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Dynamic Evaluation of the Building Envelope for Wind and Wind Driven Rain Performance

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Abstract: The building envelope should be designed to provide a comfortable indoor environment irrespective of changes in the weather. Therefore to provide a functional and durable building envelope the dynamic character of the driving forces must be recognized by the envelope designer. The dynamic performance of the building envelope can be evaluated in laboratories in which the design details and most of the dynamic properties of the driving forces are simulated. This paper discusses the dynamic processes and the need for dynamic evaluation of structural performance under wind loading and of rain penetration performance under wind driven rain conditions. Three research facilities are examined for their approach to dynamic evaluation of structural performance, rain penetration performance and both. Additional information on dynamic evaluation of the building envelope was gathered from standards and the literature. Based on this information, procedures for dynamic evaluation under wind loading and wind driven rain conditions are proposed.

1. INTRODUCTION

Comprehensive evaluation of a building envelope assembly will provide design data for durable design of similar assemblies. Knowledge gathered from such systematic investigation may also lead simple test methods for future evaluations. Nevertheless, in evaluating the performance of the building envelope assembly, comprehensive laboratory procedures have to represent actual field conditions. This requires a simulation of both the building assembly construction details and the environmental forces. Failure to reproduce either one can lead to misrepresentation of the performance of the assembly. In most existing procedures attention is paid to model the geometric and material properties of the assembly. More research is needed, however, to develop an appropriate representation for the dynamic features of the external forces.

This paper discusses the concept of a dynamic process and the need for a dynamic evaluation of structural performance under wind loading and rain penetration performance under wind driven rain conditions. Three research facilities are examined for test procedures for rain penetration control structural performance and the combination of both. Additional information on dynamic evaluation of the building envelope was gathered from standards and the literature. Based on this information, procedures for dynamic evaluation under wind loading and wind driven rain conditions are proposed.

2. DYNAMIC EVALUATION

2.1 Dynamic Process

Building envelopes are designed to separate the controlled indoor environment from the uncontrolled outdoor environment. The building envelope consist of such assemblies as the: wall, roof, window and basement. Each assembly has its unique performance requirements and functions. The outdoor environment involves several parameters which may act as dynamic driving potential (Figure 1). These include:

- wind
- rain/snow
- temperature
- solar Radiation
- earthquake
- noise.

Driving potentials may act independently or combined, for example, wind-driven rain conditions. Their intensity depends on the geographical location and seasonal conditions. [Figure 1](#) specifies weathering parameters, for summer and winter, for cold climate cities such as Ottawa. The designer has to select and design the envelope to withstand these driving forces. All of the driving potentials listed above are dynamic in nature. For example, let us take the wind-induced pressures on a building. It depends on parameters such as:

- wind speed and turbulence intensity
- wind direction and flow stability
- building topography
- building geometry
- architectural features such as exposed mullions and parapets

Figure 1 Building envelope components and driving potentials

[Figure 2](#) illustrates the effect of one such parameter building height on the pressure coefficient. Pressure traces measured in the wind tunnel are shown on the roof of two buildings with the same cross sectional area but of different height. One building is 12 m high considered as low building and the other building is 96 m high representing a tall building. Pressure fluctuation varying with respect to time is shown in the figure. The random nature of the pressure fluctuations are higher in the case of the taller building.

Wind-induced pressure on the same building will be different on different building faces. This has been illustrated in [Figure 3](#) where the pressure fluctuations on the faces of a building namely windward wall, leeward or back wall and side wall are presented. It is clear from the figure that the wind induces, mostly, positive fluctuations (pressures) on the windward wall and creates suction (negative) fluctuations on the leeward and side walls. This is mainly because when wind flows around the building it creates different type of flow pattern on different sides of the building. In this case, wind blows perpendicular to the building and forms stagnation on the windward side. It starts separating from the windward wall edges and thus the side faces of the building are in the separated region. Recirculations are developed at the back side of the building creates low intensity suction forces. What is clear from the Figures 2 and 3 is that the wind effects on buildings varies with respect to time as well as location (space). In other words the wind flow conditions around buildings and wind-induced effects on the buildings have dynamic characteristics. Similar arguments can also apply for other driving forces that will act on the building envelope. Processes of this nature are called "dynamic process". So the building facade has to be evaluated in the laboratories simulating simultaneously all or most of the forces.

PRESSURE TRACE

Figure 2 Effect of building height on wind-induced pressure fluctuations [1]

Figure 3 Pressure variations on the walls of the buildings [2]

2.2 Need for Dynamic Evaluation

Wind tunnel testing of tall buildings to quantify the wind induced effects are no more uncommon in the design stages of buildings. However, the performance prediction of the individual assemblies such as walls cannot be identified by means of wind tunnel testing alone. This warrants the testing of full scale building envelopes in the simulated dynamic environment. This testing provides many benefits, of which few are discussed below.

The dynamic evaluation will provide:

- information about the performance of the design and may disclose design and fabrication weaknesses and suggest potential improvements
- air leakage rate of the tested wall system
- structural adequacy of the assemblies and anticipated deflection on the joints and other required locations

- joint and seal performance against water tightness
- realistic fastener loads to prevent backout or pullout due to excessive fastener loading
- load distribution on roof with various deck types
- fatigue behavior of fasteners, deck and attachment systems
- effect of temperature variations on the membrane strength
- effectiveness of the thermal breaks and thermal insulation;
- official evidence and certification of the adapted design

3. RESEARCH FACILITIES FOR DYNAMIC EVALUATION

Dynamic evaluation of a building envelope assembly requires selection of a test specimen with sufficient size and necessary details. Proper knowledge and simulation of the external forces is equally important. Thus designing and constructing an appropriate experimental facility for dynamic evaluation of the building envelope is complex. As described in CIB -W61 working commission reports [3], only a few international facilities are documented for the dynamic simulation of wind and wind driven rain conditions. Three of them were examined for test procedures for rain penetration control (Section 3.1), structural performance (Section 3.2) and the combination of both (Section 3.3).

3.1. SIROWET Facility

CSIRO Wall Exposure Test (SIROWET) is one of the earliest facility for the dynamic evaluation of the building envelope [4]. The portable facility consists of a water-tight and air-tight pressure box, 7 m high by 5 m wide that is made of glass fiber reinforced polyester panels, in modules of 1 m, assembled by bolting the panels together. Laminated timber beams 85 mm x 345 mm and 6.5 m long are used at 1 m centers to hold the box to the test wall. The chamber is assembled with the test specimen through a mating surface. The assembly is pressurized by two centrifugal blowers that supply air at the rate of 940 l/s at 3.5 kPa. A uniform cyclic pressure condition is created using a butterfly valve controller. A water spray system, which is placed inside the assembly at the back of the pressure box, consists of square spray nozzles located on a 1 m grid.

A typical test sequence for evaluation of rain penetration control has three steps ([Figure 4](#)):

1. Wetting period
2. Static testing with 300 Pa pressure difference
3. Dynamic testing with maximum pressure

For all steps the water is sprayed at a constant rate of 3.4 l/min/m². For Step 3, the test pressure is based on the design requirements. The maximum operating pressure of the SIROWET facility during rain penetration tests is about 1.2 kPa and only positive pressure can be applied.

3.2. BRERWULF Facility

BRE Real time Wind Uniform Load Follower was designed by the Building Research Establishment, UK [5]. It is portable and can be incorporated into any test chamber to which the test specimen is attached. BRERWULF is designed to reproduce a long term history of wind pressures for evaluating the structural performance of the building envelope, primarily roofs. Pressure on the test specimen is developed by a centrifugal fan which circulates air through a control valve such that the pressure can be varied using either a static or dynamic controller. With the static controller the pressure can be ramped and the rate can be adjusted. With the dynamic controller the pressure may be derived from a file containing data such as field-monitored wind pressure data, data collected from a wind tunnel or data forming a sinusoidal wave. The target trace is sampled and normalized with the peak value corresponding to the design value in the range ± 8.5 kPa.

Figure 4 Typical SIROWET sequence for water penetration test [4]

Figure 5 BREWULF system response on a roof specimen [5]

The system was tested on a 5 m x 5 m roof specimen attached to a 4.25 m³ test chamber. Typical loading traces are shown in [Figure 5](#). It is clear from the figure that the system can reproduce pressure fluctuations with a negative peak of -1.8 kPa, for the driving function which had -2.0 kPa as the negative peak. This was true when the operating frequency of the controller was 0.5 Hz. Increasing the frequency to 2 Hz produced only half of the targeted pressure peak.

3.3. Dynamic Wall Testing Facility

The Dynamic Wall Testing Facility (DWTF) was designed by the National Research Council of Canada initially to study the performance of glass under the effect of wind loading [6]. Dynamic wind pressure is simulated in the DWTF by displacement of a 2.36 m diameter piston which forms part of the back wall of the facility. A 2.44 m x 2.44 m test specimen forms the front wall of the facility. The piston can generate amplitudes up to 3 kPa with sinusoidal, triangular or square pressure waves at frequencies from 0.01 Hz to 5 Hz or follow pre-recorded wind pressure data. A secondary blower maintains the steady state component of the pressure. A spray rack can supply water at rates up to 10 l/min/m².

Structural performance of the wall assembly is evaluated in the DWTF by applying a series of 0.5 Hz sinusoidal pressure variations to the exterior face of the specimen. The applied pressure increases in magnitude in a controlled manner representing that of wind storms up to the design wind load for the specimen. Rain penetration control performance is assessed at two levels. The 'face seal' value of the rainscreen, i.e., the ability of the exterior cladding to control rain penetration, is quantified by performing a static test with a continuous spray of water applied to the exterior surface of the rainscreen alone. Air pressure difference is applied in increments of 200 Pa up to 1000 Pa and the rainscreen is examined for water penetration. Rain penetration control of the complete wall assembly, i.e., the ability of all rain penetration control features working together to control rain penetration, is evaluated in three steps:

1. Static air pressure difference of 1000 Pa applied for 4 hours,
2. Cyclic air pressure difference applied at a frequency of 0.5 Hz for 1 hour,
3. Cyclic air pressure difference applied at a frequency of 1.0 Hz for 1 hour.

Each step is performed with water sprayed on the test specimen at a rate of 3.4 l/min/m².

3.4. Discussion

A comparison of the performance of the facilities is presented in [Table 1](#). Four factors were selected for the comparison: specimen size, operable pressure levels, water spray rate and mechanism used to model dynamic behavior. All values represent the maximum limit of the facilities. Each facility has its strengths and weaknesses. The SIROWET facility evaluates facades about 2 story's high and 1 bay wide and is limited to a constant water spray rate of 3.4 l/min/m². The BRERWULF, which can reproduce the designed targeted pressure trace, does not include a wind driven rain simulation capability. The DWTF is not portable and is limited to test specimens 2.44 m on a side but can simulate a range of pressure variations as well as undertaking rain penetration evaluations for water spray rates up to 10 l/min/m².

Table 1. Performance comparison of the dynamic testing facilities

Facility	Specimen Size (m)	Test Pressure (kPa)	Water Spray (l/min/m ²)	Dynamic Mechanism
SIROWET	7 X 5	3.0	3.4	3-5 sec. cycles of peaks
BRERWULF	5 x 5	8.5	N/A	Controllable rate with a minimum period of 0.1 sec.
DWTF	2.44 x 2.44	3.0	10	Sinusoidal loading up to 5 Hz

4. PROPOSED EVALUATION PROCEDURES

This section systematically examines the requirements for laboratory simulation of the two driving forces, wind and wind driven rain conditions. Another equally important factor, which is beyond on the scope of the paper, is the selection of test specimen details. For an example to represent the integrated performance of a wall assembly on buildings, it is necessary to select the test specimen with similar joint configurations. Similarly parapet wall junction's detail needs to be considered in selecting a roof test specimen.

4.1. Wind Simulation

Wind is random in nature. Attention must be paid to simulate both the required amplitudes (pressure level) and the pressure variations with respect to time (frequency). [Figure 6 \(a\)](#) shows a typical wind pressure fluctuation and its simplified representations used in the facilities described above. One of the best methods among the simplifications is cyclic loading with sinusoidal formulation. This is because a dynamic wave form such as wind-induced pressure fluctuations can be reconstructed using sine waves of different frequencies and amplitudes.

Figure 6 Simplified representation of wind pressure used for testing

Evaluating the envelope assembly for high pressure alone does not identify how quick or slow that pressure varies with time on the assembly. Indeed to describe the process in time, wind spectral density functions are necessary. [Figure 6 \(b\)](#) shows the energy levels and gust frequencies of the mean wind speed. Energy levels are significant up to about 10 Hz in the wind spectrum. The reviewed research facilities attempt to simulate wind fluctuations within this range of 10 Hz. American Architectural Manufacturers Association, AAMA [7] uses an aircraft engine to simulate wind flows. The aircraft facility may provide a clear visualization of the flow aerodynamics during testing. However, as discussed in the ref. [8] basic wind simulation criteria such as vertical distributions of mean wind velocity, variation of longitudinal turbulence intensity and power spectrum of the mean wind speed are not quantified and documented by the AAMA procedure. Thus, it may not simulate the frequency range of the turbulent winds acting on the building envelope. The National Building Code of Canada [9] recommends that cladding be designed for 3-5 sec gust pressure. In Canada, field monitoring on a high rise building [10] measured gusts lasting for 0.1 to 1 second. Pressure measurements on both low-rise and high-rise buildings in Britain [11] indicated a 3 second wind gust. Therefore, evaluating up to 10 Hz will represent the dynamic behavior of wind effects on buildings.

It is preferable to have a test facility in which the pressure level (magnitude) and the cycling rate (frequency) can be varied. Another acceptable way of obtaining this combination is simulating the design pressure levels at various frequencies. In this case, the building envelope has to undergo a series of tests, each one corresponding to a particular frequency. Then dynamic performance evaluation under wind conditions can be achieved by the following four step procedure:

- Step 1: Select the appropriate dynamic wind pressure for the building location from the building code or wind standards.
- Step 2: Determine the recommended pressure coefficient value for the building assembly. (For a building with unusual shape, this value may be obtained through wind tunnel testing.)
- Step 3: Calculate the test pressure (= pressure coefficient x dynamic wind pressure from step 1)
- Step 4: Simulate a condition with the test pressure calculated in Step 3 and repeat the evaluation for various frequencies.

4.2. Wind-Driven Rain Simulation

Results from wind tunnel testing have contributed significantly to the understanding of building aerodynamics. However, since few studies have been made for wind driven rain conditions, the dynamics of the wind driven rain conditions are less well known. This raises two questions on existing dynamic test procedures:

1. What is the required test pressure level for evaluating the wind driven rain condition?
2. How much water must be sprayed on the test specimen in order to represent the rain fall on the building?

Current requirements taken from different standards are compared in [Table 2](#). The recommended test pressure levels range from 137 Pa to 700 Pa. A constant water spray rate of 3.4 l/min/m² is recommended by ASTM E 547 [12] and it reflects a rainfall rate of about 200 mm/hour. This specification has been followed

by other standards and organizations. Canadian window standards [13] attempted a systematic approach for wind driven rain testing of windows. It recommends a test pressure derived from the mean wind velocity and mean rain fall rate. The standard does not provide explicit recommendations for the water spray rate.

Britain [14], Canada [15] and Denmark [16] have attempted to quantify the rain fall intensity through a driving rain index. The driving rain index [16] has two main uses : as an indication to designers and architects of the severity of the exposure of the site of the proposed building and as an indication of the condition to which the wall specimen should be evaluated in a driving rain test facility. The driving rain index can be correlated to the driving rain rate on a vertical surface. Lacy [16] proposed a relationship of:

1 mm of driving rain on a vertical wall = 206 x driving rain index Recently Henriques [17] proposed a relationship of:

$$100 \text{ l/m}^2 \text{ of driving rain on a vertical wall} = 1 \text{ driving rain index.}$$

For Canada, Welsh et al [18] recommended three zones for rain intensity as follows: sheltered region with maximum driving rain index of 3; moderate region with maximum driving rain index of 7 and severe region with maximum driving rain index of 13. By applying the relationship proposed by Lacy [16] and assuming a 4 hour testing period, the required water spray rate to represent the sheltered, moderate and severe regions are respectively 2.5, 6 and 11 l/min/m². This clearly reveals that using a constant spray rate of 3.4 l/min./m², as recommended in [12], is not appropriate in representing all local dynamic wind driven rain conditions.

Table 2. Current standard specification for water penetration testing

Standard	Test Pressure (Pa)	Water Spray (l/min/m ²)
AAMA 501	575	3.4
ASTM E 547	137	3.4
CAN-A440-M	700	As per ASTM E 547
European	500	1
JSI A 1517	490	4

On the basis of the above discussion, the following three step procedure is proposed for dynamic evaluation of performance under wind driven rain conditions:

- Step 1: Select the test pressure from standards such as [13] for the driving rain wind pressure.
- Step 2: Calculate the required water spray rate from the driving rain index.
- Step 3: Simulate a condition with the above test pressure and water spray rate and repeat the evaluation for various frequencies.

5. SUMMARY

The paper presented the continuing need to evaluate the dynamic performance of envelope systems for wind and wind driven rain conditions. After studying the literature, reviewing the research facilities and examining the existing standards, the paper also proposed procedures for the dynamic evaluation of the envelope systems under wind and wind driven conditions.

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