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Evaluating the hygrothermal performance of prefabricated timber frame façade elements used in building renovation

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Abstract

Refurbishing existing buildings plays a key role in reducing the overall energy consumption of the building stock. The use of prefabricated timber façade elements in the renovation of buildings is often beneficial due to their limited thickness and weight, the integration of HVAC and windows, the functionality and speed during works etc. Despite these proven benefits, these systems are not commonly used in Belgium. The research project of which this work is part of, therefore aims to stimulate the use of these elements for renovation by eliminating technical barriers that may hinder their use. In this paper, the impact of different design choices on the hygrothermal performance of elements that are installed in front of an existing façade, e.g. a cavity wall, is evaluated. The protection of the existing inner cavity leaf after demolition of the outer cavity leaf, the integration of a vapor retarder between the new element and the existing construction and the use of cellulose insulation proved to be advantageous measures to reduce the risk of degradation.

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1. Introduction

According to EU regulations the energy use for heating and cooling of buildings has to decrease by 2050. In this context, prefabricated façade elements have a large potential in the renovation of the existing building stock. They are however rarely used in the Belgian renovation market due to lack of knowledge on a technical level.

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Several research projects have already investigated the use of prefabricated façade elements for renovation, including the TES Energy Façade project which also focused on timber frame elements [1]. The basic TES façade module consists of a cladding layer, TES module and an adaption layer that fills the void between the existing façade and the new element. The module can either be a closed module, including a paneling layer at the backside of the module, or an open module.

The hygrothermal performance of these prefabricated elements is however only briefly discussed. This research therefore wants to investigate the hygrothermal behavior of prefabricated timber façade elements by means of simulations in WUFI. Previous research [2] already showed that WUFI is a good tool to determine the moisture performance of the TES Energy façade after renovation. Other hygrothermal research on timber frame elements focused on the dry-out capability of initially moisture concrete slabs and the impact of a vapor barrier on the entire envelope performance [3].

Prior research on these timber façade elements focused on what happens when the existing wall is humid, e.g. because it is left unprotected after the existing outer cavity leaf was demolished, and investigated the effect of orientation [4]. This paper wants to substantiate the prior results by means of 2D simulations and additionally investigates the effect of protection of the existing inner cavity leaf and the use of alternative sheeting boards.

2. Initial moisture content of the existing façade

In prior research [4] the initial moisture content for different wall types and orientations was evaluated. The results showed that the moisture content was the highest for inner cavity leaves that are left unprotected after the demolition of the outer cavity leaf. In terms of orientation, a south west orientation resulted in the highest moisture contents. Fig. 1(a) shows the moisture content during 1 year of exposure. In this research, the effect of protection of the inner cavity leaf is studied. In this case, the initial moisture content of the inner cavity leaf was determined from a simulation of the existing cavity wall with the outer cavity leaf present. The moisture content of the inner cavity leaf during one year is shown in Fig. 1(a). The max. moisture content of a protected and unprotected cavity leaf is respectively 20,5 and 189,7 kg/m³. These moisture contents are used in the following simulations to estimate the initial moisture content of the existing façade. It should be noted that use of the max. moisture content of 189,7 kg/m³ in the following cases in which the inner cavity leaf was left unprotected, is rather conservative. In reality, the initial moisture content will probably not be the maximum value.

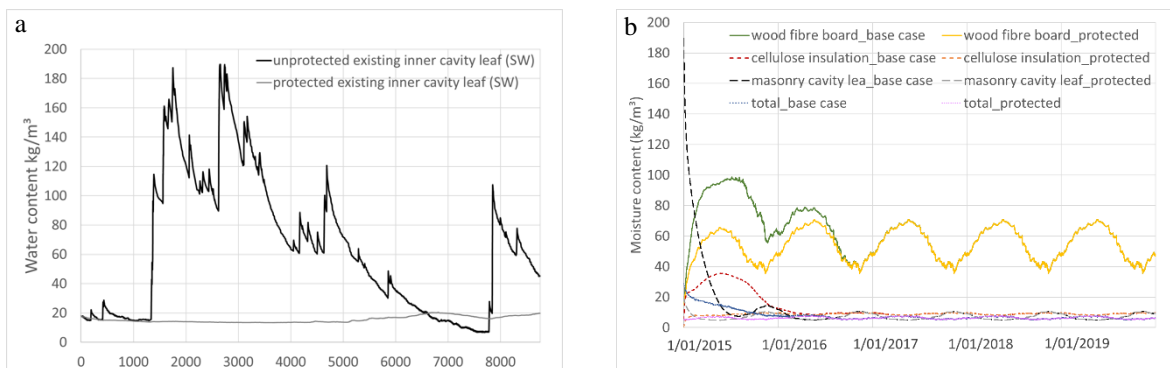


Fig. 1. Moisture content in kg/m³ of (a) a SW orientated protected and unprotected cavity leaf; (b) base case and case with protected cavity leaf.

3. Evaluation criteria

The examined timber frame façade elements contain different moisture sensitive wood based materials. To evaluate their risk of degradation (mold growth or wood rot) different evaluation criteria are used. In a first step the risk of degradation is evaluated by means of the TOW (= 'Time of Wetness') criteria by Viitanen [5]:

- TOW 20/5: the number of hours during which the moisture content is higher than 20% kg/kg and the temperature > 5°C should not exceed one month per year or max. 720 hours per year in order to prevent mold growth.
- TOW 25/10: the number of hours during which the moisture content is higher than 25% kg/kg and the temperature > 10°C should not exceed one week per year or max. 168 hours per year to prevent wood rot.

The risk of mold growth is further assessed by means of the VTT model. In this mold prediction model the growth development is expressed by the mold index (M). This index can vary between 7 mold index classes, from 0 (no mold growth) over 1 (small amounts of mold) to 6 (very dense mold). The updated version of the model, that can also be applied to other materials, was used here. A possible decrease of the mold index during unfavorable conditions for mold growth was not included in the evaluation, since Vereecken stated that this effect is not always reliable [6].

To evaluate the risk of mold growth on the wall surface, the isopleth model by Sedlbauer is used which is implemented in WUFI. The isopleth curves separate favorable from unfavorable temperature and relative humidity conditions for mold growth for different substrate groups [6].

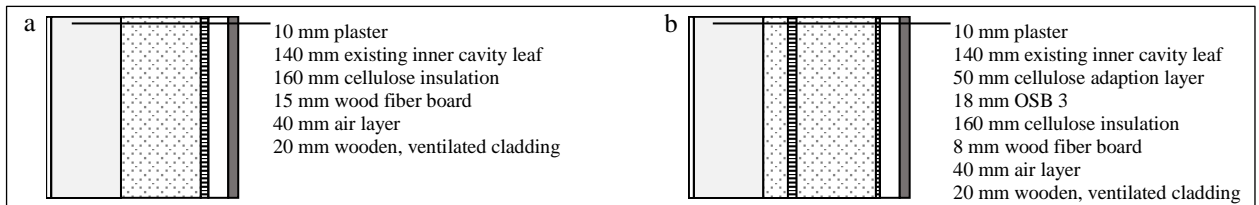


Fig. 2. (a) Open façade module; (b) closed façade module; (based on TES Energy Façade).

Table 1. Material properties (based on WUFI material database).

Material	d (mm)	ρ (kg/m ³)	C_p (J/kgK)	λ_{dry} (W/mK)	R (m ² K/W)	μ (-)	S_d (m)
Wood fiber board	8 - 15	300	1500	0.05	0.16 - 0.3	12.5	0.1 - 0.19
Cellulose insulation	160	70	2500	0.04	4	1.5	0.24
OSB	18	595	1700	0.11	0.16	165	2.97
Cellulose adaption layer	50	70	2500	0.04	1.25	1.5	0.08
Masonry	140	1900	2500	0.6	0.23	10	1.40
Mineral wool	160	60	850	0.04	4	1.3	0.21
Wooden stud	160x45	455	1500	0.09	-	130	-
Cement bonded particle board	18	1250	1500	0.35	0.05	50	0.90
Plaster board	15	1008	850	0.25	0.06	10	0.15

4. Hygrothermal evaluation

Two types of timber frame façade elements are examined: an open and a closed façade module. Fig. 2 shows the typical construction of these modules installed in front of an existing inner masonry cavity leaf. The depicted assemblies are the outset of this research and are called the base case modules. In the base case the inner cavity leaf is assumed unprotected from the rain after demolition of the outer cavity leaf.

All assemblies are modelled in WUFI PRO 5.3 and WUFI 2D - 3.4 with a south west orientation and air change rate of 10 ACH in the air cavity. The material properties used in the simulations can be found in Table 1. For the cellulose insulation, mineral wool, OSB and masonry, a constant water vapor resistance factor was used.

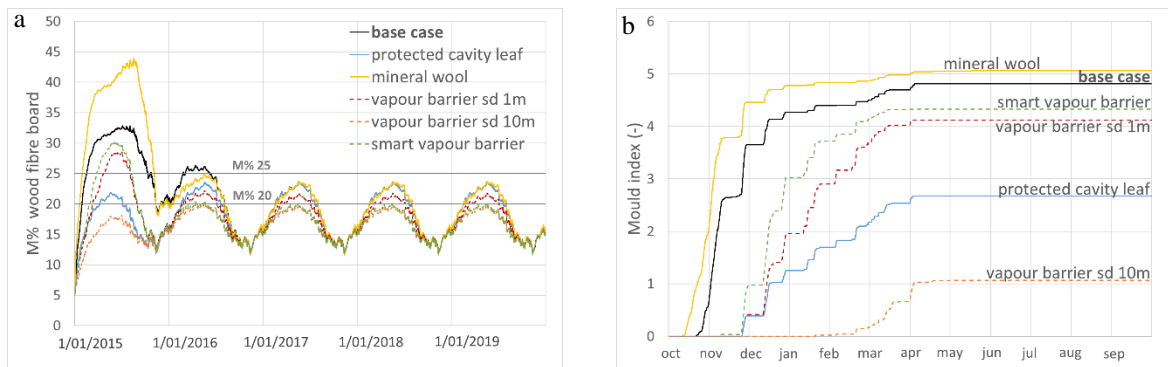


Fig. 3. (a) Moisture content in % kg/kg in the wood fiber board in the open façade module; (b) Mold index during the 1st year after drying out.

4.1. Open façade module

Fig. 1(b) shows the evolution of the moisture content in the open façade module for the base case and the case with protected inner cavity leaf. When looking at the base case, the initially humid masonry leaf dries out during the first two years. The resulting vapor flow causes a humidification of the wood fiber board (WFB) and cellulose insulation during the first year. For the case with protected cavity leaf, the moisture content of the WFB and cellulose insulation is not increased since the masonry cavity leaf is initially dry. It is now necessary to assess whether these moisture contents will cause degradation of the material. Wood based materials are, as stated above, prone to mold growth and wood rot. In order to assess these risks the moisture content in % kg/kg of the WFB is shown in Fig. 3(a) during a period of five years. In the base case the moisture content often exceeds 20% kg/kg which suggests a risk of mold growth according to TOW 20/5. Even when the cavity leaf was protected the moisture content still exceeds 20% kg/kg, yet much less than in the base case. When mineral wool is applied instead of cellulose the moisture content increases strongly. This is due to the very limited moisture buffering capacity compared to cellulose. The application of a vapor barrier between the masonry cavity leaf and the new module does seem to have a positive influence on the moisture content of the WFB. The best results are obtained by the application of a vapor barrier with an S_d -value of 10m since it mitigates the vapor flow the most. The use of a smart vapor barrier with changing equivalent air layer thickness does not show any improvement. On the contrary, the risk is higher compared to the other vapor barriers because the relative humidity at the vapor barrier initially leads to S_d -values lower than 1m. This lower S_d -value allows a faster drying out of the existing structure. For this reason, Pihelo et al. [3] recommended the use of a smart vapor barrier over the use of a normal vapor barrier. Their module however did not contain any wood based panels which they had to prevent from degrading.

The previous conclusions are confirmed when looking at the mold growth development of the WFB estimated by the VTT model during the first year (Fig. 3(b)). The application of a vapor barrier with an S_d -value of 10m reduces the risk of mold growth significantly from a mold index of almost 5 for the base case, to just over 1.

These previous results are obtained from 1D simulations in which the presence of the wooden studs is not taken into account. To check whether the application of a vapor barrier with an S_d -value of 10m will not lead to degradation of the WFB and stud in the actual case with wooden studs, a 2D simulation is conducted with a frame spacing of 400 mm. As expected, the moisture content of the WFB shown in Fig. 4(a) is higher in between two studs (marked in green) than right next to the stud (marked in orange), since the wooden stud has a higher vapor resistance than cellulose insulation (Table 1). Compared to the 1D simulation however the moisture content in the middle between two studs is significantly different, even though this is determined at a distance of about 200 mm from the stud. In any case, the 2D simulation results in safer conditions in regard to degradation of the WFB than the 1D simulation because the added wooden studs hinder the outgoing vapor flow more than the cellulose insulation. This results in a mold index of zero at every location in the WFB. For the wooden stud itself, the mold index is zero as well.

Since a vapor barrier is located between the existing structure and the new module, part of the vapor will dry out to the inside. This can possibly cause mold growth at the inner surface. Fig. 4(b) shows the isopleths on the inner surface calculated in WUFI 2D. The limiting isopleth is only exceeded during the period immediately after the existing cavity leaf is drying out (displayed in yellow). The risk of mold growth on the inner surface is therefore considered limited.

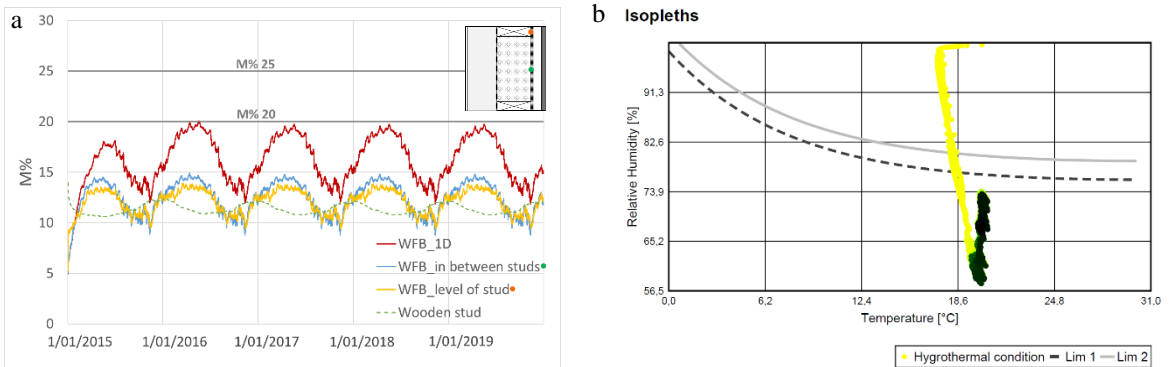


Fig. 4. (a) Moisture content in % kg/kg and (b) isopleths on the inner surface, for the case with a vapor barrier with an S_d -value of 10m.

Finally, in the case of cellulose insulation, a change in texture might occur due to the binding of moist cellulose flakes. This phenomenon was called "caking" by Rose and McCaa [7], yet specific criteria to assess this risk are still lacking. Langmans conducted experiments on cellulose insulation and measured moisture contents up till 35% kg/kg without any visual deformations or caking [8]. The max. moisture content of the cellulose insulation in the base case is 35,54 kg/m³, as shown in Fig. 1(b), or 51% kg/kg. Since this exceeds 35% kg/kg, potential caking cannot be ruled out. For the other cases the max. moisture content of the cellulose insulation ranges from 14% kg/kg for the case with protected cavity leaf to 17% kg/kg for the case with smart vapor barrier. Since the moisture content of the cellulose in all the other cases is significantly lower than 35% kg/kg, it is assumed that caking will not occur.

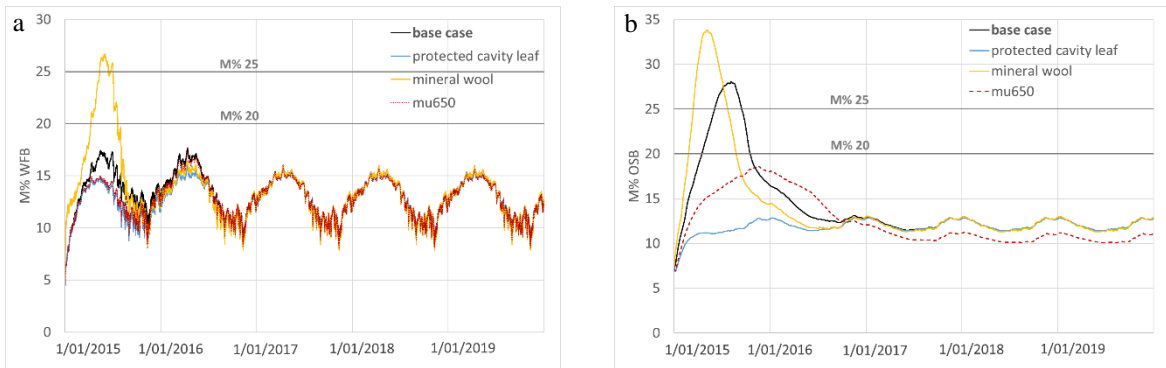


Fig. 5. Moisture content in % kg/kg of (a) the WFB and (b) the OSB panel in the closed façade module during a period of five years.

4.2. Closed façade module

Unlike the open façade module, the closed façade base case module does not lead to a risk of degradation of the WFB as shown in Fig. 5(a). For the OSB panel however, Fig. 5(b) shows a significant risk of degradation. As with the open façade module, the risk increases when mineral wool is applied instead of cellulose and the risk decreases when the existing cavity leaf is protected before renovation. When the OSB panel is replaced with a 4 times more vapor tight OSB panel ($\mu=650$ instead of 165) the moisture content in the OSB panel is damped to such an extent that there is no longer a risk of degradation of both the WFB and OSB panel according to the TOW criteria.

For the cellulose in the base case the max. moisture content over 5 simulated years is 16% kg/kg. Since this is significantly lower than the 35% kg/kg measured by Langmans, it is assumed that no caking will occur in the cellulose.

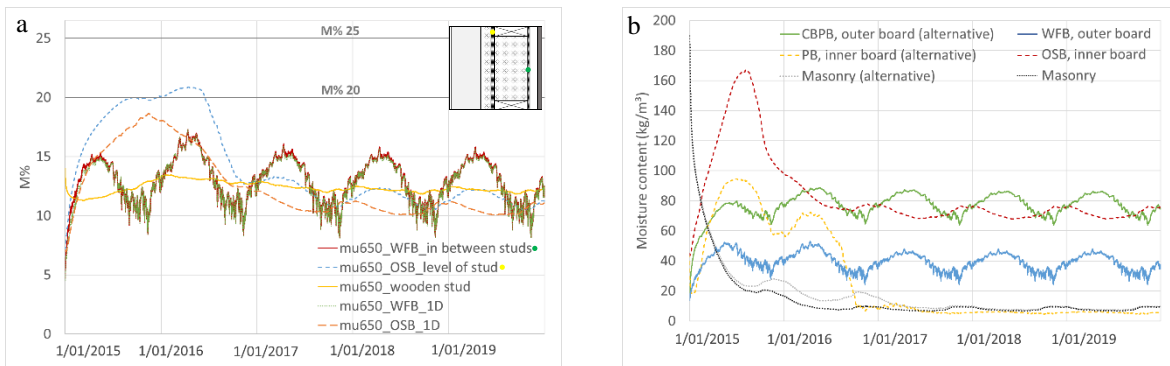


Fig. 6. Moisture content in (a) % kg/kg of the wood based materials (for "mu650" in 2D), (b) kg/m³ during 5 years for alternative and base case.

To check whether the case with protected cavity leaf and the case with a more vapor tight OSB panel are still without risk for degradation in the actual case with wooden studs, 2D simulations are conducted. Fig. 6(a) shows the moisture content of the wood based materials for the latter case. Only the most humid points of the materials were analyzed, which are right next to the stud for the OSB panel, since the drying out of the OSB panel is there more

hindered by the stud, and in the middle between two studs for the WFB, since the cellulose insulation hampers the vapor flow the least. Fig. 6(a) shows that similar to the open module, the moisture content of the WFB in the closed module is slightly lower than in the 1D simulation. This is however not the case for the OSB panel. Since the wooden stud has a higher μ -value than the cellulose, the stud hampers the drying out of the OSB panel more, which leads to more hazardous conditions for degradation than in the 1D simulation. Fig. 6(a) also shows that only for the OSB panel in the case with a more vapor tight OSB panel the moisture content does exceed 20% kg/kg for quite some time, which implies a risk of degradation. For the case with protected cavity leaf the same conclusions were drawn, except for the OSB panel which never exceeds 20% kg/kg. Thus, only for this case there is no risk of degradation. Degradation risk assessment using the VTT model confirms this: the mold index is zero for every wood based material in the case with protected cavity leaf. Lastly, the risk of mold growth on the inner surface was evaluated. It was shown that the limiting isopleth is only exceeded right after the existing cavity leaf is drying out and therefore the risk is considered limited.

In the previous cases, moisture sensitive wood based panels were used as sheathing boards, but of course non-wooden based sheathing boards can also be used. To assess the hygrothermal performance of alternative sheathing boards in a closed module, the WFB was replaced by a cement bonded particle board (CBPB) and the OSB panel by a plaster board (PB). A vapor barrier was added to the outside of the plaster board to ensure vapor and air tightness. Fig. 6(b) shows the evolution of the moisture content in this element compared to the moisture content of the closed façade base case during five years. This module has a slightly longer drying out period, since the cement bonded particle board is more vapor tight compared to the WFB in the base case. Evaluation of the temperature and relative humidity at the inner surface showed that the limiting isopleth is only exceeded during the period immediately after the existing cavity leaf is drying out and the risk of mold growth is therefore considered limited.

5. Conclusion

In general, the hygrothermal simulations showed that the use of cellulose insulation is preferred due to its moisture buffering effect. In addition, also the application of a vapor retarder between the new element and the existing construction and the protection of the existing inner cavity leaf proved to be advantageous.

For the open module, the simulations showed that the best results are obtained when a vapor barrier with an S_d -value of 10m is integrated. This however depends on the initial moisture content of the existing wall. If it is unclear how moist the existing wall is, it is always recommended to integrate such a vapor barrier. For the closed module, the inner cavity leaf should be protected after demolition of the outer cavity leaf in order to rule out degradation of the OSB paneling layer. Application of an OSB panel with a high diffusion resistance as vapor retarder in the construction also has a positive effect. The use of alternative sheathing boards in the closed module led to a slightly longer drying out period, but may be advantageous as the degradation risk of these non-wood based materials is considered lower.

Acknowledgements

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