ISBP2015
1st International Symposium on Building Pathology

Comparison between uniform rain loads and point sources to simulate rainwater leakage with commercial HAM-models

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ABSTRACT

It is well known that wind driven rain (WDR) is one of the most important parameters that affects the hygrothermal behaviour of a construction. Research is still on-going to define the amount of rain that reaches the wall surface, considering it depends on the height and geometry of the building, the position on the façade and local effects as e.g. overhangs. This knowledge is important to assess the effect of rain on the hygrothermal behaviour of a construction. The information is used in Heat-Air-Moisture (HAM) – simulations, to assess the behaviour of constructions as accurate as possible for realistic climates. However, the WDR intensity is typically calculated in a simplistic way, and constructions are assumed to be 100% watertight. Only in rare cases plausible defects of the façade are taken into account, as e.g. missing pieces of sealant, unfilled joints, etc. The reason for neglecting deficiencies is the fact that very little is known about the amount of water that can be expected to infiltrate at a specific deficiency, and how that relates to WDR intensities, wind loads and other boundary conditions. Only recently HAM-software allows the user to incorporate leaks in the simulation by means of so called 'moisture sources' at specified locations. The impact of the position of the source and the quantity one should allocate, is still a point of discussion.

In this paper, two different HAM-software models (WUFI & Delphin) are used to simulate a water leak in a wood-frame wall with an OSB sheathing. The influence of the position of the moisture source is analysed for the wetting and drying behaviour of the sheathing and the bottom plate. By means of 2D-simulations, point sources are compared to the current uniform wetting approach. The results are validated with experimental measurements of the same wood frame assembly subjected to intermitted wetting and drying in lab conditions.

For this wall type, it can be concluded that a *uniform* load at the interface of OSB and insulation may give realistic results for the moisture content of the *sheathing* when occasional leakage is considered. Nevertheless, at places where water is likely to accumulate, it is necessary to include additional *point sources*, in this case e.g. at the joints of the *bottom plate*.

KEYWORDS: HAM, moisture source, leakage, Delphin, WUFI, moisture distribution

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1 INTRODUCTION

Water penetration is one of the most problematic and widespread sources for damage of building envelopes. According to 'good building practice', a building assembly is designed in such a way that the exterior cladding deflects the largest part of the impinging raindrops, whereas the drainage layer is designed to drain the water that penetrated into the cavity. However, small deficiencies might occur during construction or after deterioration of the material, which could lead to the presence of water in the construction. Normally, the design does not include any precautions for this type of events.

In order to create more robust constructions, that can deal with occasional water infiltration, Heat-Air-Moisture (HAM) simulations can be used to predict and analyse the behaviour for leakage. In the current HAM models, users can assign a 'water source' in addition to the 'exterior climate file', to incorporate a plausible defect and its infiltration water. However, the quantity that has to be assigned to this source, or the position at which one should place it in the model, are subject to discussion. Little information is available on the amount of water that has to be expected inside the construction, and the only present guideline on this topic is ASHRAE 160-p [2009] , which suggests an amount of 1% of the wind driven rain (WDR) that reaches the building façade. Previous research on this topic pointed out that this amount can vary significantly in reality [Van Den Bossche *et al.* 2011].

In order to investigate this problem, the following steps must be made:

1. Weather data with a sufficiently small time step (in the order of 5-10min)
2. Correct assessment of the amount of rain reaching the surface: WDR calculation
3. Rating the quantity of water penetrating into the building: classifying defects and rating their infiltration load
4. Correct modelling of the wetting and drying behaviour of the wall assembly by accounting for leakage

In this paper it is focused on the fourth step, and elaborated on the current possibilities to introduce a moisture source in a construction in HAM-simulations. Two commercial software packages, WUFI [Künzel 1994] and DELPHIN [Grunewald and Nicolai 1997], are considered and compared for 2D-simulations. The results are validated with experimental data. The main goals are to

- investigate the effect of the use of point sources at different position, and compare this method to the common approach of uniform loading
- compare the results of two commercial programs concerning moisture sources.

2 SIMULATING MOISTURE SOURCES

State-of-the-art HAM-simulation programs are able to produce similar results concerning hygrothermal behaviour of constructions, as was confirmed by a round robin exercise in 2001 in the framework of the Hamstad project [Hagentoft *et al.* 2004]. The exercise comprised 5 cases, each focusing on a particular aspect of heat, air or moisture transport. The study revealed that the available 1D-models were able to generate similar results. Differences were most likely to occur during rapid climate changes, such as the presence of rain. Case 4, a 1D- exercise that dealt with an equally distributed moisture flux at the outside boundary (simulating rain) [Hagentoft et al. 2004], also showed good agreement among the different models, but the largest discrepancies emerged during the wetting and drying of the materials, or when it came to redistribution of moisture at material interfaces. Although this round robin exercise proves consistency between the programs for general 1D-problems, as e.g. large, widespread and uniform leaks, it does cover the questions that arise in case of point-loads, as e.g. small occasional leaks (typically a 2D-problem). Carmeliet *et al*. [2007] illustrated the different wetting patterns that can occur in a wood frame wall assembly. The wetting patterns are complex and depend on the type of sheathing material. However, it was shown that water is likely to follow certain pathways in a wall (e.g. along the studs) and that certain locations are exposed to the accumulation of water, e.g. the bottom plate of the construction.

For the above mentioned reasons, the current modelling methods for infiltration water can be criticized:

- the *positioning of the infiltration load* on the exterior surface of the water resistive barrier (WRB), as proposed by ASHRAE 160-p [2009], can be questioned. Straube and Finch [2009] indicated that modelling the infiltration at the *exterior* or *interior* surface of the WBR can lead to different conclusions for stucco clad rainscreen walls. Nevertheless, many studies on the topic of local water penetration tend to simulate the impact of a source as a 1D phenomenon uniformly distributed over the complete outer surface, e.g. [Künzel *et al.* 2008].
- the *distribution* of water in a construction becomes of interest in the case of leakage through deficiencies. A uniform load at every point in the construction does not take into account the possible accumulation of water at lower parts of the construction due to gravity. Therefore it is necessary to use 2D-models: they give more detailed information on the vulnerability and moisture tolerance of building envelope interfaces. Next to that, the resemblance with reality is more pronounced, as leaks tend to occur in an unevenly distributed way, as isolated spots in the construction [Straube and Finch 2009].
- Next to these 'geometric' modelling issues, the *amount* of water that has to be defined as leakage is still unclear. The lack of measurement data from experimental set-ups in lab conditions or on site renders it difficult to develop reliable guidelines. Furthermore, the approach is also complicated by the large variety of leakage problems, depending on the type of construction and the materials used.

Most quantitative water penetration experiments have been performed on masonry walls [Van Den Bossche *et al.* 2011], or window-wall interfaces [Van Den Bossche 2013]. Efforts have been undertaken by members of the MEWS project [Lacasse *et al.* 2003] to quantify the infiltration rate for defects at wall-window interfaces, duct penetrations and junction leaks. In this paper, the experimental data has been adopted from a previous study on the wetting pattern in a wood frame wall, after rainwater penetration took place through a wall-window-interface defect [Teasdale-St-Hilaire 2006]. The results of this study are reported in literature, and are used here as *qualitative* validation for the simulations results of the present research. Since no material properties of experimental setup are measured, it is difficult to compare the exact values of moisture content. Nevertheless, the general trends of the water distribution are available and used to compare with the wetting pattern generated by hygrothermal models.

3 EXPERIMENTAL DATA FROM LITERATURE

The investigated construction consists of a wood frame wall (100x16.7x100cm) for which the schematic drawing can be found in 'Fig.1(a)'. During the experiment, water was inserted at the top of the construction, 5 cm below the top plate. This source represents the water penetration through a defect of 10x5mm in a window sill, which could be located above the presented wall part. The rain infiltration amount was determined in 2 steps. To begin with, a watertightness test was performed according to ASTM E331-00 [2000] (3.4l/m²min @137Pa). The average percentage of infiltration water was calculated for a test of 1minute and 15minutes, i.e. 5.3% of the spray rate. This rate was then applied to the most rainy month for Montréal (August, 1.93l/m²), and a catch ratio of 0.12 (center of a building, 1/3 of building height and wind speed for Montréal), resulting in an infiltration rate of 12ml/m²h (5.3% x 1.93l/m²h x 0.12 = 0.012l/m²h). The general wetting pattern on the sheathing board can be found in 'Fig.1(b)'.

In summary, the water is applied at the top, and streams downwards. Point A receives more water than point B, because some of the water adheres at or is absorbed by the OSB along its way down. At the bottom plate of the construction, the water accumulates and causes the highest moisture contents (MC) in the bottom plate. At points A, B, C (in the sheathing), and D and E (in the bottom plate @ 6mm below surface) the MC was measured by means of moisture pins ('Fig.1(a)'). The wetting period lasted for 28 days, repeating 4 times the weekly pattern ('Fig.1(c)'), followed by a drying period of 56 days (2x28). The indoor temperature was kept constant at 21°C. On the other hand, the outdoor temperature was set to 21°C during the wetting period, but changed to a daily sinusoidal variation, with an average of 6.3°C and 13.7°C for the first and second drying period respectively. The relative humidity (RH) on the exterior side of the construction was set to 60%, 64% and 63% for each respective phase, while the interior RH reached only 50% during the wetting phase, followed by 40 and 43% during the drying periods (see also Teasdale-St-Hilaire [2006] for more information).

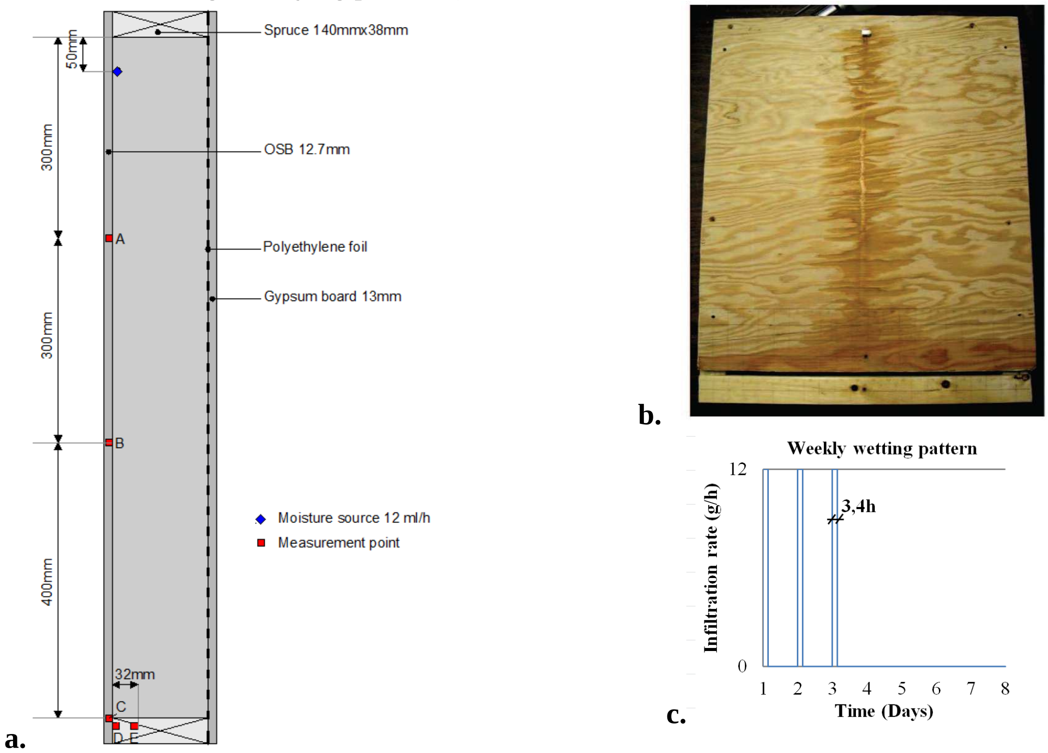

Figure 1. (a) Concept of the investigated wood-frame wall assembly with moisture measurement points A-E. **(b)** Experimental wetting pattern of the sheathing after a 3.4h wetting event of 12ml/h (reproduced from [Teasdale-St-Hilaire 2006]) **(c)** The weekly wetting pattern which is repeated 4 times during the wetting period.

4 SIMULATION APPROACH

The assembly shown in Fig. 1 was modelled in both WUFI 2D (v. 3.3) and Delphin 5 (2D-construction – planar transport). In a first step, the problem was approached from an engineering point of view, with materials available in the material databases of the respective software. In a second step, the materials were set to be equal in both programs, in order to filter out discrepancies due to material properties, or due to modelling issues. The material properties as found in the databases, are presented in Table 1. The interior and exterior climates were set identical to those in the experiment (see §3).

In order to evaluate the effect of the location on the distribution throughout the wall, a number of 2D-simulations were performed with the source at different positions: at the original position (called 'top'), at point A or at point C (in the sheathing), at point D (in the bottom plate). In both programs, the sources were modelled as 15x15mm squares, party located in the oriented strand board (OSB) and partly in the insulation layer. These dimensions are a trade-off between 'as small as possible' and numerical stability. It was noticed that the simulation results are sensitive to dimensions of the moisture source. When taken too small, the simulation diverges due to numerical instability in non-linear effects for high MC. The accompanying water production was defined by the wetting pattern as shown in 'Fig.1(b)', i.e. 12ml/h (or 489.6ml for the total wetting period of 28days).
The results of the simulations using point sources, are compared to 2D-simulations with the common uniform wetting approach for:

- an exterior load of 1% of the amount of WDR for August (1% x1.93l/m² x 0.12 = 2.3 ml/m²),
- a load of 12ml/m² uniformly distributed at the interior side of the OSB
- for a load of 12ml/m² uniformly distributed at the exterior side of the OSB

Table 1. Material properties in WUFI and Delphin.

Property	*Oriented Strand Board*		*Insulation*		*Spruce*	
	WUFI	*Delphin*	*WUFI*	*Delphin*	*WUFI*	*Delphin*
ρ [kg/m³]	630	630	30	30	455	425
w_{cap} [kg/m³]	378	270	361	900	600	570
w_{max} [kg/m³]	470	350	361	900	600	590
w_{80} [kg/m³]	95	36.8	0.4	0.16	80	72.7
Porosity	0.6	0.4	0.95	0.92	0.73	0.7516
µ [-]	650	280	1	1	130	73

with 'ρ' the density, 'w_{cap}' the water content at capillary saturation (short term), 'w_{max}' the water content at complete saturation (long term), 'µ' the vapour diffusion resistance.

The results are validated with the experimental measurements, where the source is located at the top of the construction only. It is investigated which simulation approach is able to reproduce similar wetting patterns.

4.1 Results using materials from database

Two locations, A (Fig. 3(a)) and D (Fig. 3(b)), are chosen to present the results of the simulations. The MC over time can be found for the cases with the point sources at top and at the respective point, and for a uniform loading at the interior surface of the OSB for 2 different infiltration amounts: 12ml/m²h or 1% of WDR. The experimental data (for an infiltration rate of 12ml/h at top) collected at the respective points, are added in the graphs to compare the general tendencies.

4.1.1 Point A

The experimental measurements show periodical increments of the MC in point A, when the water –coming from the top- runs over this point. As OSB is not a very absorptive material, the water will run down due to gravity, resulting in rather small variations in moisture content (peaks of 2-3 %).
It was found that a point source at the top (red) introduces some small periodic peaks for WUFI (0.5%), whereas in Delphin a more general increase in MC (without peaks) can be found. In case a uniform load of 12ml/m²h is used (yellow), Delphin shows a wetting pattern that is more similar to that of the experiment (peaks of similar size).

When the source is applied directly at point A (green), extremely high peaks occur, as was expected. In Delphin, the material reaches saturation at the third moisture load, but due to its low vapour resistance, the material is allowed to dry out sufficiently before the next loading period takes place. On the other hand, in WUFI a significant difference in the peak load is noticed, although the same amount of water was added to the construction. This could be related to the fact that the insulation in Delphin is more capillary active, and therefore causes higher MC in the OSB-panel. In both programs however, the MC exceeds 20% at the point of infiltration during the wetting events, but the material dries out immediately when the water supply ends. The uniform 1%-load at the exterior side barely influences the MC of the sheathing, partly because it is applied at the exterior side of the OSB, and partly because the amount is much smaller.

4.1.2 Point D

In the experiment, it was noticed that the inserted water collected at the bottom plate of the construction, a conditions that can be expected to occur in practice as well. This leads to very high moisture contents , as can be read from the measurements in point D ('Fig. 3b' -blue). This graph also shows that none of the proposed strategies for water leakage in simulations is able to represent the moisture accumulation in an appropriate way. Only in Delphin, for the source at point D, a similar behaviour is found. Again this is attributed to the different insulation properties: in Delphin the water is absorbed in the insulation near source, making the wood to stay wet for a longer period of time.

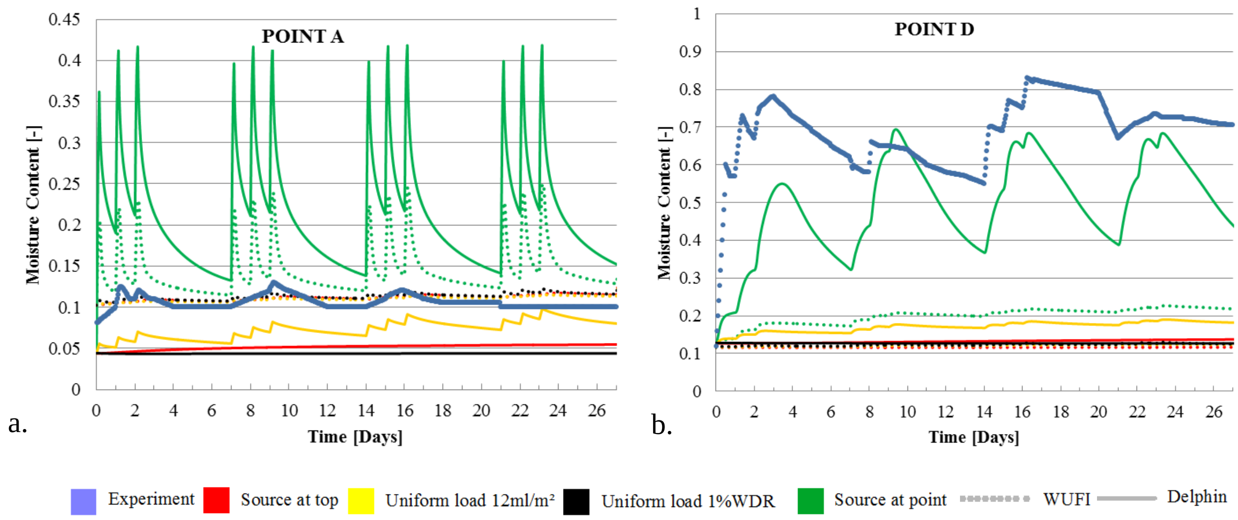

Figure 3. Moisture content at point A **(a)** and D **(b)** for the experiment and 2D-simulations with the moisture source at different positions

In order to identify the reasons of discrepancy between the distinct models on one side, and the models and the experiments on the other side, the simulations are repeated for Delphin, but now with the same material properties as for WUFI. Because the driving potential for liquid transport is capillary pressure in Delphin (Eq.1) and water content in WUFI (Eq. 2), different material properties are requested (the main conversion being liquid diffusivity to liquid conductivity). The properties as given in WUFI, are translated to the properties needed in Delphin using the formulas reported in [Hagentoft 2001].

Liquid transport in Delphin *Liquid transport in WUFI*

$$j_l = -K_l\left[\frac{\partial p_l}{\partial x} + \rho_l g\right] \quad (1)$$

$$j_l = -D_l(w)\frac{\partial w}{\partial x} \quad (2)$$

with 'j_l' the liquid moisture flux, 'K_l' the liquid conductivity, 'p_l'liquid water pressure, 'ρ_l' density of liquid phase, 'g' the gravity constant, 'D_l' the liquid diffusivity and 'w' the moisture content

In general, it can be noticed that in Delphin (solid lines) the moisture content at the end of the wetting period (28 days) is mostly higher than the results for WUFI. A possible explanation can be traced back to the gravitational component that is accounted for by Delphin. For example, when the source is introduced at the top (red), Point A (see 'Fig.4 (a)') will receive more water in Delphin than in WUFI. This makes it more convenient to use point sources in Delphin, compared to WUFI (e.g. when the source is located at the top (red line in Fig.4.a): in Delphin more water reached point A at the end of the wetting period (an increase in MC of 3.5%) compared to WUFI(1.2%). In the experiment, the MC increased with 2% in point A, but with peaks of 4%. The results in Delphin are consequently closer to the real situation, and more conservative.

4.2 Results using equal materials in both software packages

Next to the gravitational difference, also the moisture redistribution is different in both programs. In WUFI, this property is typically approximated as 10% of the liquid transport coefficient for suction. For the OSB material, the value for redistribution at w_{cap} is 1e-9m²/s. In Delphin, the reverse water retention curve contains the same values as the water retention curve (leading to 1e-12m²/s for w_{cap}).

This difference can clarify the difference of the green curves in Fig. 4.a: in WUFI no saturation occurs because the moisture is spread more rapidly. In Delphin, the MC in point A reaches saturation, and because the vapour resistance is more than twice the vapour resistance of the original material, it cannot dry out very fast. Fig. 4.a clearly illustrates the impact of the position of the moisture source. In Delphin, the uniform load of 12ml/m², as well as the point source, cause a moisture content above 20% at certain locations in the construction. This might cause moulding and decay of the material. In WUFI however, this critical level is exceeded only for shorter periods only at the location of the source, but immediately dries out at the end of a wetting event.

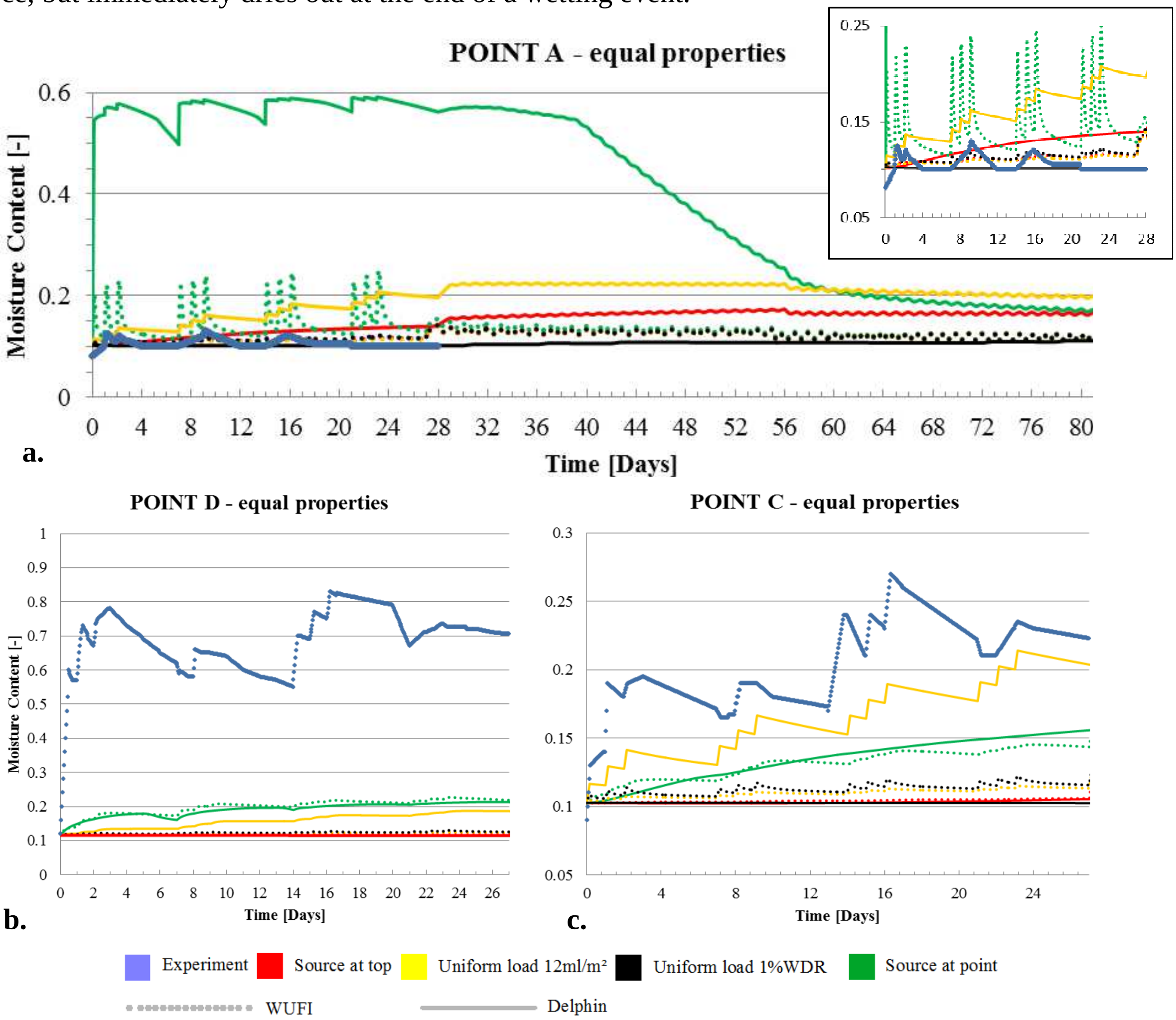

Figure 4. Moisture content at point A **(a)** , D **(b)** and C **(c)** for the experiment and 2D-simulations with the moisture source at different positions, and equal material properties for WUFI and Delphin.

In 'Fig. 4(b)', it is illustrated that the results for WUFI and Delphin are similar when the source is located at point D (green), but the high moisture level as in the experiment is not reached. Nonetheless, only this approach leads to a MC above 20%, which could warn the designer.

These results assume that the combination of a uniform loading at the interior side of sheathing, and an additional point source at the bottom plate to account for water accumulation, might be the best approximation for each point in the construction. This is also confirmed by the data for point C ('Fig 4(c)). The results for a uniform load (yellow) or the proximity of a point source (green) come most closely to the experimental observations.However, the different results between WUFI and Delphin point out that the results of 2D-simulations highly depend on the model used and the way moisture is applied to the construction. The results should not be taking for granted and must be analysed very carefully before drawing conclusions.

5 CONCLUSION

In this study, the use of a point moisture source to simulate water leakage in a wood frame wall is compared to the approach of a uniform moisture load, for both WUFI and Delphin. The results are validated with experimental measurements obtained from literature.

Because gravity is taken into account in the Delphin-software, this program shows a more realistic distribution in case of point sources. However, none of the models is able to reproduce the moisture accumulation at the bottom of the wall, when the conditions are modelled as in the experimental setup. From these preliminary results, it can be concluded that for this wall type, the approach of a uniform moisture load at the interior side showed the best results for the sheathing material. An additional moisture source at the bottom plate is necessary to simulate the moisture accumulation there. For the exact amount and position of the source, further research is needed. Evidently, the material properties have a big influence on the result. For this case, the vapour diffusion resistance of the OSB and the water content of the insulation material turned out to be significant parameters.

ACKNOWLEDGMENTS

This research is founded by the agency for Innovation by Science and Technology-Belgium (IWT), Project 131699. The authors thank Anik Teasdale-Saint-Hilaire for her experimental data.

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