WATER INFILTRATION THROUGH OPENINGS IN A VERTICAL PLANE UNDER STATIC AND DYNAMIC PRESSURE CONDITIONS

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ABSTRACT

Moisture is the cause of many building deterioration problems, and rain is the prevalent source of moisture to building envelopes. Little information has to date been published on the mechanisms of water infiltration through openings in facades that also includes quantitative information to help demonstrate infiltration phenomena. A better understanding of the mechanisms that govern water entry through openings present on vertical surfaces such as cladding will lead to improvement in watertightness performance of building components, provide enhanced knowledge of boundary conditions needed to complete hygrothermal simulations, and render a more scientific approach to the design watertightness test protocols. In this paper, a quantification of the driving forces is offered and qualitative analyses of interacting phenomena is presented that help characterize water ingress through openings in facades. Experimental research was done on two types of openings in a vertical polycarbonate plate similar in configuration to deficiencies on exterior cladding: round holes (1 mm, 4 mm and 8 mm diameter), and three slits (2 mm wide, under different angles). These deficiencies made in the plate had dimensions calculated to cover a range of capillary pressures and these were subjected to a simulated wind driven rain by means of pressure differences and water spray. Pressure differences of 0, 200, 400, 600 and 800 Pa were applied, in combination with typical water spray rates used in test protocols (2.0 L/min.-m² and 3.4 L/min.-m²).

The driving forces for water ingress are gravity, pressure differences, kinetic energy of film flow, capillary action and the surface tension of the meniscus. The capillary pressure at a specific temperature is mainly determined by the dimensions of the deficiencies and the contact angle of water on the substrate. The results of the experiments clearly indicated that the capillary pressure introduced a threshold for water ingress: water entry rates were predominantly defined by the geometry of the deficiencies in relation to the contact angle. Furthermore, the surface tension of the meniscus on the interior side of the front plate defines a pressure threshold that strongly affects the way water may infiltrate through openings; and it offers interesting insights in the effect of static and dynamic boundary conditions on infiltration rates.

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INTRODUCTION

Moisture is the cause of many building deterioration problems, and rain is the prevalent source of moisture to building envelopes. Several studies have been published that relate to water infiltration of building facades. These include: (i) studies derived from investigations in the field and hence provide some insight into the significance of the types of problem that ensue due to water infiltration into wall assemblies [1-5], and; (ii) those carried out under laboratory conditions that attempt to quantify the degree of water entry in relation to simulated climate loads [6-8].

In respect to field studies, there are a number of reports on the effects of water intrusion on wall assemblies of homes located on the coastal areas of Canada, an example of which is the survey of building envelope failures in the coastal region of British Columbia [1]. The information in this study indicated that 25% of the moisture problems associated with water ingress into wall assemblies were directly attributed to penetration through the windows or the window-wall interface. In the USA one might cite the work of Crandell and Kenny [2] in which moisture damage in single-family homes was investigated for the coastal city of Wilmington, NC. Of course the issue of building envelope failure is not limited to coastal climates. For example, numerous recent failures of newly constructed building envelopes have occurred in the state of Minnesota [3]. The building inspection division of the town of Woodbury has reported that an appreciable number of homes built since 1990 have experienced major durability problems. Specifically, 276 of 670 stucco homes built in Woodbury in 1999 (ca. 41%) experienced severe within-wall damage within six years. The primary causes for failure were window leaks, lack of kick out flashing at eave ends of roof-to-wall junctures, and improper deck flashing [2]. Cautley [4] also found that water intrusion associated with windows can occur in contemporary residential buildings in an upper Midwestern state. Likewise the CMHC undertook studies to assess the extent of damage to Alberta homes [5]. Hence there is considerable information available regarding the prevalence of rain water related moisture problems of wall assemblies across North America and hence the importance of rain as a source of moisture to walls. This in part has spurred several laboratory studies on assessing the risk to premature deterioration of wall assemblies from water entry.

Laboratory testing may also provide a measure of the expected risk of moisture related problems due to water entry. Such studies have been completed for EIFS wall assemblies [6], [7] following local investigations on their in-situ performance [2]. Water entry testing of several different types of wall assemblies was completed in the NRC-IRC Moisture Management for Exterior Wall Systems Consortium (MEWS) [8] in which stucco, exterior insulated finish systems (EIFS), brick veneer and hardboard and vinyl siding clad assemblies were subjected to simulated wind-driven rain test conditions. In some of these assemblies, water entry through deficiencies in the cladding at location of penetration such as a ventilation duct, electrical outlet or window, was determined as a function of simulated wind-driven rain loads (i.e. pressure difference across wall specimen and water spray rate applied to the exterior cladding). In this same test series, testing was also completed on an 8-ft. square cladding assembly consisting of a set of three parallel vertical Plexiglas panels affixed to a 2 by 4-in. wood fame, the intent being to replicate the configuration of a typical wood frame wall and be able to view the entry and path of water migration through the assembly at points of water entry given that the panels were transparent. In this wall, three through wall penetrations were installed including a window, a ventilation duct and an electrical outlet (Figure 1). Openings above the ventilation duct and electrical outlet were purposely included in the assembly to emulate deficiencies that might occur in a typical installation (e.g. missing bead of caulking at the perimeter of the duct or outlet). A means to collect water directly behind the cladding permitted determining water entry rates in relation to water loads deposited on the exterior cladding. An example of the data collected for water entry through a 1-mm by 45-mm deficiency located above an electrical outlet is provided in Figure 2. Rates of water entry in L/min. are presented as a function of static differential chamber pressure for water spray rates ranging from 3.9 to 6.1 L/min-m^2.

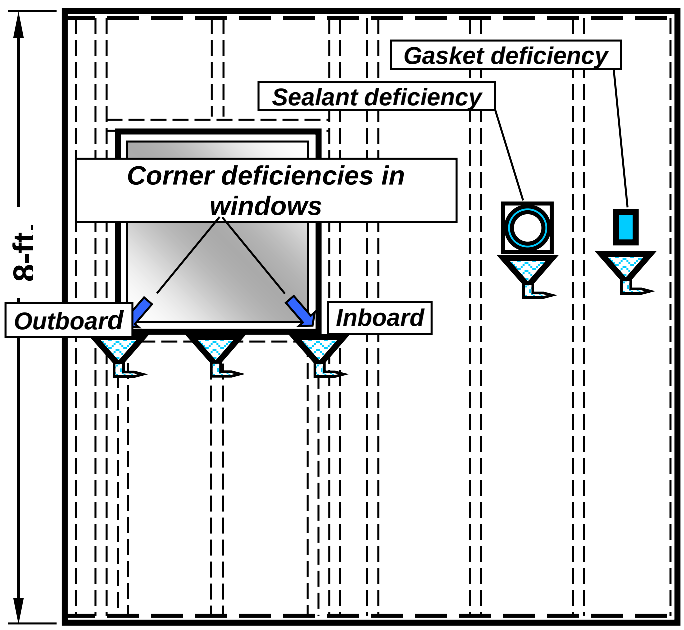

FIGURE 1: Schematic of wall assembly in which were located a window, a ventilation duct and an electrical outlet; a purposely placed deficiency above the electrical outlet consisted of a missing length of caulking (45-mm) that offered an opening of 1 mm by 45 mm [8]

From the information provided in Figure 2 it is apparent for this size of deficiency (i.e. 45-mm^2) that, in general, there is an increase in the rates of water entry for increase in differential pressure at the four different spray rates at which tests were conducted. This is however more prevalent for tests conducted at the lowest and highest water spray rates as these appear to be monotonic functions of the chamber pressure whereas for the intermediate spray rates this phenomena is not apparent. It also appears that higher spray rates yield greater rates of water entry at given pressure levels. Finally, water entry is evident when no pressure is applied across the assembly; entry occurs under gravity alone.

Although entry rates have been provided for given water spray rates and pressure differences across the test specimen and the prevailing air leakage conditions across

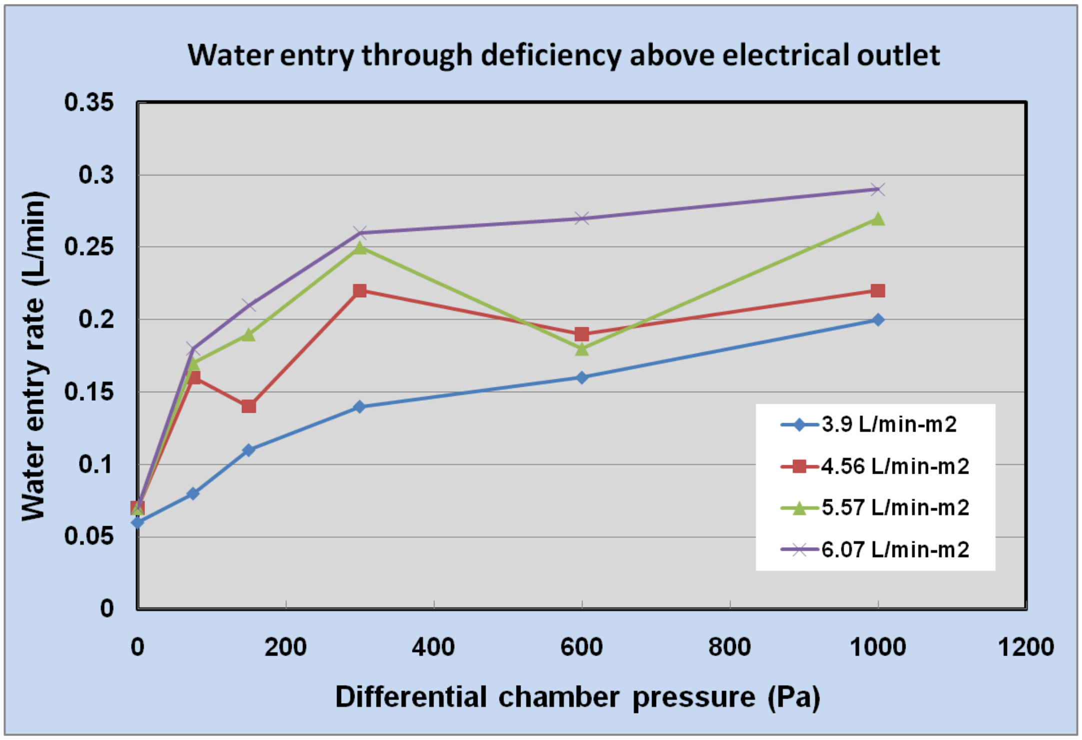

FIGURE 2: Water entry rates through deficiency above electrical outlet for given water spray on the exterior cladding and differential chamber pressures

the test specimen, the information provided is only useful for the given size of deficiency, the location of the deficiency in relation to the water deposition conditions (i.e. water flow upstream of deficiency), and the tendency for water to stool at the deficiency and related attributes that contribute to water entry at an opening.

Carll [9] has made the point regarding the need for additional information related to moisture loads on buildings and the need to characterize the degree of water entry in relation to such loads. Although some work has indeed been completed in regards to generating such information, as previously described in this paper, little information has to date been published on the mechanisms of water infiltration through openings in facades that also includes quantitative information to help demonstrate infiltration phenomena.

This paper offers an overview and quantification of the driving forces and qualitative analyses of interacting phenomena that help characterize water ingress through openings in a vertical plane. Experimental research was done on different types of openings of varying geometric configuration (refer to figure 4), and subjected to a range of pressure differences and water deposition rates that simulated wind-driven rain conditions on a facade. Additionally, the sensitivity of the results is demonstrated for various features of the test setup such as spray nozzle type, uniformity of water film formation and significance of prior wetting of the vertical surface.

EXPERIMENTAL

Overview

An experimental program was developed in which a test specimen (with openings through which water might enter) was subjected to simulated wind driven rain conditions for a specified test period. Over a test sequence the pressure difference across the external vertical plane (polycarbonate plate) of the specimen, the water spray rate onto the plane and the degree of air leakage were controlled and recorded. A description of the test apparatus, test specimen, and the test protocol is provided in the subsequent sections.

Test apparatus and specimen

Test apparatus — The test apparatus, a schematic of which is shown in Figure 3, consists of two adjoining sections each 610 mm square by 230 mm deep (2 ft. ☐ by 9 in.) aluminum frames. In one frame the test specimen (described below) was placed, and the other was used as pressure chamber in which the water spray nozzle (BEX F series; model 1/8F11003) was located. Static pressure in the chamber affront of the external plate was maintained by an air blower (Shop Vac®, model QUM650) and under static pressure conditions, test specimens could be subjected to pressures upwards to 1kPa. Dynamic pressure fluctuations were applied with the use of a computer controlled electro-mechanical pressure actuator (Intempco i-Actuator; model: 001-0408) that imparted sinusoidal pressure fluctuations on the specimen. The frequency of the pressure fluctuation could also be selected between a range of 0.1 and 2 Hz. Variations in the mean pressures were provided by the constant flow air blower. Using the pressure actuator together with air blower to maintain chosen mean pressure levels, dynamic conditions could, for example, be applied with mean pressures of 400 or 600 Pa and pressure variations ranging between ± 80 to ± 480 Pa at a selected frequency.

Pressure taps were placed in the pressure chamber as well as in the cavity between the external and internal plates and a pressure sensor (GE Druck LPM1110 1.25 kPa ± 1 Pa) measured the differential pressure applied across the external plate.

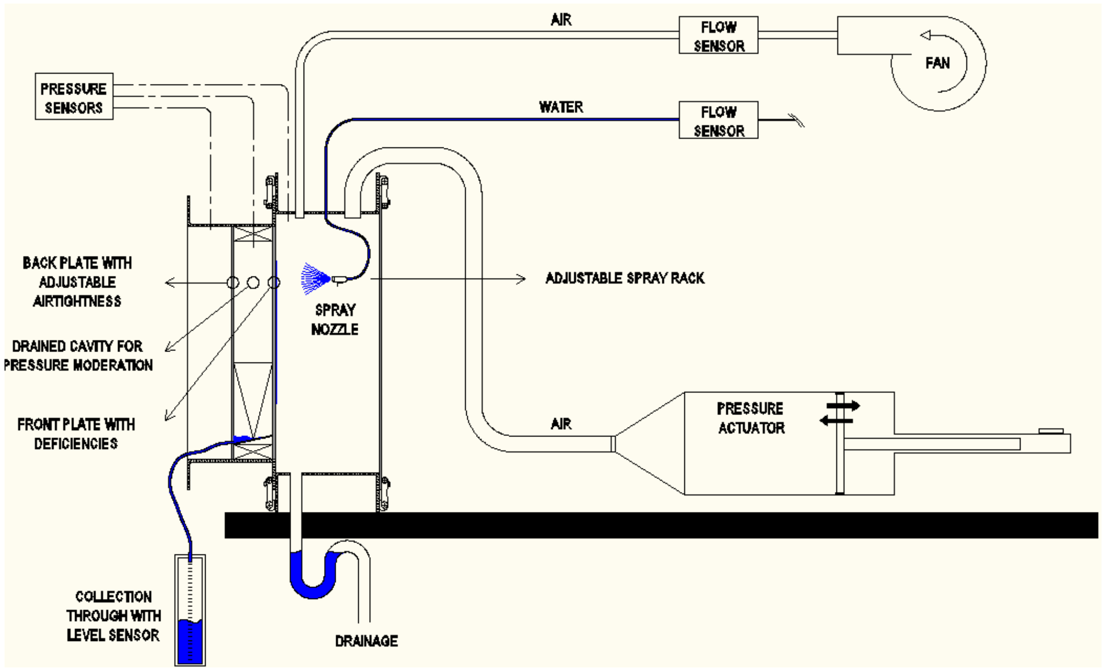

FIGURE 3: Test apparatus schematic

The air leakage rate of the test specimen (L/s-m^2) was determined with the use of a laminar flow element (MIRIAM Model 50MW20-1F) from the application of selected pressure differences across the test specimen and reported at 75 Pa.

Water spray was applied to the external plate of the specimen in known quantities by varying the water pressure applied to the water spray nozzle. The volume flow rate to the nozzle was known (Kobold model: DPM1170N2F300), but as well, the nozzle spray rate (L/min-m^2) was calibrated gravimetrically from the collection of water to a vessel over a specified period of time. Water nozzles could provide spray rates of 2.0 and 3.4 L/min-m^2.

The scenario investigated in this study was that of water runoff from a 3m window, the height corresponding to typical floor heights in office buildings, and considered representative of conditions found at interfaces located at storey-high components in façades such as for example, floor-to-ceiling windows and prefabricated rainscreen panels. To replicate these conditions, it was determined that a flat fan axial spray nozzle produced a sharply defined linear spray pattern with a uniform liquid distribution on the plate. As this work only focused on infiltration due to the effect of water runoff, and not the effect of direct impingement of water drops, the water spray was pointed at the location just above the deficiencies in the exterior plate (lower point of impact area about 20mm above the top of the deficiency. This produced a very uniform runoff that was stable when it reached the deficiencies (without formation of rivulets or fingering) and thus allowed converting the water spray rate intensity (L/min-m^2) to a water runoff intensity (L/min-m), taking into account the width of the impact area on the specimen. Given the constant rate of water flow provided to the nozzle, the variation in water runoff intensity was accomplished by varying the distance of the nozzle from the exterior plate for each spray rate condition (i.e. nozzle position to achieve 3.4 L/min-m^2 was closer to the exterior plate than the position to obtain a spray rate of 2.0 L/min-m^2).

A PC based control system (Intempco) was used to monitor, display and acquire data; pressure, water flow rate and water collection rates were continuously monitored over the course of a test sequence at a rate of 10 Hz.

Test specimen — A schematic of the test specimen is shown in Figure 4.

The specimen was comprised of two parallel polycarbonate plates, the plates being affixed to either side of a 38 mm by 100 mm (2-in. by 4-in) wood frame and the entire assembly being housed in a 610 mm square by 229 mm deep (2- ft. □ X 9-in) aluminum frame. The cavity between external and internal plates was 100 mm (4 in.) the depth of the wood stud, the external plate being affixed to the front of the stud and the interior plate to the backside of the stud. The exterior plate was exposed to water spray and the internal plate acted as an air barrier.

Different types of openings placed in the external plate were meant to replicate deficiencies that can be found in cladding systems, as depicted in Figure 4; these included a series of round holes, respectively, of 1 mm, 4 mm and 8 mm diameter, located at 267 mm from the bottom of the test specimen, and oblique slits (offset 30° and 60° with the horizontal) of 2 mm width and having lengths of 70 mm (30° slit) and 120 mm (60° slit) respectively. The slits were located at 457 mm from the bottom of the specimen. Openings placed in the interior plate permitted controlling the degree of air leakage through the air barrier.

The size of openings in the exterior plate was selected on the basis of water occluding, or not, the opening by capillary action given flow of water across the opening, with smaller holes providing a greater capillary effect. The capillary pressure effect, based on the Young-Laplace equation, was calculated for the different diameters:

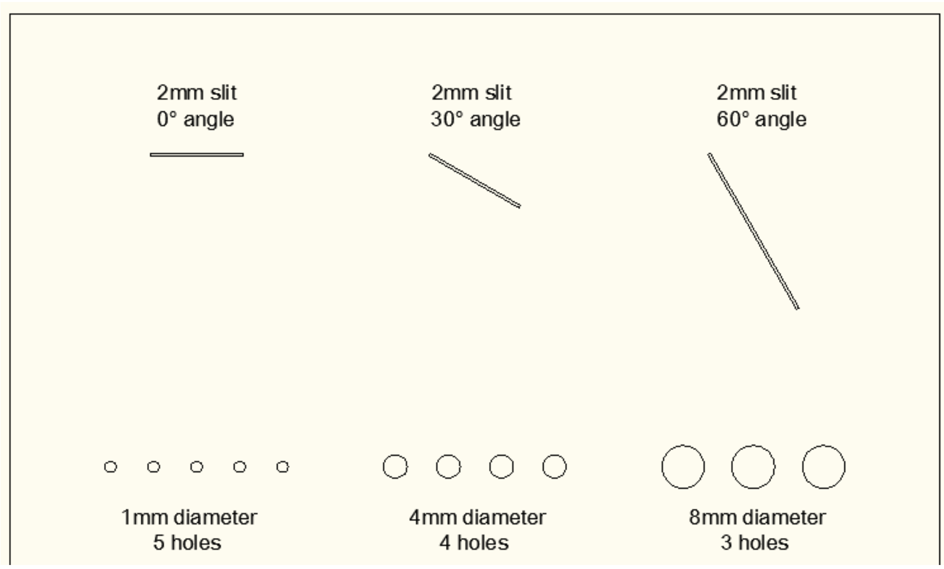

FIGURE 4: Schematic of test specimen (front side, deficiencies not on scale for clarity)

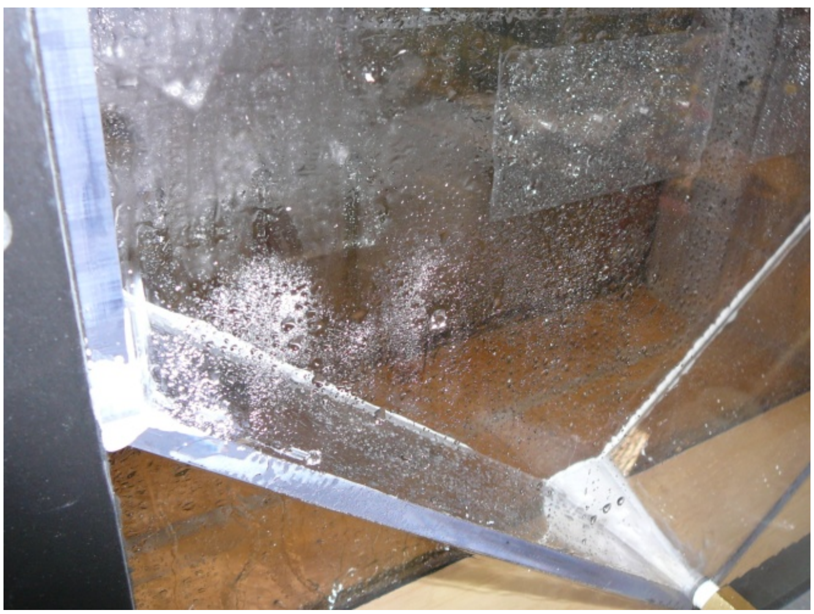

FIGURE 5: Water drainage from test specimen and accumulation in collection vessel

Test protocol

The test protocol consisted of: (i) pressure characterization tests to adjust the control system for the air blower (static pressure) and pressure actuator (dynamic sinusoidal pressure) to achieve the specified differential pressure across the external plate in relation to the number, the size of deficiencies, and air leakage conditions across the interior plate; for dynamic pressure test conditions, the frequency was also varied (ii) subjecting the external plate, in which deficiencies were placed, to selected water spray rates, and differential pressure (static or dynamic) and air leakage conditions, as provided in Table 1 and Table 2.

The deficiencies were subjected to simulated conditions of wind driven rain by means of pressure differences applied across and water spray deposited onto the external plate. The water spray rate intensities applied in the test program corresponded to those typically specified in test protocols (i.e. 2 L/min-m² for European standards, whereas North American standards use 3.4L/min-m²) [10]. Air leakage conditions were selected to provide a measure of the effect of increased leakage in the air barrier system (interior plate) on the degree of water entry through deficiencies; hence air leakage test conditions included a set, nominally, for which no air leakage was present and a set for which some air leakage was included as defined by the area (mm^2) of openings in the interior plate.

For the dynamic tests, the amplitude of pressure fluctuations was determined based on the desired mean pressure of either 400 or 600 Pa. For each installation 4 amplitudes were considered: 20%, 33%, 50% and 80% of the mean pressure. Test sequences, undertaken in either dynamic or static conditions, lasted for at least eight (8) minutes so that data could be averaged over at least a 6 minute interval. The tests were conducted only once.

Test program

Information on the test program described in this paper is given in Table 1, Table 2 and Table 3. In Table 1, the test conditions are given under which dynamic pressure characterisation were completed. It provides the dynamic pressure conditions, frequency of the sinusoidal pressure function and air leakage conditions, together with the area of the opening for air leakage for each of the two different deficiencies for which tests were conducted.

In Table 2 is given information on the water entry test program under static pressure conditions; for each of the three deficiency sizes tested is given the water spray rate, differential static pressure conditions and air leakage condition. The range of pressure differences (0-800Pa) covers those pressures typically found in standardized test methods for assessing the watertightness of different building components [8], which in turn are designed to relate to realistic boundary conditions. For this series of tests, the air leakage conditions provided the greatest degree of leakage across the air barrier.

The water entry test program under dynamic pressure conditions is provided in Table 3. For each of the two deficiency sizes tested are given the water spray rate, dynamic differential pressure conditions across the external plate, frequency of the sinusoidal pressure function and the air leakage condition. Results are only given for the tests conducted at a frequency of 1 Hz; the results from tests undertaken at the other three frequencies will be published elsewhere.

TABLE 1: Dynamic pressure characterisation of test specimen

	Testing conditions			
Deficiencies	**Dynamic pressure conditions (Pa)**	**Pressure function frequency (Hz)**	**Air leakage condition**	**Air leakage opening (mm^2)**
3 X 8 mm Ø ($150.8\ mm^2$)	400 ±200	0.2, 1.0	1 X 1 mm Ø	0.785
			5 X 1 mm Ø	3.93
			1 X 4 mm Ø	12.6
			2 X 4 mm Ø	25.1
			1 X 8 mm Ø	50.3
			1 X 4 mm Ø + 2 X 4 mm Ø	37.7
			1 X 8 mm Ø + 2 X 4 mm Ø	75.4
		0.2	All open	79.3
	400 ± 80, ±133, ±200, ±320	0.1, 1.0	Nil	~0
		0.1, 0.2, 1.0	2 X 2 mm Ø	6.28
			1 X 4 mm Ø	12.6
			2 X 4 mm Ø	25.1
4 X 4 mm Ø ($50.3\ mm^2$)	400 ± 80, ±133, ±200, ±320	0.1, 1.0	Nil	~0
		0.1, 0.2, 1.0	2 X 2 mm Ø	6.28
		0.1, 0.2, 1.0	1 X 4 mm Ø	12.6
		0.1, 0.2, 1.0	2 X 4 mm Ø	25.1

TABLE 2: Water entry test program under static pressure conditions

Static pressure test conditions	Testing conditions		
Deficiencies	Water spray rate (L/min-m^2)	Differential static pressure conditions (Pa)	Air leakage condition (mm^2)
5 X 1 mm Ø ($3.93\ mm^2$)	3.4	400, 600, 800	79.3*
4 X 4 mm Ø ($50.3\ mm^2$)	2.0	0, 200, 400, 600, 800	79.3
	3.4	0, 200, 400, 600, 800	79.3
3 X 8 mm Ø ($150.8\ mm^2$)	2.0	0, 200, 400, 600, 800	79.3
	3.4	0, 200, 400, 600, 800	79.3

* all openings open (5 X 1 mm Ø, 2 X 4 mm Ø, 1 X 8 mm Ø)

TABLE 3: Water entry test program under dynamic pressure conditions

Dynamic pressure conditions	Testing conditions			
Deficiencies	Water spray rate (L/min-m^2)	Dynamic pressure conditions (Pa)	Pressure function frequency (Hz)	Air leakage condition (mm^2)
4 X 4 mm Ø (50.3 mm^2)	2.0	400 ± 80, ±133, ±200, ±320	0.1, 0.2, 0.333, 1.0	< 0.1
				25.1*
		600 ± 120, ±200, ±300, ±480	0.1, 0.2, 0.333, 1.0	< 0.1
				25.1
	3.4	400 ± 80, ±133, ±200, ±320	0.1, 0.2, 0.333, 1.0	< 0.1
				25.1
3 X 8 mm Ø (150.8 mm^2)	2.0	400 ± 80, ±133, ±200, ±320	0.1, 0.2, 0.333, 1.0	< 0.1
				25.1
		600 ± 120, ±200, ±300, ±480	0.1, 0.2, 0.333, 1.0	< 0.1
				25.1
	3.4	400 ± 80, ±133, ±200, ±320	0.1, 0.2, 0.333, 1.0	< 0.1
				25.1

* air leakage openings of 2 X 4 mm Ø

RESULTS

Test results derived from water entry through deficiencies are first provided for those tests sequences undertaken under static differential pressure conditions and thereafter for tests completed under dynamic pressure test conditions.

Results of water entry under static differential pressure conditions

Test results for water entry rates through the three specified deficiencies under conditions of static pressure differential and subjected to two different water spray rates are given in Figure 6. The sequence of testing was such that those tests having nominally the largest deficiency and the highest spray rate were first conducted (i.e. those for deficiencies of 3 X 8 mm Ø) from the lower to the higher pressure difference; thereafter for the same deficiency, the lower spray rate was applied. As is evident from a review of the results, increasingly less water was collected at smaller deficiencies and at the reduced spray rates. Hence, no tests were conducted at a spray rate of 2 L/min-m^2 for the smallest deficiency (5 X 1 mm Ø) since little or no water had been collected at a pressure difference of 400 and 600 Pa at the next higher spray rate for this same deficiency size.

What may be evident from these test results is that a greater rate of water entry was observed through deficiencies if the spray rate applied to the deficiency was increased; hence for the 4 X 4 mm Ø deficiency increases in water entry rates, respectively, of 80 and 45% were evident for applied pressures 600 and 800 Pa when the spray rates increased from 2 to 3.4 L/min-m^2.

This phenomena was likewise evident for the larger deficiency of 3 X 8 mm Ø; increase in water entry rates was evident at every pressure step with increasing water spray rates (i.e. respective increases of 35, 46, 57, 47% at pressure steps of 200, 400, 600 and 800 Pa). Water entry was evident for this deficiency when no pressure was applied across the exterior plate at both water spray rates. An increased rate of entry was also observed at the higher spray rate when no pressure was applied

There are also increases in water entry rates with corresponding increases in pressure difference across the assembly. This is not however apparent for all test conditions but most evident for the larger deficiency of 3 X 8 mm Ø. In this instance, rates of entry at a water spray rate of 2 L/min-m^2 increased monotonically from 1.5 to 27.2 mL/min over a pressure range from 0 to 800 Pa (just over 1 order of magnitude); likewise for a spray rate of 3.4 L/min-m^2, the water entry rate increased from 4.6 to 40.1 mL/min over the same pressure range (just under 1 order of magnitude).

Hence substantial amounts of water can enter small deficiencies simply under the action of gravity, and increasing amounts of water can penetrate deficiencies with increasing pressure difference across the openings .

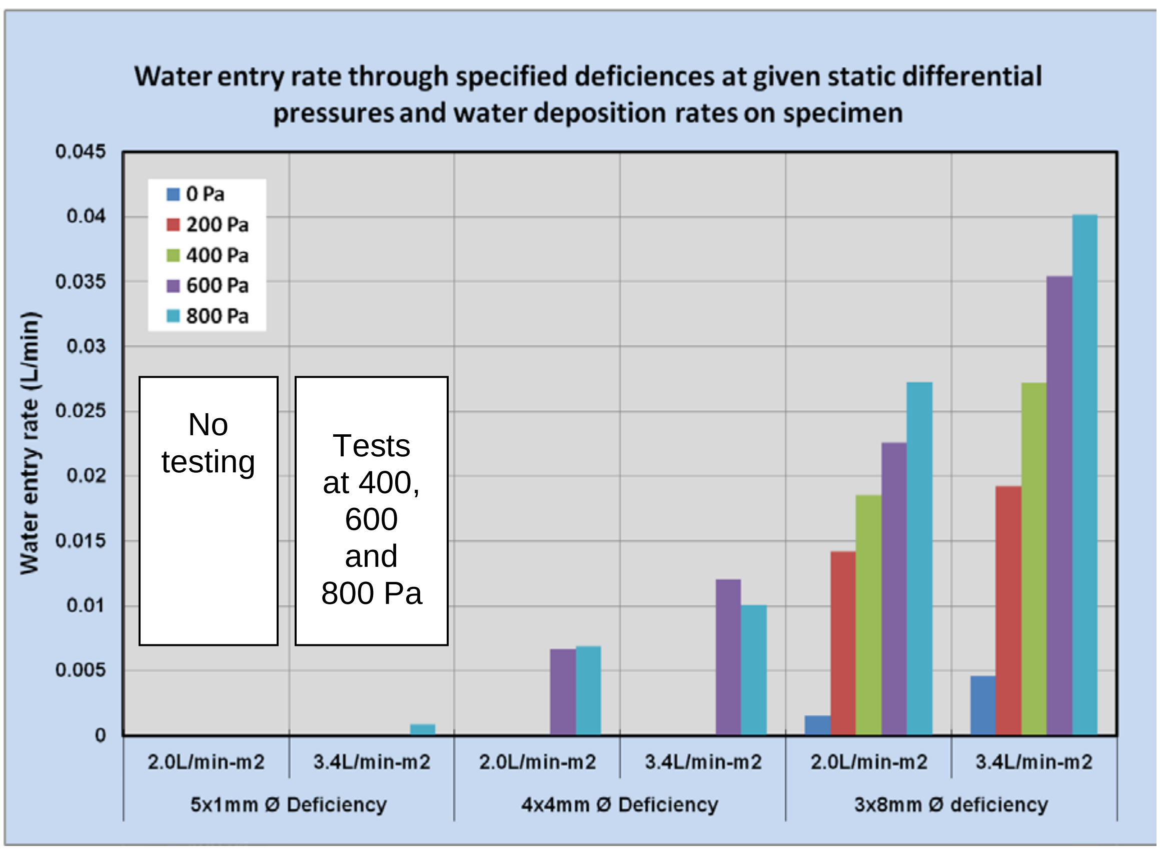

FIGURE 6: Water entry rate through specified deficiencies at given static differential pressures and water deposition rates on specimen

Results of water entry under dynamic differential pressure conditions

Results of water entry rates through openings in a vertical polycarbonate plate, nominally representative of cladding deficiencies, when subjected to dynamic differential pressure conditions (1Hz) are given in Figure 7 to Figure 10. Information provided in Figure 7 and Figure 8 refer to results obtained from tests on deficiencies of 4 by 4 mm Ø (~50 mm^2) and those of Figure 9 and Figure 10 for deficiencies of 3 x 8 mm Ø (150 mm^2).

In Figure 7, water entry rates (L/min) through deficiencies (4 X 4 mm Ø) under 400 Pa mean pressure differential are given in terms of pressure level, air barrier leakage conditions for the two water spray rates (2 and 3.4 L/min-m^2) at which tests were conducted. The pressure level refers to the sinusoidal variation to the 400 Pa mean pressure at which tests were completed; these varied by 20, 33, 50 80% of the mean pressure in four distinct steps. At each of these pressure levels, results were obtained at two different ABS leakage conditions as given in Table 3.

What is apparent from these results derived at a mean pressure of 400 Pa is that:

- Increases to the water spray rate onto the exterior plane increased the rate of water entry through deficiencies
- Increases to the degree of air leakage likewise lead to increases in water entry rates through deficiencies

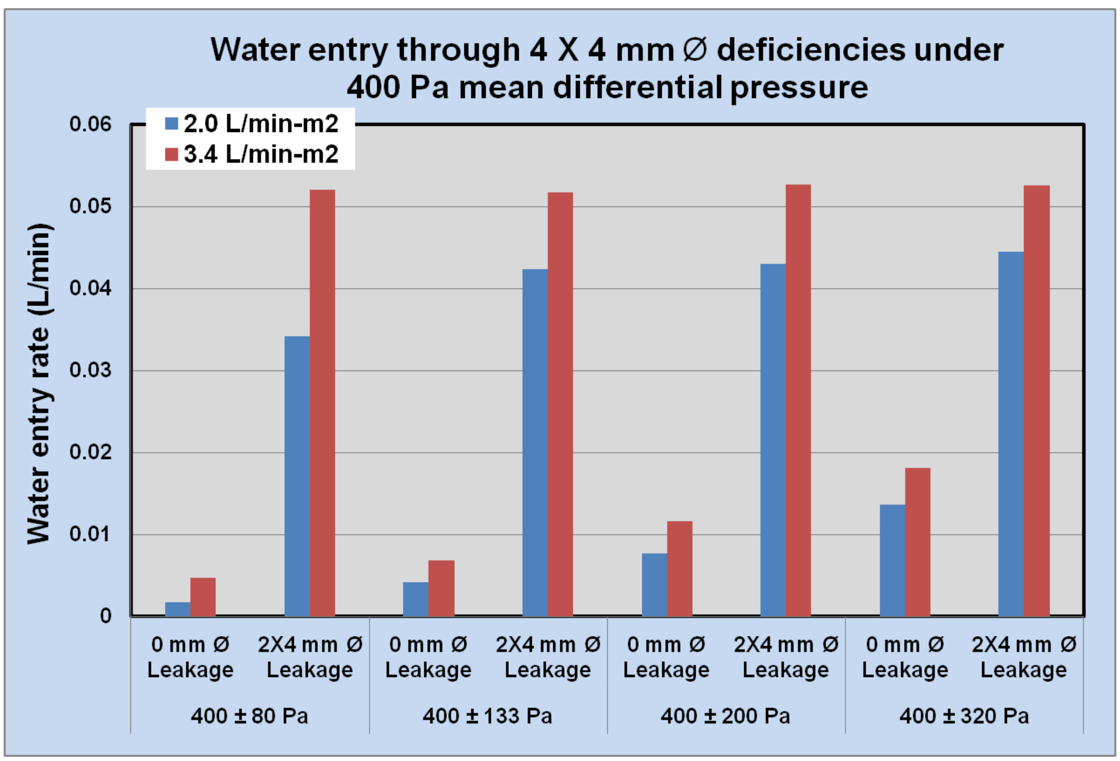

FIGURE 7: Water entry (L/min) through 4 x 4 mm Ø deficiencies (~50 mm^2) under 400 Pa mean pressure differential at given water spray rates and air barrier leakage conditions

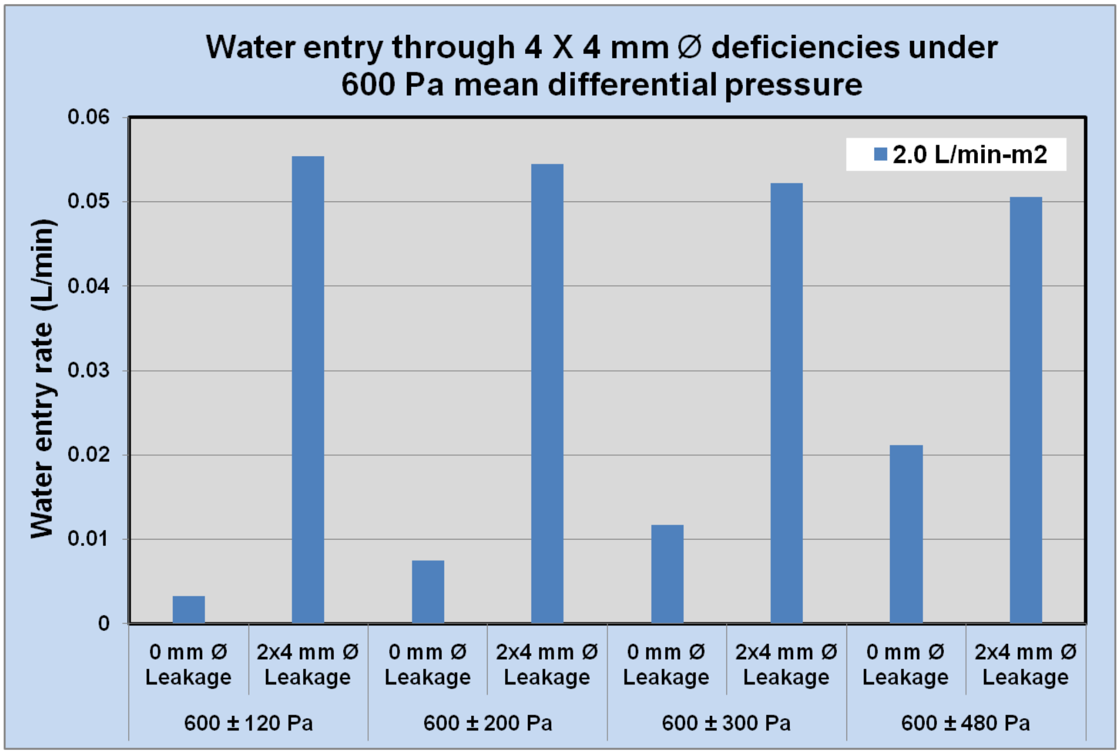

FIGURE 8: Water entry (L/min) through 4 x 4 mm Ø deficiencies (~50 mm^2) under 600 Pa mean pressure differential at given water spray rates and air barrier leakage conditions

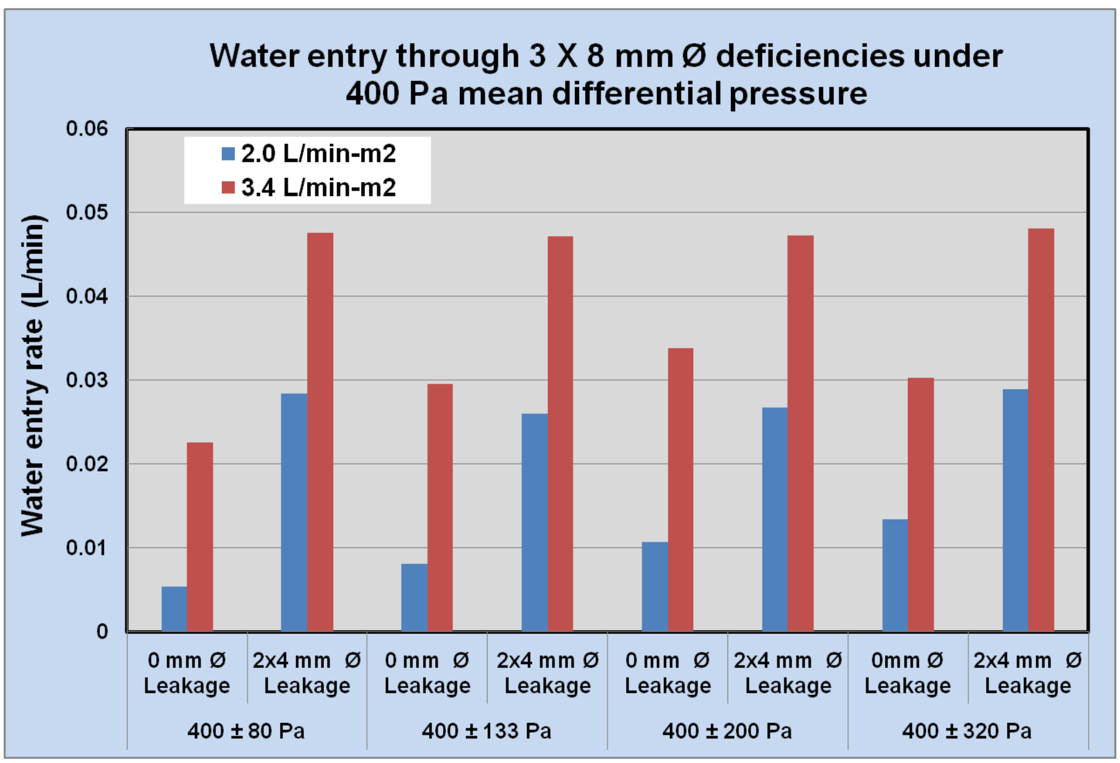

FIGURE 9: Water entry (L/min) through 3 x 8 mm Ø deficiencies (150 mm^2) under 400 Pa mean pressure differential at given water spray rates and air barrier leakage conditions

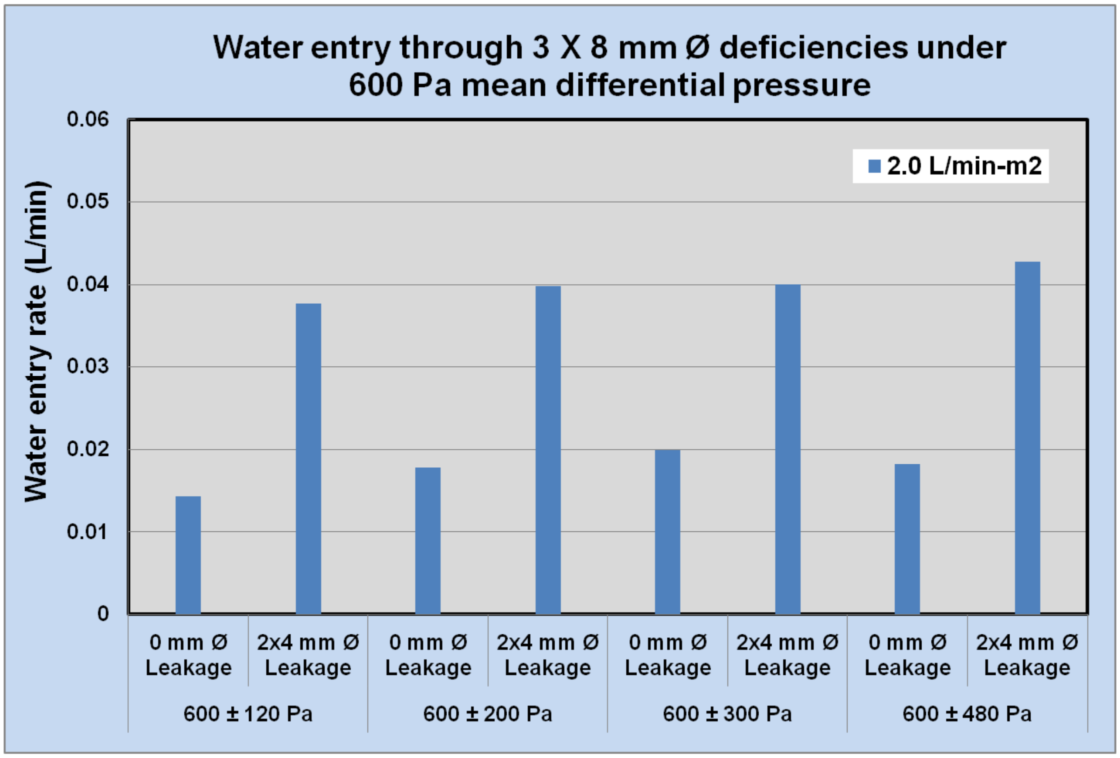

FIGURE 10: Water entry (L/min) through 3 x 8 mm Ø deficiencies (150 mm^2) under 600 Pa mean pressure differential at given water spray rates and air barrier leakage conditions

- Increases to the variation in pressure level at the 400 Pa mean pressure may bring about an increase in water entry rate; this was apparent for the conditions where there is little or no air leakage across the test specimen (i.e. ~ 0 mm leakage) whereas, this same situation is not evident when a greater degree of air leakage was present in the test specimen (i.e. 2 X 4 mm Ø leakage)

In Figure 8 are given comparable results to those previously cited but these were completed at a mean pressure differential of 600 Pa and only at a water spray rate of 2 L/min-m^2. From these results it is apparent that, as was the case for results obtained at a mean dynamic pressure of 400 Pa:

- Increases to the degree of air leakage lead to an increase in water entry rates through deficiencies;
- Contrary to the tests at 400Pa, the increase in water infiltration with pressure amplitude was less evident for the case with little or no air leakage across the test specimen.

In Figure 9, water entry rates (L/min) through deficiencies (3 X 8 mm Ø) in a vertical plane subjected to a 400 Pa mean pressure differential are given. The same observations as were made for the smaller aggregate size deficiency can be made for this set of larger deficiencies; specifically increases to the rate of water entry through deficiencies due to:

- Increases to the water spray rate onto the exterior plane
- Increases to the degree of air leakage

In Figure 10, water entry rates (L/min) through deficiencies (3 X 8 mm Ø) in a vertical plane subjected to a 600 Pa mean pressure differential are given; these indicated similar results for those obtained at the lower mean pressure level (400 Pa) in that increases to the rate of water entry through deficiencies were observed for increases to the degree of air leakage across the test specimen.

In both sets of tests for assessing water entry through deficiencies of 3 X 8 mm Ø, water entry results were not sensitive to increases in pressure level, although this was less evident for the case where there was reduced or no air leakage across the assembly. In these instances, water entry was somewhat sensitive to increases in amplitude pressure level over the four steps to which the specimens were subjected.

A comparison of results between water entry tests carried out at the same mean pressure level (400 or 600 Pa) but for different size of deficiencies indicates that greater rates of entry were achieved for the larger set of deficiencies (i.e. 3 x 8 mm Ø deficiencies; 150 mm^2), as might be expected, as compared to those obtained for the smaller deficiency set (i.e. 4 x 4 mm Ø deficiencies; ~50 mm^2); this was evident for the respective air leakage conditions, water spray rates and pressure levels.

DISCUSSION

The results presented in this paper represent results for a limited range of tests undertaken for only one frequency and only circular deficiencies. Thus this selected set of results provides a general overview of the types of information achievable with this type of controlled testing. As such, useful base information on water entry through characteristic openings has been provided. Where previously water entry has typically been referred to as a phenomenon for which entry was dependent on the presence of an opening, water at the opening and a force to drive water through it, the information provided in this paper at the very least offers the magnitude of entry in relation to driving forces for different types of openings Future publications will focus on offering results obtained for testing at different frequencies and deficiencies, and as well, will provide some insights regarding the effect of film flow and the formation of rivulets on a vertical plane on water ingress.

Discussion on water entry test program under static pressure conditions

The surface tension of water will introduce a meniscus on the interior side of the front vertical plate. Water will only enter the cavity once the surface tension is breached by an imposed pressure, the pressure, F, calculated as follows:

deficiency this results in a pressure of 297 Pa, whereas the 4 mm and 8 mm deficiency require a pressure difference of 74 Pa and 37 Pa respectively.

The force due to the hydrostatic head at the opening works against the capillary force; thus for the 4 mm and 8 mm diameter openings this pressure (γgh) is estimated to be ~40 and ~80 Pa respectively. This implies that water should not occlude larger openings such as those of 8 mm diameter and should readily flow across these openings. Where in the case of 1 mm and 4 mm diameter openings, there would still need to have pressure differentials to drive water across these openings; at least 30 Pa in the case of the 4 mm openings and ca. 290 Pa for the 1m diameter openings.

Consequently, a significant difference in water ingress is expected for the small deficiency (1mm Ø) compared to the larger deficiencies (4mm and 8mm Ø). The results reported in Figure 6 confirm the difference in infiltration rate. The small deficiency showed a limited amount of water ingress at 800 Pa pressure difference. However, contrary to expectations the calculated pressure threshold based on the surface tension of the meniscus (about 290 Pa) is thus far lower than the observed pressure difference for water to infiltrate (800 Pa). Similarly, based on the required force to breach the meniscus for the 4mm Ø deficiency water ingress would be expected for an imposed pressure of 30 Pa. The results point out that infiltration was only recorded at 800 and 600 Pa pressure difference. Again the required pressure difference for water ingress to occur lies significantly higher than the calculated pressure to breach the surface tension of the meniscus. For the 8mm Ø deficiency the hydrostatic pressure (~80Pa) is higher than the required force to breach the surface tension of the meniscus (37Pa). Consequently, infiltration can already be expected for the test without imposed air pressure difference, which is confirmed by the results in Figure 6. An increased rate of entry was also observed at the higher spray rate when no pressure was applied, which indicates that the thickness of the water film that runs down does indeed affect the hydrostatic pressure.

The effect of the meniscus thus explains to some degree the difference in infiltration rates for the deficiencies tested in this study. Large deficiencies require only a minor pressure difference to breach the surface tension; e.g. for the 8mm deficiency water can infiltrate without an imposed external air pressure difference due to hydrostatic pressure. For smaller deficiencies, a discrepancy was found between the calculated pressure to breach the meniscus, and the pressure threshold found in the experiments for water to infiltrate into the cavity. No apparent explanation was found for this discrepancy.

A number of uncertainties may influence the pressure threshold for water to infiltrate and the amount of water ingress through the deficiency. First of all, the edge of the deficiency may affect the meniscus. Secondly, the surface of the interior of the deficiency may influence the contact angle and thus the capillary action. Thirdly, the geometry of the deficiency will also affect the friction loss and pressure drop in the deficiency itself and hence the amount of water that will infiltrate.

One might consider the fact that a shift in pressure difference will cause a volume change in the cavity of the sample. If this volume change is very small, it might define whether or not the volume of water in the deficiency will enter the cavity. If the volume change caused by the pressure fluctuation in the airtight installation is very small, it might be possible that the water only oscillates around a mean position. However, based on the ideal gas law, it can easily be calculated that the air volume change is significantly larger than the volume of water in the round deficiencies. For the smallest amplitude of 80Pa, a volume change of 41cm³ is caused, whereas the larger deficiencies comprise a volume below 2cm³. This indicates that the volume change will not determine whether or not the water occluded in the deficiencies can be pushed inwards.

Discussion on water entry test program under dynamic pressure conditions

Similar to the tests under static boundary conditions, the water spray rate, deficiency diameter and airtightness of the back plate have a significant effect on the results. During the dynamic tests a pressure fluctuation was imposed around the mean pressure with a frequency of 1Hz. The amplitude of the fluctuation was set to 20%, 33%, 50% and 80% of the mean pressure difference. However, the effect of the amplitude was only evident for the installations with good airtightness: for these installations there was good pressure moderation, and the meniscus of the deficiency was not continuously breached. The installations with a leaky back plate had a larger mean pressure difference over the front plate, and a continuous water ingress was installed. Consequently, the mean pressure difference over the test specimen became the predominant parameter, and the effect of the fluctuation amplitude was relatively small.

- Increases to the variation in pressure level at the 400 Pa mean pressure may bring about an increase in water entry rate; this was apparent for the conditions where there is little or no air leakage across the test specimen (i.e. ~ 0 mm leakage) whereas, this same situation is not evident when a greater degree of air leakage was present in the test specimen (i.e. 2 X 4 mm Ø leakage)
- However, the required pressure to breach the meniscus was about 30Pa for these deficiencies. Subsequently, every imposed pressure pulse can breach the meniscus and the volume of water in the deficiency will be pushed into the cavity. For the installation without leakage (0mm leakage) the pressure over the front plate will be significantly lower than the overall pressure difference: here water only infiltrated during the pulses, and the amplitude of the pulse is the predominant parameter that determines how much water is pushed into the cavity. Conversely, the installation with a leaky back plate (2*4mm leakage) showed poor pressure moderation and a high pressure difference over the front plate. Consequently, the mean pressure difference was strong enough to impose a continuous water infiltration into the cavity, and is thus the predominant parameter that determines the infiltration rate.

CONCLUSIONS

Rain water intrusion is one of the main causes of building deterioration. Although significant research efforts have been done by the building industry on a component level, the fundamentals of water infiltration through openings have not yet been studied in depth. In order to study water ingress though openings in a vertical plane under static and dynamic boundary conditions, a test setup, protocol and program have been developed to test the effect of pressure difference, water spray rate, type of deficiency and airtightness of the test specimen.

Under static boundary conditions, the infiltration rate increased for rising spray rate, pressure difference and air leakage of the construction. The surface tension of the meniscus on the interior side of the front plate defines a pressure threshold that determines at which pressure water will enter into an assembly. Once the meniscus has been breached, the degree of entry through a deficiency will also be determined by the capillary pressure of the deficiency (which is significantly smaller than the pressure to breach the meniscus), and the pressure drop due to the friction loss inside the deficiency. The required pressure to breach the surface tension of the meniscus could to some degree explain the differences in water ingress between larger and smaller deficiencies. Based on the calculations an additional force is required for push water through the 1mm and 4mm Ø deficiencies. However, there was a discrepancy between the calculated pressures and the pressures in the experiments at which water started infiltrating. Under dynamic conditions the pressure was fluctuated around a mean pressure difference with varying amplitudes, at a 1Hz frequency. However, the amplitude only had a significant influence for those tests with an airtight back plate: here the pulses defined whether or not the meniscus was breached. For those test sequences having a heightened degree of airtightness there was a larger mean pressure difference and continuous water ingress was installed.

The results reported in this paper indicate that the formation of a water meniscus in a deficiency is an important parameter for water infiltration, as compared to capillary pressure. Furthermore, the results suggest that water deposition rate, pressure difference and airtightness are important parameters to consider in watertightness testing. Dynamic tests indicate that the amplitude seems to be of lesser importance, but the degree of airtightness affects water entry phenomena: less airtight test specimens allowed a continuous entry rate whereas airtight test specimens only allowed water to enter during the positive pulses.

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REFERENCES

[1] Morrison Hershfield Limited (1996), “Survey of Building Envelope Failures in the Coastal Climate of British Columbia”, Canada Mortgage and Housing Corporation, Ottawa, 43 p.

[2] Crandel, J. C. and T. Kenny, (1995), Investigation of Moisture damage in single-family detached houses with exterior insulation finish systems in Wilmington, NC, NAHB Research Centre, August

[3] Anon (2005), "Stucco in Residential Construction“, City of Woodbury (MN), Building Inspection Division, Update, February 9, 2005.

[4] Cautley, D. (2004), Comparative Measured Moisture Performance of Woodframe Walls, Proceedings of Conference on Woodframe Housing Durability and Disaster Issues: October 4-6, 2004, Las Vegas, NV, Forest Products Society, Madison, WI USA, pp. 201-209

[5] Building Envelope Engineering (1999), “Wall Moisture Problems in Alberta Dwellings”, Canada Mortgage and Housing Corporation, Ottawa, 60 p.

[6] Brown, W.C.; Ullett, J.M.; Karagiozis, A.N.; Tonyan, T. (1997), Barrier EIFS clad walls: results from a moisture engineering study, Journal of Thermal Insulation and Building Envelopes. Vol. 20, pp. 206-226 (NRCC-40643)

[7] Brown, W.C.; Adams, P.J.; Tonyan, T.; Ullett, J.M. (1997), Water management in exterior wall claddings, Journal of Thermal Insulation and Building Envelopes, Vol. 21, pp. 23-43 (NRCC-42089)

[8] Lacasse, M. A., O’Connor, T. J., Nunes, S. and 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 133, Institute for Research in Construction, National Research Council Canada, 133 p., February (IRC-RR-133).

[9] Carll, C. (2001), Rainwater Intrusion in Light-Frame Building Walls, Proceedings of the 2nd Annual Conference on Durability and Disaster Mitigation in Wood-Frame Housing: November 6-8, 2000, Madison, WI, Forest Products Society, Madison, WI USA, pp. 33-40.

[10] 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.