min to later verify or not the existence of water penetration to the interior; however, no mechanism for air pressure is included. To reproduce the wind effect, tightness tests should be performed in laboratories using carpentry samples. There are other research studies conducted in other countries, but none of them is similar to the procedure proposed in this study. It is worth mentioning some studies performed in Florida (USA) [17–19], all related to water action under wind pressure (wind-driven rain). Their goal was to approach to the effects of hurricanes as these phenomena are usual in the area and damage buildings. However, unlike the procedure proposed, isolated samples are reproduced and expressly built to be tested through large devices located in facilities adapted for that purpose to perform tests at a large scale with elements that simulate wind (turbines).

It is also worth stressing the study conducted in the Laboratory of Building Physics at the Catholic University of Leuven, in Belgium [20], with the so-called vliet test building, i.e. a test building expressly built to assess envelopes. Within this research, experimental studies were conducted to test the hygrothermal performance of certain building solutions. For this purpose, tests were performed in the building under the natural meteorological conditions taking place during the test and without simulating artificial rain or wind pressure.

To sum up, the previous sources have proven that today, except this research line, there is no in situ assessment technique for built buildings that reproduce water conditions and variable wind pressure to assess the permeability of façade cavities. Moreover, there is no reference on the use of the procedure proposed that combines the several technologies simultaneously used (infrared thermography, blowerdoor systems, sprinkling systems, etc.).

The novelty of the procedure suggested and tested after the empirical stage has been valued thanks to the large number of sources consulted. In addition, there are no similar antecedents in relation to the application versatility and tool simplicity, with a particular reproduction of the solicitations that involve rain water combined with wind.

3 Methodology

The technique proposed aims to assess in situ the behaviour of window cavities in building envelopes regarding both their water permeability and the external air from meteorological phenomena called wind-driven rain.

To describe the operative methodology tested by this study, it is worth describing first the equipment used. The simultaneous use of these systems, together with a coordination based on the protocol established and the lines marked, allows valid results to be obtained regarding the characteristics and possible failures of the windows placed under actual performance conditions. In particular, the instrumental systems used are as follows:

a. To reproduce the wind effect on the façade in each pressure step defined, pressure differences should be created between the internal rooms of the building where the cavities to be assessed are placed and the external atmosphere.

   For this purpose, one or more ventilator equipment were put in one or several ventilators included in blowerdoor devices (Nº 9 in Figs. 1 and 2), which were placed at the door of the interior zones to pressurize, so a range of pressure differences, positive or negative, were created through air flows between the interior and the exterior, including equipment to measure those pressure, air flows, and temperature. For this purpose, commercialized blowerdoor equipment were used as they include a management hardware (Nº 8 in Figs. 1 and 2) that was useful to control parameters during the test. To reproduce accurately the wind effect on the building façade, the pressure range should be negative, i.e. the pressure jump should be lower in the room tested than in the external atmosphere, so air flows were produced from the exterior to the interior. Thus, all fixed values for test pressure (measured in Pascals (Pa)) were understood as the magnitude that the exterior pressure should exceed in comparison with the interior one through this equipment.

b. The rain effect was simulated simultaneously to the wind effect, i.e. by using a sprinkling water system directly from the exterior of the building in the whole surface of the cavity or cavities to be tested (Nº 4 in Figs. 1 and 2). This water projection, which was conducted through water equipment with variable volume and tools to measure such volume, should cover the window and the junctions

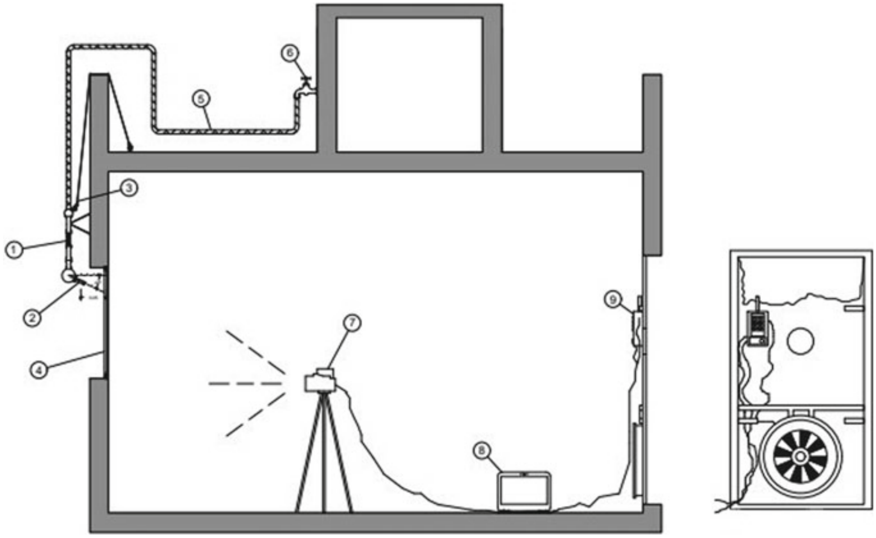

Fig. 1 Sketch of the test. Part I

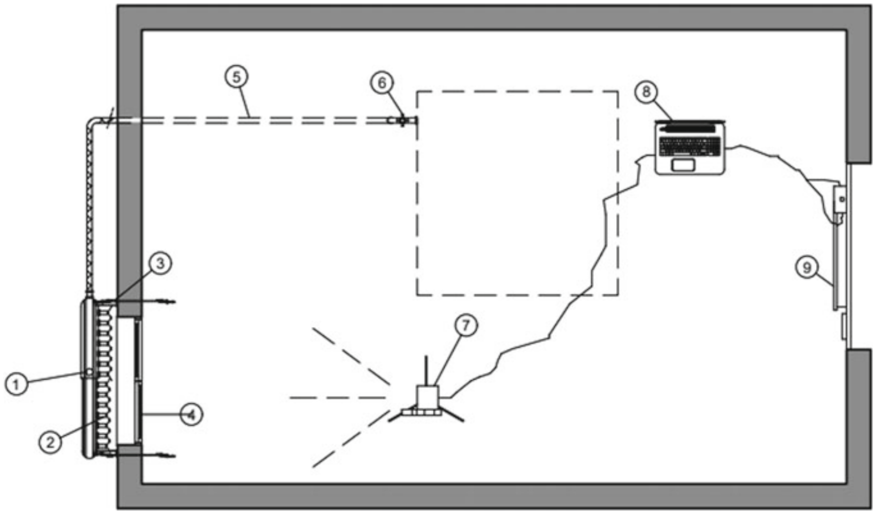

Fig. 2 Sketch of the test. Part II

of the various construction elements (woodwork, stonework, cladding, etc.). To set the volume to be reproduced in each test, rainfall criteria included in the respective building standard should be considered, according to climate zones and exposure zones. In Spain, there is a test standard, mentioned in the introduction, to check tightness without pressure (UNE 85247:20118). This standard establishes volume values that could also be used in the test proposed with pressure. For this purpose, a flowmeter of variable area was used (a rotameter) (Nº 1 in Figs. 1 and 2), a sprinkling system with circular conical nozzles and a sprinkling angle of 120°, horizontally placed 150 mm above the lintel and separated 400 mm amongst them (Nº 2 in Figs. 1 and 2). The flowmeter had a v-bracket so that the system was placed at the vertical position of the façade. Likewise, the flowmeter and sprinkling systems had a clamping system called support anchored to the façade or to the roof of the building (Nº 3 in Figs. 1 and 2). Water was supplied by a flexible pipe with a diameter of ½ inch primped by a water intake point (Nº 5 and 6 in Figs. 1 and 2).

c. To complement the assessment of the behaviour of the cavity of the elements unnoticeable by human eyes, a usual infrared camera was used (Nº 7 in Figs. 1 and 2) to test the surfaces affected, according to the methodology from UNE-EN 13187:1998.

After defining the tools, it is worth stressing the time sequence required by this methodology. The study of the requirements of each window sample to be tested, together with the analysis of the information that the development of the test provides, leads to a set of specific premises that those responsible for tests should always consider.

The number of windows to be tested in each test depends on the availability of equipment that could be simultaneous used in the several tool procedures described. In principle, there is no maximum limitation of the number of rooms to be pressurized with cavities sprinkled by water, although the experience based on tests for air permeability recommends to divide them into limited areas. If various spaces of a same building are included, the difficulty of maintaining a constant pressure increases due to the increase of the number of internal joints and cavities that produce uncontrollable air flows. However, if equipment is powerful enough, pressurization tests could be performed in spaces such as premises and halls in which the existing cavities could be instrumented with water projection and large tests could be conducted.

Nonetheless, the implementation and development of each test should be adjusted to the specific methodological scheme that has been successfully experimented by the research studies conducted, corresponding to the following steps:

1. Establishment of a protocol before performing each test to establish the number of simulation steps to be reproduced and their values.

   Each step consisted of a different combination of pressure and water volume during a specific period of time (no lower than 5 min).

   For this purpose, the goals of each test are considered, including both the exposure and the climate conditions required for building walls. For instance, in Spain, the climatic parameters set by the national application standard (The Spanish Technical Building Code) could be used. In addition, values internationally recognized are also useful, such as the Beaufort scale for the wind force. For coefficients and other calculation aspects, the EN-ISO 15927-3: 2011 standard called "*hygrothermal performance of buildings. Calculation and presentation of climatic data. Part 3: Calculation of a driving rain index for vertical surfaces from hourly wind and rain data*" could be used.
2. Preparation of the area. Temporary sealing of the existing gaps in the interior rooms to be pressurized different from those existing in the cavity or cavities of the façade to be assessed. The aim is to remove all the elements that cause controlled air infiltrations, i.e. the infiltrations foreseen in the performance design of the building. Air conditioning grills, ventilation gaps, junctions amongst elements that are not watertight, etc., should be fully sealed to not cause air flows that could alter the development of the test, at the same time, the performance of the ventilator is optimized, thus achieving greater performance of the blowerdoor equipment placed for each case. Only the air pressure could affect the joints and assemblage existing in both the window and its construction perimeter.

   In addition, the correct performance of the window to be tested should be verified, i.e. its closure and opening (the window should be fully closed during the test), and all the elements influencing the detection of weird situations should be visually inspected, as well as the shadow elements and the accessories to be placed in the position established by the previous conditions of the tests should be operated.

Likewise, the equipment previously defined is placed and its correct performance should be verified for the test, since it is important to guarantee both the continuous supply of water volume established and the energy sources.

3. The test starts by reproducing rain and wind in situ through the simultaneous action of the tools described and according to the steps pre-established in Point 1. Controlling the correct pressure and volumes in each test phase is crucial.
4. Visual observation to inspect affected surfaces (the window, specially its perimeter junctions, as well as all surface areas of its interior outline and accessories such as shutter boxes and window cranks) during the whole test and after it is finished, for a period of time, no lower than 30 min. Any impact produced should be written down, although it is minimum, to monitor and assess if it is repeated.

   Likewise, the infrared equipment should be activated in the inspection to always complement the assessment of elements through this technique, thus detecting the critical points and possible defects unnoticeable by human eyes. This information is useful to mark areas liable to suffer anomalies in the next steps of the test.

   After finishing the test and the observation period, all permanent water infiltration and moisture in the interior that affect elements not foreseen to be wet should be considered.
5. The result report will include

   - Situation data of the spaces tested with levels of the existing cavities and their constructive characteristics.
   - Number of steps executed, collecting the following information in each one: time in minutes, pressured measured in Pascals (and equivalent wind speed in m/s) and water volume in l/m^2h. The maximum values applied are justified according to the climate conditions or specific conditions of the test.
   - Detail of the water infiltration and moisture stains observed, and the step in which they appeared, indicating the wind pressure and speed of the last acceptable step, i.e. the previous to that causing anomalies. These conformance values are useful to tabulate and classify the characteristics of the cavity of the window tested.

Figure 3 includes a flowchart of the methodological process described, whose study and application have been useful for the goals proposed.

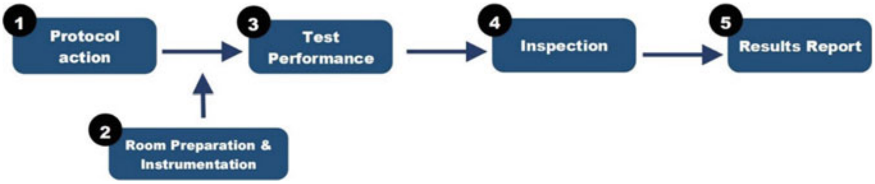

Fig. 3 The flowchart of the methodological process

4 Intervention Example

An intervention example developed in the empirical phase of the research is provided. Many applications are conducted in actual cases to quantify values, define specific adjustments, and obtain all the data required to implement the method appropriately. The example is presented as a guide for interventions to be conducted, and based on it, the versatility of the process allows characteristic and detailed parameters to be changed to be adapted to another possible requirement, always considering the initial methodological basis.

This case corresponds to a standard situation amongst all those analyzed. It is a flat located in the second floor of a multi-family residential building in Seville (Spain), where the behaviour of a window cavity is tested. There are no previous requirements, and the test only determines the maximum capacity of the window tested regarding water-wind solicitation. This is a type case conducted by the research team to implement the test system that could be extrapolated to other similar performances in various locations and with other requirements.

After inspecting the dwelling and compiling all the existing information, a window cavity was selected; in this case, it is the only window in the room. It is an aluminium window, with two sliding leaves of total dimensions 145 cm × 205 cm, with a roller blind. The wall is of ceramic brick with double-leaf and internal insulation, and the window is placed in the plan of the interior surface.

The protocol established for the test was based on the following steps:

Assembly of the blowerdoor equipment in the front door of the room chosen as test room in the dwelling. It was previously surveyed and measured according to the procedure of air permeability tests in buildings described by ISO 9972:2015.

Assembly and adjustment of the sprinkling system outside the window as it is described in the methodology and always following the guidelines provided by the UNE 85247:2011 Spanish standard.

Preparation of the infrared camera to take images.

Initial performance verification of the equipment used, as well as the correct closure and lack of anomalies in the cavity to be tested.

Start of the test whose subsequent steps of water pressure (in Pascals) and projection are initially presented with the following rate:

- Water projection without pressure (15 min)
- Water projection + difference air pressure 50 Pa (5 min)
- Water projection + difference air pressure 100 Pa (5 min)
- Water projection + difference air pressure 150 Pa (5 min)
- Water projection + difference air pressure 250 Pa (5 min)
- Water projection + difference air pressure 300 Pa (5 min)
- Water projection + difference air pressure 450 Pa (5 min)
- Water projection + difference air pressure 600 Pa (5 min).

If there are no visible water infiltrations after this test sequence, the series of pressure steps continue with variations of 150 Pa in each.

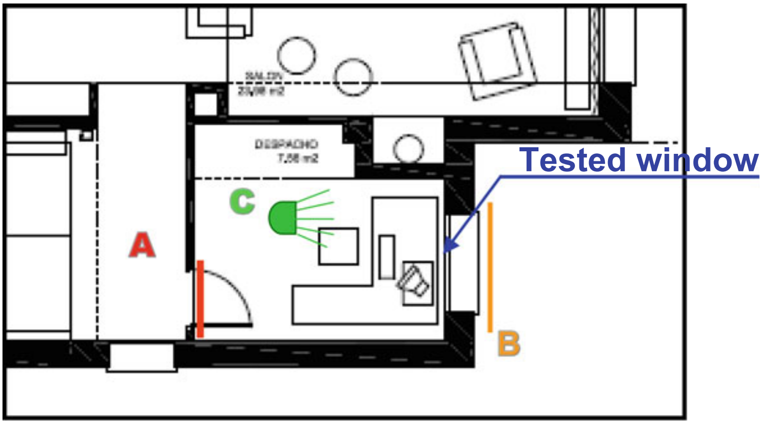

Fig. 4 Plan sketch of the room tested: (A) blowerdoor; (B) water spray instrumentation, and (C) infrared camera

If there are water infiltrations or constant moisture in surfaces not foreseen to be wet, the test is considered finished. In this case, the maximum acceptable pressure to be considered is that of the step immediately lower than that in which the failure has been detected. This pressure, with its equivalent to wind speed, provides referential parameters to value the maximum capacity of the cavity regarding wind-driven rain, which should be studied from the point of view of meteorology and exposure to the façade in which the window tested is located. Thus, a clear vision of the vulnerability of the window or windows tested could be obtained regarding the appearance of failures due to infiltration or moisture caused by actual rain.

On the one hand, Fig. 4 includes the plan sketch of the room tested and the test layout, and on the other hand, Fig. 5 corresponds to photographs of the equipment used to reproduce wind pressure, and Fig. 6 corresponds to the tested window.

In the case tested, the results showed continuous water infiltrations to the interior in the third step of the test corresponding to 100 Pa (Fig. 7). Consequently, the allowable rating pressure for wind-driven rain was 50 Pa, equivalent to 33 km/h of wind speed.

Based on these results, several aspects are discussed:

- First, the results approve the proposed methodology as the test was fully satisfactory. The reproduction of combined rain and wind phenomena was faithfully simulated.
- Second, the adaptability of the test is obvious as all tools were easily placed, and the protocol established was easily developed.
- Moreover, the practical sense of the test was also shown as interior infiltrations were detected during the water-wind process, thus fulfilling the goal of the procedure, which was to obtain the maximum characteristics with which the window could operate without anomalies in its location and under current conditions. In the case tested, this limit was 33 km/h regarding rain + wind.

Fig. 5 Equipment used to reproduce wind pressure

Fig. 6 Tested window

Fig. 7 Window during test

- Finally, the possible failures to be solved were detected. In the unit tested, the failures were the watertight sealing of the joints between the window and the perimeter of the façade in which it was located.

In addition, other actual applications of the proposed method were conducted in several building typologies and window cavities, obtaining different values regarding their characteristics. Nonetheless, the results of the test performance were always satisfactory.

5 Conclusions

The testing method to assess the behaviour of windows regarding water and wind action responds to the following scheme:

1. Means are used to pressurize the building envelope from the interior in one or several rooms. In particular, blowerdoor equipment are used to generate a specific range of constant pressure differences, which are controlled between the exterior and the indoor rooms of the building in which the cavity or cavities to test are placed, by putting a device to make air movements in the interior with measurement of air flow rates and pressures.
2. Similarly, a water sprinkling system is used in the exterior area of the cavity or cavities to be tested and in the perimeter of the façade. Its volume should always be controlled by a metre or flowmeter, and the orientation of the projection system should be adapted to both the configuration of the cavity of the window and the requirements of each test.
3. The test consists in using two equipment that operate in a combined way, thus reproducing identical conditions than that caused by simultaneous water and wind on the façade. Several combinations of pressure and volume could be used according to the climate actions (rainfall and wind) to be tested.
4. Moreover, possible water infiltration or moisture appearance is monitored in the tested zone. To distinguish the aspects related to infiltrations unnoticeable

by human eyes, infrared thermography is used as a simultaneous mean to study and obtain references during tests.

5. Finally, for each of the simulated combinations, the critical points and failures detected are assessed, thus evaluating the maximum resistance of the window to water-wind.

Thus, a tool is defined, and its actual application examples show that it is effective to establish the water-wind solicitations that window cavities could support, as well as to detect their construction or design failures. Using this, method to a great scale will provide useful databases for future decision-making for those responsible for the construction process at a project, execution, or maintenance level.

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