Water Infiltration through Openings in a Vertical Plane under Static and Dynamic Pressure Conditions

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Overview

• Introduction
• Why bother: 2 cases
• Experimental set-up and procedures
• Results
• Conclusions
Introduction

Concepts for watertightness

Perfect barrier system

Mass buffering

Drained cavity
Introduction

Drained cavity

Water shedding
Drainage
Airtightness
Introduction

Drained cavity

• Will water enter?
• How much?
• Where?
• Why?

• Is that a problem?
Case 1

Drained cavity

- Will water enter?
- How much?
- Where?
- Why?

- Is that a problem? => Heat-Air-Moisture Simulations
  => need for input data!

(Künzel et al., 11th DBMC, 2008)
Case 2

Drained cavity

Pressure difference at moment of failure according to EN 12208

- 2 vents
- 1 vent
- 0 vents
- 0 Weep holes
- 1 Weep hole
- 2 Weep holes
- 3 Weep holes

- 900
- 750
- 450
- 300
- 250
- 200
- 150
- 0

- 300
- 250
- 200
- 150
- 100
- 50
- 0

- 1.22m
- 1.44m

vent

weep hole

closing point

pressure tap

stay
Objectives

Water infiltration through openings

- Wind driven rain intensity
- Pressure difference
- Gust (length)
- Type and size of deficiencies
- Balance of forces
Experiments
Test apparatus
Experiments
Test apparatus
Experiments
Test apparatus
Experiments
Test apparatus
Experiments
Test specimen

2mm slit
0° angle

2mm slit
30° angle

2mm slit
60° angle

1mm diameter
5 holes

4mm diameter
4 holes

8mm diameter
3 holes
Experiments
Test specimen
Experiments
Test protocol

Water spray rate

• North American standards: 3.4 L/min-m²
• European standards: 2.0 L/min-m²

• Only run-off was considered, no direct impingement
• Run-off intensity corresponds to 3m tall window pane
Experiments
Test protocol

Airtightness of back plate

• Simulates air barrier system
• Different levels of performance
• Pressure moderation in the cavity?
Experiments
Test protocol

Pressure differences

• 0 – 200 – 400 – 600 – 800 Pa
• correspond to a range wind loads

Dynamic tests:

• 400 and 600 Pa mean pressure difference
• Amplitudes 20%, 33%, 50% and 80% of mean
• Pressure frequencies 0.1 – 0.2 – 0.333 – 1 Hz
Results

Static

Water entry rate through specified deficiencies at given static differential pressures and water deposition rates on specimen.
Results

Static

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

- Diameter introduces pressure threshold
**Results**

**Static**

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

- Diameter introduces pressure threshold
- Infiltration ~ spray rate

<table>
<thead>
<tr>
<th>Water entry rate (L/min)</th>
<th>2.0L/min-m2</th>
<th>3.4L/min-m2</th>
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<th>2.0L/min-m2</th>
<th>3.4L/min-m2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5x1mm Ø Deficiency</td>
<td>0.015</td>
<td>0.025</td>
<td>0.035</td>
<td>0.045</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3x8mm Ø deficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.035</td>
<td>0.045</td>
</tr>
</tbody>
</table>

Tests at 400, 600 and 800 Pa

No testing
Results

Static

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

- Diameter introduces pressure threshold
- Infiltration ~ spray rate
- Infiltration ~ pressure difference

No testing

Tests at 400, 600 and 800 Pa
Results

Static

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

- Diameter introduces pressure threshold
- Infiltration ~ spray rate
- Infiltration ~ pressure difference
- Infiltration ~ poor airtightness

<table>
<thead>
<tr>
<th>Diameter and Deficiency</th>
<th>Water entry rate (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0L/min-m2 5x1mm Ø Deficiency</td>
<td>0.015</td>
</tr>
<tr>
<td>3.4L/min-m2 5x1mm Ø Deficiency</td>
<td>0.022</td>
</tr>
<tr>
<td>2.0L/min-m2 4x4mm Ø Deficiency</td>
<td>0.030</td>
</tr>
<tr>
<td>3.4L/min-m2 4x4mm Ø Deficiency</td>
<td>0.038</td>
</tr>
<tr>
<td>2.0L/min-m2 3x8mm Ø Deficiency</td>
<td>0.040</td>
</tr>
<tr>
<td>3.4L/min-m2 3x8mm Ø Deficiency</td>
<td>0.045</td>
</tr>
</tbody>
</table>

Tests at 400, 600 and 800 Pa

No testing
Results

Static

Power law

\[ Q = C \Delta P^n \]

\[ Q = C \Delta P^n \]

\[ C = 0.00043 \text{ L/min} \]

\[ C = 0.00029 \text{ L/min} \]

8mm Ø deficiency infiltration

- 2.0 L/min.m²
- 3.4 L/min.m²

C=0.00043 L/min

C=0.00029 L/min
Expectations

- At what pressure difference will infiltration occur?

Results

Phenomena

\[ p_c = \frac{2\gamma \cos \theta}{\rho} \]

- Capillary pressure
- Hydrostatic pressure
- Exterior wind pressure
- Surface tension
Expectations

- At what pressure difference will infiltration occur?

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flat meniscus [Pa]</td>
</tr>
<tr>
<td>1 mm</td>
<td>297</td>
</tr>
<tr>
<td>4 mm</td>
<td>74</td>
</tr>
<tr>
<td>8 mm</td>
<td>37</td>
</tr>
</tbody>
</table>
Expectations

- At what pressure difference will infiltration occur?

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat meniscus [Pa]</td>
<td>297</td>
<td>274</td>
</tr>
<tr>
<td>Spherical meniscus [Pa]</td>
<td>74</td>
<td>70</td>
</tr>
<tr>
<td>1 mm</td>
<td>297</td>
<td>274</td>
</tr>
<tr>
<td>4 mm</td>
<td>74</td>
<td>70</td>
</tr>
<tr>
<td>8 mm</td>
<td>37</td>
<td>36</td>
</tr>
</tbody>
</table>

Results Phenomena
Results

Phenomena

Expectations

• At what pressure difference will infiltration occur?

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat meniscus [Pa]</td>
<td>297</td>
<td>274</td>
<td>121</td>
</tr>
<tr>
<td>Spherical meniscus [Pa]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capillary pressure [Pa]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 mm
4 mm
8 mm

\[ p_c = \frac{2\gamma \cos \theta}{r} \]

\[ \theta = 66^\circ \]
### Expectations

- **At what pressure difference will infiltration occur?**

### Results

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>297</td>
<td>274</td>
<td>121</td>
<td>41</td>
</tr>
<tr>
<td>4 mm</td>
<td>74</td>
<td>70</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>8 mm</td>
<td>37</td>
<td>36</td>
<td>15</td>
<td>5</td>
</tr>
</tbody>
</table>

\[
p_c = \frac{2y \cos \theta}{r}
\]

\[
\theta = 82^\circ
\]
Expectations

- At what pressure difference will infiltration occur?

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat meniscus [Pa]</td>
<td>297</td>
<td>274</td>
<td>121</td>
<td>41</td>
<td>10</td>
</tr>
<tr>
<td>Spherical meniscus</td>
<td>74</td>
<td>70</td>
<td>30</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>Capillary pressure</td>
<td>37</td>
<td>36</td>
<td>15</td>
<td>5</td>
<td>80</td>
</tr>
<tr>
<td>Capillary in drilled hole [Pa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrostatic pressure [Pa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results

Phenomena
**Results Phenomena**

**Expectations**

- At what pressure difference will infiltration occur?

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>A (Flat meniscus [Pa])</th>
<th>B (Spherical meniscus [Pa])</th>
<th>C (Capillary pressure [Pa])</th>
<th>D (Capillary in drilled hole [Pa])</th>
<th>E (Hydrostatic pressure [Pa])</th>
<th>F (B - D - E [Pa])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>297</td>
<td>274</td>
<td>121</td>
<td>41</td>
<td>10</td>
<td>223</td>
</tr>
<tr>
<td>4 mm</td>
<td>74</td>
<td>70</td>
<td>30</td>
<td>10</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>8 mm</td>
<td>37</td>
<td>36</td>
<td>15</td>
<td>5</td>
<td>80</td>
<td>-49</td>
</tr>
</tbody>
</table>
Results

Phenomena

Expectations

• At what pressure difference will infiltration occur?

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>F</th>
<th>B - D – E [Pa]</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>223</td>
<td></td>
<td>High threshold</td>
</tr>
<tr>
<td>4 mm</td>
<td>20</td>
<td></td>
<td>Low threshold</td>
</tr>
<tr>
<td>8 mm</td>
<td>-49</td>
<td></td>
<td>No threshold – infiltration at 0 Pa</td>
</tr>
</tbody>
</table>
Results

Static

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

Water entry rate (L/min)

<table>
<thead>
<tr>
<th>2.0L/min-m²</th>
<th>3.4L/min-m²</th>
<th>2.0L/min-m²</th>
<th>3.4L/min-m²</th>
<th>2.0L/min-m²</th>
<th>3.4L/min-m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>5x1mm Ø Deficiency</td>
<td>4x4mm Ø Deficiency</td>
<td>3x8mm Ø deficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

223 Pa threshold
20 Pa threshold
0 Pa threshold
Results

Static

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

- **223 Pa threshold**
- **20 Pa threshold**
- **0 Pa threshold**
- **600 - 800 Pa**
- **400 - 600 Pa**
- **0 Pa**
## Experiments

### Test program

<table>
<thead>
<tr>
<th>Dynamic pressure conditions</th>
<th>Water spray rate (L/min-m²)</th>
<th>Dynamic pressure conditions (Pa)</th>
<th>Pressure function frequency (Hz)</th>
<th>Air leakage condition (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deficiencies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>4 X 4 mm Ø (50.3 mm²)</strong></td>
<td>2.0</td>
<td>400 ± 80, ±133, ±200, ±320</td>
<td>0.1, 0.2, 0.333, 1.0</td>
<td>&lt; 0.1, 25.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>600 ± 120, ±200, ±300, ±480</td>
<td>0.1, 0.2, 0.333, 1.0</td>
<td>&lt; 0.1, 25.1</td>
</tr>
<tr>
<td></td>
<td>3.4</td>
<td>400 ± 80, ±133, ±200, ±320</td>
<td>0.1, 0.2, 0.333, 1.0</td>
<td>&lt; 0.1, 25.1</td>
</tr>
<tr>
<td><strong>3 X 8 mm Ø (150.8 mm²)</strong></td>
<td>2.0</td>
<td>400 ± 80, ±133, ±200, ±320</td>
<td>0.1, 0.2, 0.333, 1.0</td>
<td>&lt; 0.1, 25.1</td>
</tr>
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<td></td>
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<td>600 ± 120, ±200, ±300, ±480</td>
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<td>&lt; 0.1, 25.1</td>
</tr>
</tbody>
</table>
Results

Dynamic

Water entry through 4 X 4 mm Ø deficiencies under 400 Pa mean differential pressure

- 2.0 L/min-m²
- 3.4 L/min-m²

Water entry rate (L/min)

<table>
<thead>
<tr>
<th>Leakage</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 mm Ø</td>
<td>400 ± 80 Pa</td>
</tr>
<tr>
<td>2X4 mm Ø</td>
<td>400 ± 133 Pa</td>
</tr>
<tr>
<td>0 mm Ø</td>
<td>400 ± 200 Pa</td>
</tr>
<tr>
<td>2X4 mm Ø</td>
<td>400 ± 320 Pa</td>
</tr>
</tbody>
</table>
Results

Dynamic

Observations

• Under static conditions: no infiltration at 400 Pa
• Infiltration ~ spray rate
• Airtightness has a significant effect!
Results

Dynamic

Observations

**Good airtightness**

- **Good** pressure moderation
- **Low** pressure difference over outer plate
- **Low** infiltration rates
- Mean pressure does not breach meniscus
- **Amplitude determines** infiltration rates
## Results

### Dynamic Observations

<table>
<thead>
<tr>
<th>Good airtightness</th>
<th>Poor airtightness</th>
</tr>
</thead>
<tbody>
<tr>
<td>• <strong>Good</strong> pressure moderation</td>
<td>• <strong>Poor</strong> pressure moderation</td>
</tr>
<tr>
<td>• <strong>Low</strong> pressure difference over outer plate</td>
<td>• <strong>High</strong> pressure difference over outer plate</td>
</tr>
<tr>
<td>• <strong>Low</strong> infiltration rates</td>
<td>• <strong>High</strong> infiltration rates</td>
</tr>
<tr>
<td>• Mean pressure <strong>does not</strong> breach meniscus</td>
<td>• Mean pressure <strong>does</strong> breach meniscus</td>
</tr>
<tr>
<td>• <strong>Amplitude determines infiltration rates</strong></td>
<td>• <strong>Mean pressure overrides effect of amplitude</strong></td>
</tr>
</tbody>
</table>
Observations

30 degree slit: hydrostatic pressure, small surface

Horizontal slit: threshold, large section
Water entry through 4 X 4 mm Ø deficiencies under 400 Pa mean differential pressure

- Water entry rate (L/min) for 2.0 L/min-m² and 3.4 L/min-m²

<table>
<thead>
<tr>
<th>Leakage</th>
<th>Water entry rate (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 mm Ø</td>
<td>2.0 L/min-m²</td>
</tr>
<tr>
<td>2X4 mm Ø</td>
<td>3.4 L/min-m²</td>
</tr>
<tr>
<td>Leakage</td>
<td>0 mm Ø</td>
</tr>
<tr>
<td>Leakage</td>
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<td>400 ± 133 Pa</td>
</tr>
<tr>
<td>400 ± 200 Pa</td>
<td>400 ± 320 Pa</td>
</tr>
</tbody>
</table>
Conclusions

Static

- Diameter introduces pressure threshold
- Infiltration $\sim$ spray rate
  $\sim$ pressure difference
  $\sim$ poor airtightness
- Infiltration described by power law
Conclusions

Dynamic

• Diameter introduces pressure threshold
• Infiltration ~ spray rate
  ~ pressure difference
  ~ poor airtightness
• Higher infiltration as compared to static conditions
• Infiltration mode shifts from mean pressure to amplitude when the construction becomes more airtight
Acknowledgements

Co-authors:

Dr. Michael A. Lacasse and Mr. Travis Moore

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Thank you for your attention!

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