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HYGRO-THERMAL EXPERIMENTAL ANALYSIS OF A FLAT ROOF STRUCTURE INTEGRATING A VARIABLE VAPOR-DIFFUSIVITY MEMBRANE

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ABSTRACT: The work presented hereby aims at verifying the hygro-thermal performances of a non-ventilated timber frame flat roof structure integrating a variable vapor-diffusivity membrane. In particular, the objective is to verify the drying up process of the specimen after a humidity storage phase. These two phases have been determined referring to the typical conditions occurring in a European continental winter period (when, usually, humidity coming from indoor environments is stored by the structure) and a summer period (when, typically, the structure has should dry up). Hence, considering the specific use of variable vapor-diffusivity membrane, the main objective is to verify whether a drying process is allowed towards the indoor environment. An experimental test on a specimen has been performed in a double climatic chamber and the results have been used in order to validate an hygrothermal model. The model allowed then to study the structure's hygrothermal behaviour in different climatic conditions, showing promising outcomes related to the use of a variable vapor-diffusivity membrane in such envelope component.

KEYWORDS: Dynamic hygro-thermal behaviour, Modelling and simulation, Membrane and timber-based construction

1 INTRODUCTION

Vapor membranes are used to manage vapor transfer through the building structures.

It is well-known that excessive humidity levels within the building envelope may cause relevant damages to structures and materials, affecting both structural and physical performances (e.g., decreasing thermal conductivity) [1] [2] [3]

Typically, in continental climates, vapor-retarder or barriers membranes are used to prevent high level of moisture to reach the outer layers of the envelope in order to avoid condensation issues during the cold season.

Nowadays, the use of variable vapor-diffusivity membrane in the building sector is growing [4]. These membranes can vary their vapor permeability properties depending on the humidity of the environment in which they are embedded. In particular, they reach high vapor permeability when surrounded by high humidity levels and vice versa.

However, it is not a common approach to use this kind of membranes in roof structures since, in order to avoid condensation issues in the outer layer of the structure during cold season, vapor barriers or retarders are usually installed on the inner side of the structure. Actually, this approach does not consider eventual criticalities occurring on the building site while installing these membranes, since the posing procedure may cause dangerous leakages for vapor within the structure. Small damages, scratches and imperfections during the laying of those membranes may be the cause of potentially critical one-way vapor leakages through the envelope, in particular if timber based. The variable vapor-diffusivity membrane can potentially solve this issue, behaving as a vapor retarder within typical indoor relative humidity ranges, while becoming more vapor-open when surrounded by higher humidity values.

Hence, in this study, an alternative solution to the application of vapor retarders or barriers has been investigated, namely adopting an innovative variable vapor-diffusivity membrane. Such membrane has the capability of varying its permeability to vapor, behaving as a vapor open layer when embedded in high moisture conditions hence, allowing a higher flexibility in the application procedure, ensuring a drying potential to the structure containing high humidity levels. A detailed dynamic model of the construction has been setup, supported by experimental tests and a set of simulations has been run to calculate the whole construction hygro-thermal performance under different climates, aiming at validating the use of such innovative layer.

2 METHODOLOGY

To access the performances of the proposed solution, a typical timber frame roof structure integrating a variable vapor-diffusivity membrane has been tested in a controlled environment and a numerical model performed in Delphin 6 has been calibrated with test results. The

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model has been run for 10-years-long hygro-thermal simulations in different climatic conditions.

The following steps have been followed in order to set up the analyses:

1. Assembling of the prototype – the prototype has been assembled at EURAC Research laboratories, in order to allow an easy installation of the hygrothermal sensors within the material layers.
2. Pre-conditioning – the different layers, still not completely assembled, have been kept in a climatic chamber at high relative humidity level (~80%) and constant temperature for 3 days. This procedure ensured that the humidity content of the specimen would have been high enough at the beginning of the dynamic test, having reached an hygrothermal balance with the surrounding environment, and could have highlighted the drying process during in the following testing phases.
3. Dynamic test – after the pre-conditioning, the prototype has been completely assembled and installed within the testing facility (i.e., the Multifunctional Façade Lab, namely a double climatic chamber at EURAC Research laboratories). Here, dynamic test has lasted 15 days. Temperature and relative humidity of a continental summer weather condition have been replicated on the outer side of the specimen (one of the two chambers of the Multifunctional Façade Lab) in order to verify the drying potential towards a constant-condition inner side of the prototype (facing the other chamber of the testing facility).
4. Model calibration and extended simulations – measuring realistic dynamic hygrometric behaviours within building materials would require very long timespans, in the range of seasonal climatic variations, and this is of course not feasible to be performed in a laboratory on large scale specimens. Therefore, it has been decided to use the results from the tests to calibrate and validate a numerical model using Delphin 6. The model allowed to evaluate the hygrothermal behaviour of the structure in an extended timespan and in different climate conditions.

2.1 EXPERIMENTAL SET-UP

The tested prototype has an area of 1.44 m² (1.2m x 1.2m). The layer and material properties within the structure are described in Table 1.

Table 1: *Structure layers and material properties*

Layer (inside to outside)	Thickness	Density	Heat Capacity	Conductivity	Vapor Permeability
	[mm]	[kg/m³]	[J/kgK]	[W/mK]	Sd[m]; μ[-]
Gypsum fibre Board	12.5	744	1384	0.21	μ =4
Variable Vapour Diffusivity Membrane	*	*	*	*	Sd_variable = 0.15 ÷ 5
Mineral Wool Insulation	240	110	1030	0.036	μ = 3.5
OSB Panel	20	530	1880	0.1	μ = 280
Self-Adhesive Bituminous Membrane	*	*	*	*	Sd= 200
Self-adhesive Slate Bituminous Membrane	*	*	*	*	Sd= 280

** Delphin is not requiring this parameter for simulations*

The above-mentioned values have also been used in the simulation model. Anyway, for some of the materials, detailed data sheets were not available. For these specific cases, assumptions have been made using typical values for similar products. These values have been considered as main parameters to be calibrated in order to match model and test results.

The test has been performed in double climatic chamber and in order to monitor the hygrothermal conditions within the specimen, it has been equipped with 8 Amphenol T9602 sensors, measuring temperature (-20÷70°C ± 0.3°C) and relative humidity (0÷100% ± 2%). In Figure 1, Figure 2 and Figure 3, sensors' position within the prototype is represented.

Sensors 1,2 and 3 are placed between the OSB partner and insulation layer, being embedded in this last.

Sensors 4,5 and 6 are placed between the vapor variable diffusivity membrane and the insulation; hence, they are not in contact with the gypsum-fibre board.

Sensors 7 and 8 are positioned between two insulation layers, approximately in middle of the specimen thickness.

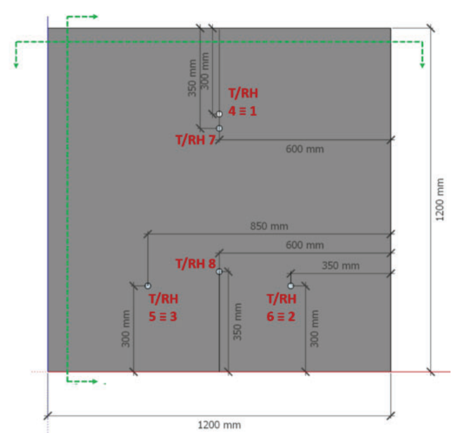

Figure 1: *Sensor positioning scheme, specimen front view*

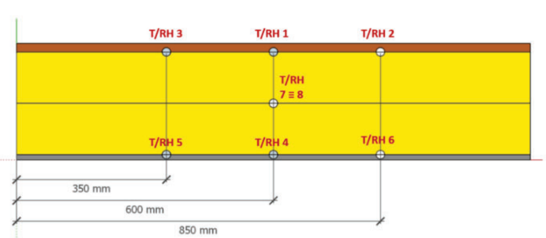

Figure 2: *Sensor positioning scheme, horizontal section*

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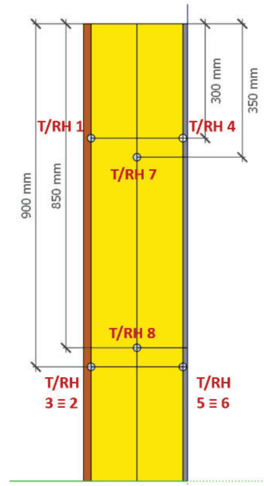

Figure 3: *Sensor positioning scheme, vertical section*

2.2 DYNAMIC TEST

Once the pre-conditioning phase, used to load the specimen of vapor, has been concluded (3 days at 80% relative humidity), the dynamic test started. Hence, operative conditions typical of a summer continental European climate have been reproduced within the facility.

In particular, in order to determine the external temperature and relative humidity conditions to be applied during the test, a typical climatic year related to Munich (Germany) has been used the weather file has been made available by the World Meteorological Organization (https://public.wmo.int/en) and downloaded by the Energy Plus website (https://energyplus.net/weather). From this reference hourly data, 4 summer days (middle of June) have been extrapolated and used to build the temperature and relative humidity curves to be reproduced by the testing facility's chamber representing the outdoor environment. Concerning the conditions set on the indoor side, where humidity is free floating between 30% and 60%, temperature has been set to 20°C. A scheme of the test setting in shown in Figure 4, while a picture of the specimen installed in the Multifunctional Façade Lab is in Figure 5.

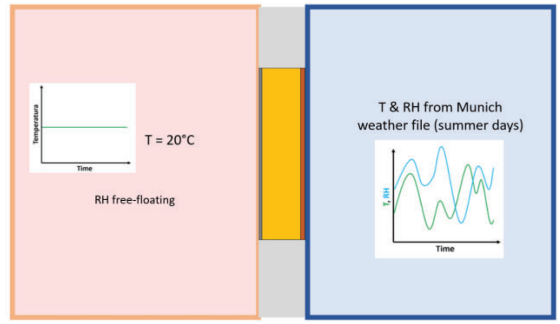

Figure 4: *Schematic view of the test setting within Multifunctional Facade Lab; the specimen is between indoor and outdoor conditions created in the chambers*

Figure 5: *Prototype installed in the testing facility*

Dynamic tests took about 17 days. In Figure 6 and Figure 7, the graphs are showing the monitored boundary conditions in the chambers during the test.

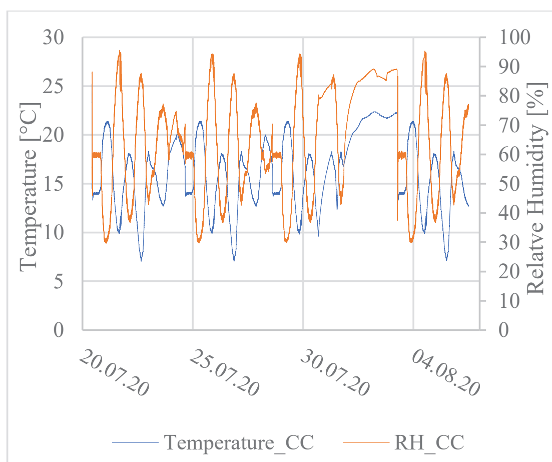

Figure 6: *Temperature and Relative Humidity conditions on the Outdoor side of the specimen during the test. "_CC" stand for "Cold Chamber", referring to the facility chamber reproducing the outdoor environment*

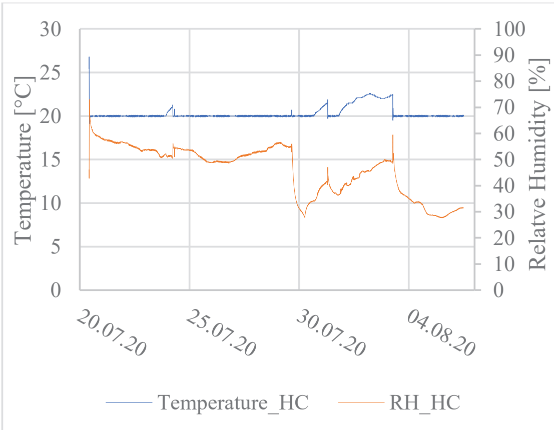

Figure 7: *Temperature and Relative Humidity conditions on the Outdoor side of the specimen during the test. "_HC" stand for "Hot Chamber", referring to the facility chamber reproducing the indoor environment*

2.3 MODEL CALIBRATION

After about two weeks of dynamic test, the data acquired by the sensors within the specimen have been used to calibrate a bi-dimensional hygro-thermal model, developed with the software Delphin 6. Hence, the model aimed at reproducing faithfully the testing conditions, also taking into account the gravity effect on vapor transfer dynamics, due to the vertical position of the prototype.

In Figure 8, a schematic representation of the bi-dimensional prototype geometry modelled is shown. The initial values for material properties used by the model are reported in Table 1.

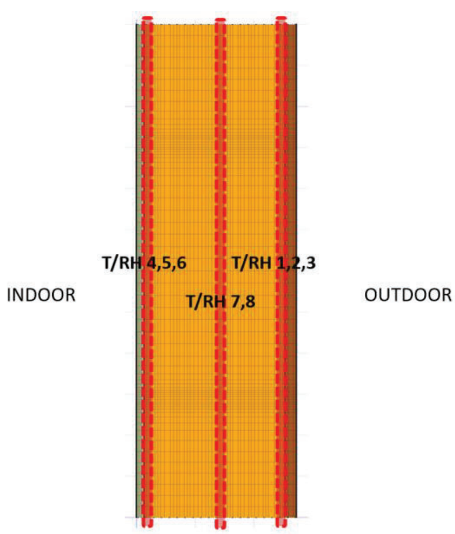

Figure 8: *Geometrical model used in Delphin 6; it is possible to notice the calculation mesh and the layers (marked in red) where the model outputs have been evaluated*

Figure 8 is also showing (in red) the layers in which temperature and relative humidity outputs from the model has been taken, as averaged value of the selected nodes within the mesh.

As a consequence of this, temperature (T) and relative humidity (RH) measured by sensors T/RH 1, 2 and 3 will be compared respectively with model outputs called T123 and RH123; values from sensors T/RH 4,5 and 6 will be compared with output T456 and RH456; values from sensors T/RH 7 and 8 will be compared with output T78 and RH78.

In the following graphs (from Figure 9 to Figure 14), calibration process' results are shown. In these graphs, it is possible to notice the comparison between monitored data and results from the model in the specific layer.

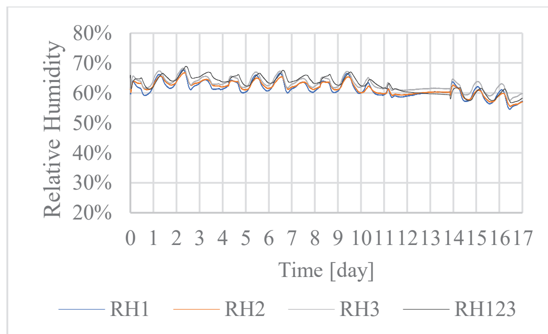

Figure 9: *Comparison between RH 1, 2 and 3 from tests with model results RH123*

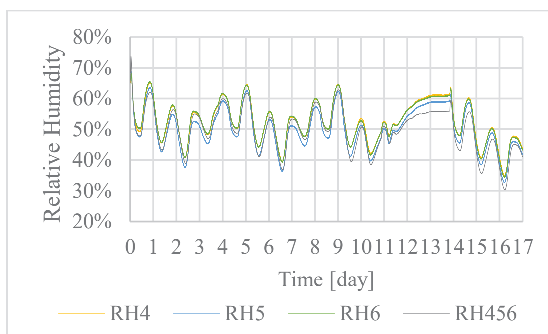

Figure 10: *Comparison between RH 4, 5 and 6 from tests with model results RH456*

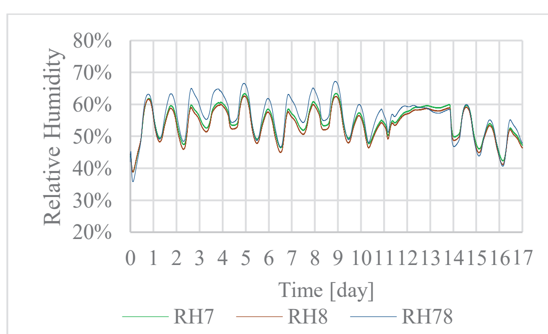

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Figure 11: *Comparison between RH 7 and 8 from tests with model results RH78*

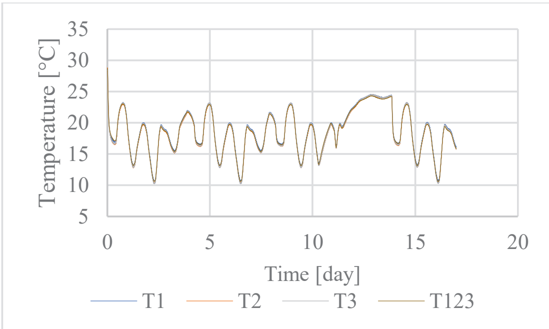

Figure 12: *Comparison between T 1, 2 and 3 from tests with model results T123*

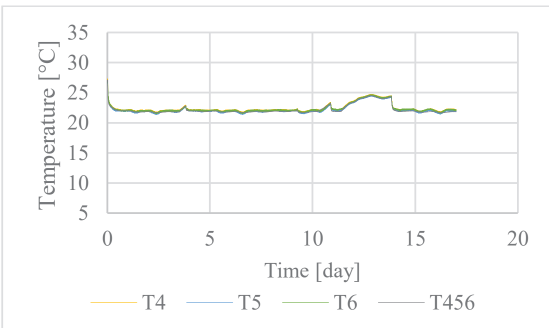

Figure 13: *Comparison between T 4, 5 and 6 from tests with model results T456*

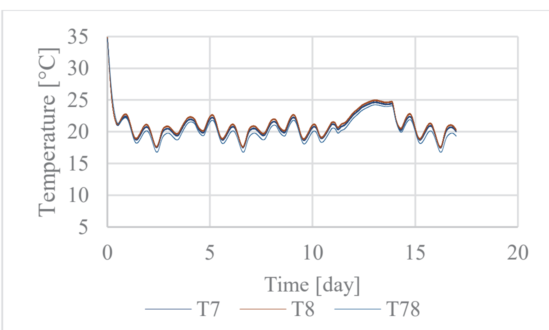

Figure 14: *Comparison between T 7 and 8 from tests with model results T78*

In the following Table 2 and Table 3, the Mean Absolute Error (MAE) and the Root Mean Square Error (RMSE) between model output and the average value of the sensors within the same layer are reported.

Table 2: *MAE and RMSE for relative humidity values*

	RH 123	RH 456	RH 78
MAE	0.014	0.019	0.023
RMSE	0.017	0.024	0.027

Table 3: *MAE and RMSE for temperature values*

	T 123	T 456	T 78
MAE	0.14	0.15	0.56
RMSE	0.17	0.18	0.60

To calibrate the model which brought to the above-mentioned results, it has been necessary to slightly modify the materials' properties within the software, applying some small variations on the values taken from the datasheets. Calibrated material properties used in the model are shown in Table 4. In particular, some change in the vapor permeability of the insulation layer has been applied. Nevertheless, this variation is acceptable, especially considering the high-compression and high-humidity levels of the material within the specimen. Some other variations of the vapor permeability of material have been adopted, but always within ranges reported on their technical sheets. Table 4 shows the material properties used in the calibrated model.

Table 4: *Material properties used after calibration process; for those values which have been modified respect to the initial one, this last is shown between brackets.*

Layer	Thickness	Density	Heat capacity	Conductivity	Vapor permeability
	[mm]	[kg/m³]	[J/kgK]	[W/mK]	Sd: [m]; μ:[ ]
Gypsum fibre Board	12.5	744	1384 (n.d.)	0.21	μ =4
Variable Vapour Diffusivity Membrane	*	*	*	*	Sd_variabile = 0.15 - 6
Mineral Wool Insulation	240	110	1030	0.036	μ = 3.5 (1)
OSB Panel	20	530	1880 (n.d.)	0.1	μ = 280 (90 – 150)
Self-Adhesive Bituminous Membrane	*	*	*	*	Sd=200
Self-adhesive Slate Bituminous Membrane	*	*	*	*	Sd=280

** Delphin is not requiring this parameter for simulations*

3 EXTENDED ANALYSIS IN DIFFERENT CLIMATES

Once performed the model calibration, it has been used to extend the hygrothermal study in different climatic conditions for 10-years-long simulations. The objective is to verify the effective drying potential of the structure in the summer period after and eventual humidity storage during the coldest season. Furthermore, a simulation set up (namely "Condition 2") verified a slightly different stratigraphy, also considering an additional insulation layer and a gypsum fibre board in the inner layers.

Being the simulation referred to a roof structure, the model has been set in horizontal direction, taking into account the gravity effect on moisture transport. This allowed to verify the real hygrothermal behaviour of the roof structure.
Table 5 is reporting the configurations used for extended hygrothermal analyses.

Table 5: *Boundary conditions for extended analyses*

Condition	Model stratigraphy	Internal condition T and RH	External condition T and RH
Condition 1	Stratigraphy calibrated with test results (**Errore. L'origine riferimento non è stata trovata.**)	WTA adaptive indoor climate model[1] implemented in software Delphin6.0	Yearly weather file Central Europe[2] Munich
Condition 2	Stratigraphy calibrated with test results (**Errore. L'origine riferimento non è stata trovata.**) + 5 cm insulation + gypsum fibre board	WTA adaptive indoor climate model[1] implemented in software Delphin6.0	Yearly weather file Central Europe[2] Munich
Condition 3	Stratigraphy calibrated with test results (**Errore. L'origine riferimento non è stata trovata.**)	WTA adaptive indoor climate model[1] implemented in software Delphin6.0	Yearly weather file hot and humid conditions[2] Brisbane
Condition 4	Stratigraphy calibrated with test results (**Errore. L'origine riferimento non è stata trovata.**)	WTA adaptive indoor climate model[1] implemented in software Delphin6.0	Yearly weather file hot and humid conditions[2] Abu Dhabi

[1] WTA Adaptive Indoor Climate Model provided from DIN EN 15026; it allows to determine indoor temperature and relative humidity conditions in relation to the outdoor ones
[2] Outdoor climatic data to run the simulations have been provided by the World Meteorological Organization and taken on the Energy Plus website (https://energyplus.net/weather)

Here below, for the modelled configurations, the trends for integral humidity content within the stratigraphy and the relative humidity value in the layer between insulation and OSB board (RH123) are reported. It may be noticed from Figure 15, Figure 16, Figure 17 and Figure 18 related to Condition 1, 2, 3 and 4 that the humidity content during the 10-years-long simulation is periodically increasing in winter seasons while dries during summer periods. It is important to highlight that humidity content peaks are growing in the first simulated years (around 3) and then they are constant for the rest of the simulation. Furthermore, these peaks are not even reaching critical relative humidity leading to over-hygroscopic content (95%). Indeed, higher relative humidity values within the structure, reached in Condition 1 simulation, are around 87%.

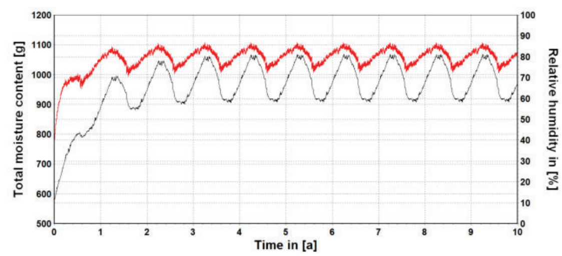

Figure 15: *Condition 1 Munich (Germany) - humidity content trend (black curve) and relative humidity at interface insulation-OSB (red curve)*

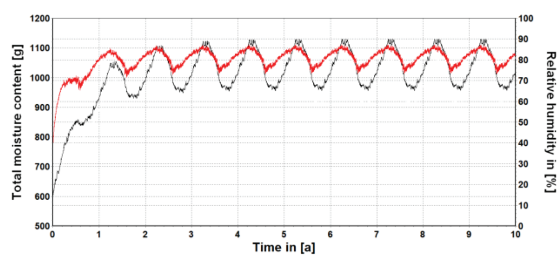

Figure 16: *Condition 2 Munich (Germany) - humidity content trend (black curve) and relative humidity at interface insulation-OSB (red curve)*

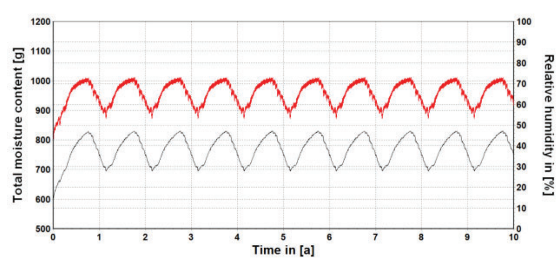

Figure 17: *Condition 3 Brisbane (Australia) - humidity content trend (black curve) and relative humidity at interface insulation-OSB (red curve)*

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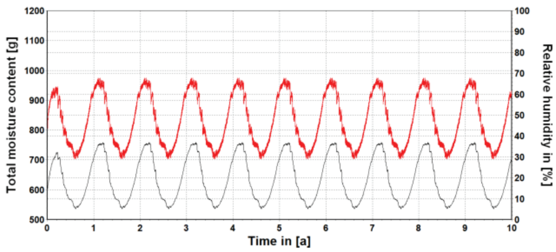

Figure 18: Condition 3 Abu Dhabi (United Arab Emirates) - humidity content trend (black curve) and relative humidity at interface insulation-OSB (red curve)

In Figure 19, the comparison of internal moisture content in Condition 1 (Munich climatic condition) with and without variable vapor diffusivity membrane is shown. It can be noticed that the moisture content is clearly higher in the condition without the membrane and, furthermore, this configuration is leading to cyclical creation (up to ~150 g) of over-hygroscopic content (Figure 20).
Despite the condensate dries every year, this condition is potentially dangerous for the envelope due to a possible mould-growth phenomenon or deterioration of materials.

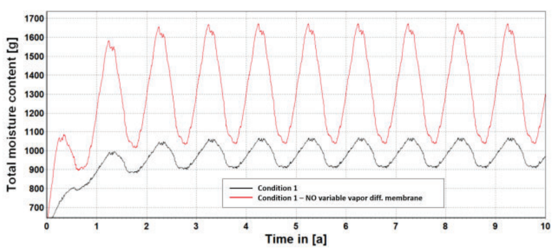

Figure 19: Condition 1 - moisture content with (black curve) and without (red curve) variable vapor diffusivity membrane

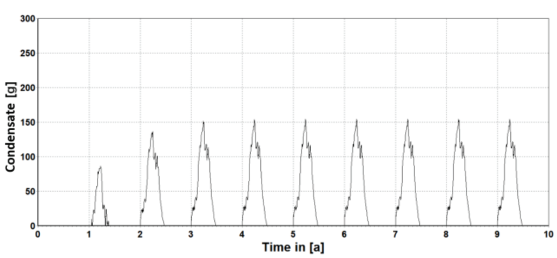

Figure 20: Condensate in Condition 1 without variable vapor diffusivity membrane

4 CONCLUSION

The methodology described allowed to successfully verify the hygro-thermal behaviour of a flat roof structure integrating a variable vapor diffusivity membrane.
After having performed 15-days-long experimental tests with dynamic boundary conditions across the specimen, temperature and relative humidity monitored values have been used to calibrate a numerical model developed with the software Delphin 6.
Once a detailed level of precision of the model was reached, it has been used to extend the analyses to 10-years-long period, evaluating the behaviour of the flat roof stratigraphy in different climatic conditions.
In all the simulated cases, the stratigraphy has not presented critical issues related to condensate formation, suggesting that the use of the variable vapor diffusivity membrane is effective to prevent from excessive moisture storage within the structure, allowing its drying during the warmer season.
As demonstrated by the simulation in Central European weather condition, without using the variable vapor diffusivity membrane, its presence is crucial to avoid periodical condensation events in the outer layers of the envelope during winter conditions.
The methodology applied to the specific stratigraphy analysed in this paper may be successfully replicated for developing further analyses, varying the application context and, hence, boundary conditions of the evaluated envelope structure.

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