European Journal of Wood and Wood Products
https://doi.org/10.1007/s00107-024-02149-0

ORIGINAL ARTICLE

Crack size in coating and moisture problems comparing thermally modified and native spruce window frame profiles using hygrothermal simulations

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Received: 9 April 2024 / Accepted: 29 August 2024

Abstract
Fungal growth and degradation of wood may be caused by damage in the surface coating. The larger the cracks, the greater in principle the possibility of moisture-induced problems. Measuring basic unknown material parameters and employing hygrothermal simulations, the suitability and the maximum acceptable vertical crack size in the surface coating for a given bottom window profile made of thermally modified (TM) spruce(wood) with that made of native spruce were compared for location Ljubljana. Validation with the field test data was the second objective of the respective research. The average calculated maximum moisture content in TM spruce is about 4% (kg/kg) lower than that of native spruce. The 3 mm wide crack in the surface coating of a window frame made of native spruce is of the highest concern, whereas a 9 mm wide crack in the coating of a TM spruce profile is still acceptable. As far as moisture content is concerned in our study the TM spruce window frames were proved to be significantly more suitable for installation than the corresponding frames made of native Norway spruce. It was shown that isopleth, VTT and biohygrothermal models for mould growth do not properly capture the comparison between both materials, mainly because they classify both in the same material class/substrate category and they do not consider the material moisture content.

1 Introduction

Various studies on wood-degrading fungi have shown that the minimum moisture content of wood suitable for decomposition depends on the fungal species and the wood, and ranges between 25 and 30% (a few percent below fibre saturation) (Schmidt 2006; Brischke and Alfredsen 2020). In extreme cases, it has been shown that mycelium can grow on wood with a moisture content of 17.4% in cases where a nearby water source is available (Meyer and Brischke 2015; Meyer et al. 2016). Liquid water penetration into the wooden window profiles should, therefore, be avoided.

Protective surface coatings limit liquid water penetration but do not fully prevent it, especially if the coatings are damaged. This is also true for thermally modified (TM) wood (Humar et al. 2020a). Therefore, it is desirable to determine the dynamics of moisture transport and accumulation in the wooden objects and the corresponding climatic circumstances. In addition, the relationship between climate-induced wood damage and moisture content is of great interest as well. Keeping the MC of wood low can extend its service life (Meyer and Brischke 2015; Thybring et al. 2018; Ringman et al. 2019). Additionally, water exclusion efficacy decreases with weathering due to photodegradation, blue stain fungi infestation and microcracks formation (Žlahtič-Zupanc et al. 2018).

It is known that wooden window profiles need to be maintained after a certain period. The period depends on the quality of the coating, wood species, orientation of the building, quality of the craftsmanship and climatic conditions. The study of Ahn and Park (2022), performed on aluminium-wood window frames, confirmed that surface defects are much more present in uncoated frames. Surface coatings can be affected by moisture oscillation, weathering, mechanical damage or hail. These factors result in unwanted

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cracks in the surface coatings. The probability that the penetrating moisture will cause fungal colonization increases with the crack size increase and the damage duration. Most coating related damages in windows occur by very fine cracks in the coating. The ingress of liquid water is possible by capillary action whereas the evaporation is hindered, but cracks become larger during the time. In their combined experimental and numerical study, including mechanical deformations, Luimes and Suiker (2021) showed that the (highest) deformation between the cleated end and the vertical boards is not negligible if the relative humidity varies. Such variations stimulate crack development with oak wood ageing (George et al. 2005). Our previous preliminary study on native Norway spruce(wood) window profile (Vidmar and Jukić 2022) investigated the maximum acceptable crack size in surface coating (always, when in the paper spruce is mentioned, the sprucewood is meant). This study is a step further in using thermally modified spruce to confirm the value, meaningfulness and utilization of thermal modification of the wood, whereas also for native spruce here more relevant results were obtained. The word "crack" in this work always indicates damage to the surface coating only, and not to damage to the substrate/wood.

In the past years, thermal modification (TM) was one of the most important procedures for wood modification. It is a commercial procedure based on heating the wood in semi-anoxic conditions at a temperature between 160 and 240 °C (Hill 2006; Zelinka et al. 2022), and no potentially dangerous chemicals are used during TM procedure (Poncsak et al. 2009). Improved resistance to fungal decay is one of the most important effects of TM, together with reduced hygroscopicity and improved dimensional stability, while the main drawbacks are loss of strength and increased brittleness (Hill 2006; Tjeerdsma et al. 1998; Rapp 2001; Rep and Pohleven 2002; Hill et al. 2012; Olek et al. 2012; Srinivas and Pandey 2012; Sandberg and Kutnar 2016; Sandberg et al. 2017; Lahtela and Kärki 2016; Humar et al. 2020b; Repič et al. 2023).

The first comprehensive document for the assessment of wood service life was developed in Australia, which was based on predicting the mean time to reach specified performance states such as depth of decay or 30% loss of initial strength. Further attempts to predict the performance of wood and components made of wood have been developed in Europe (Isaksson et al. 2013). They are basically following the idea of the factor method approach described in ISO 15686-1:2011, using different types of dose–response models (Isaksson et al. 2013; Niklewski et al. 2016). For service life planning according to the factor method, a reference service life (RSL) is multiplied by a couple of different modifying factors. Current rethinking within European standardisation bodies leads to the development of performance-related classification systems for timber products and requires delivery of respective performance data (Kutnik et al. 2014). Within this process moisture behaviour of wood and wood-based products will be considered for performance classification.

Besides decay fungi, the growth of moulds on building materials is also important. The growth of mould in buildings can have a negative impact on human health, living conditions, and the longevity of structures, creating a significant issue for residents (Pietrzyk 2015; Brambilla and Sangiorgiob 2020). Mould growth on building materials is the result of a combination of environmental conditions (temperature, relative humidity), moisture content, material properties, surface properties, and mould characteristics (Johansson et al. 2014). Some materials are susceptible to mould growth at low levels of humidity, down to 75% RH, while others can tolerate high moisture levels, above 95% RH, without showing any mould growth (Johansson et al. 2012, 2013; Hofbauer et al. 2008). Biological building materials are one of the most susceptible materials to mould growth (Viitanen et al. 2010). Over the years, different models have been developed to evaluate the risk of mould growth (Viitanen et al. 2010; Hukka and Viitanen 1999; Sedlbauer 2002; Sedlbauer and Martin 2003; Thelandersson and Isaksson 2013; Johansson et al. 2014; Boardmana et al. 2023). It is important to note that all mould growth models are made for indoor use. Other factors such as solar irradiation and rain also influence the growth of mould outdoors, but these factors change over the year (Kržišnik et al. 2018).

One major disadvantage of the Glaser method in comparison to hygrothermal simulations is its inability to account for wind-driven rain (Zirkelbach 2016; Fang et al. 2021; Gao et al. 2017), as also discussed in Vidmar and Jukić (2022). The methodology in the study is similar to that presented in Vidmar and Jukić (2022), but due to the new version of the standard, different climate, different material parameters and some other changes the model from Vidmar and Jukić (2022) was recalculated and considered here anew. In the paper, the TM spruce is added, surface heat and water transfer coefficients changed, newer climatic data and the water retention factor for rain falling on a vertical surface, which is taken as 0.7 here—according to EN 15026:2023 (in the previous study it was 1.0).

The first goal of our study was to prove that the considered window profile configuration is suitable for the chosen location (and orientation) as far as maximum MC in the wood is concerned. The second goal was to assess the maximum acceptable crack size in the surface coating, for which the mould fungi or decay fungi are not expected to damage the wood material. Thus it is the study of the influence of the cracks on the moistering of the window frame. The determination of the critical conditions can be provided with many different methods: (1) the maximum daily-averaged acceptable MC in wood, which is 18% [kg/kg] according to the

WTA Guideline 6-8 (2016), (2) VTT mould growth model, (3) WTA wood degradation model, (4) isopleth model, (5) VTT wood degradation model, (6) biohygrothermal model and other models. According to our knowledge, the effect of the variation of the crack size has not been addressed so far. Our third goal was to compare the results of simulations presented in the study for TM spruce with those for native Norway spruce.

2 Materials and methods

2.1 Materials

Norway spruce (*Picea abies*) was used in this study as it is a common species in the boreal and subalpine conifer forests (Caudullo et al. 2016) for the wooden windows. Despite the widespread use of Norway spruce, it is classified as not durable (sapwood) or slightly durable (heartwood), according to EN 350:2016 standard. Due to the poor natural durability of spruce, thermally modified spruce was also used in this study. Thermal modification (TM) of wood is a common well-established, environmentally friendly process that improves the biological durability of wood (Hill 2006). Wood was thermally modified at a temperature of 210 °C according to the commercial Silvapro® process (Rep and Pohleven 2002; Rep et al. 2012). The entire modification process took about 24 h and the mass loss after modification was between 8 and 9%. After modification, wood was conditioned under standard laboratory conditions ($T = 20$ °C; relative humidity = 65%) for 3 weeks before further processing. Furthermore, 2 different surface coating systems (M SORA 03–08 and M SORA DB703) manufactured by Remmers Baustofftechnik GmbH (DE) were applied to the surface using an industrial process (M SORA d.d., SI) according to the manufacturer's instructions (Remmers Baustofftechnik GmbH, DE).

To determine the material properties (see Supplementary Information), experiments were performed, on native (untreated/reference) spruce and thermally modified (TM) spruce coated with one or the other of the two coating systems.

The window frame used in this research was made of two materials (see Fig. 1, right plot): native Norway spruce and TM spruce. The window frame was exposed on a model house at the Biotechnical faculty of Ljubljana, facing west. Window profiles had a thickness of 68 mm with integrated two sealings and aluminium covers on the bottom casement and frame, whereas the entire window of 400 mm × 600 mm (width × height) included a triple insulated glass unit (IGU) with TGI spacer. The window frame in the experiment is composed of both types of wood, each half with a different wood (see Fig. 1, right plot). Window frame elements were surface treated with M SORA 03-08 synthetic coating (Remmers Baustofftechnik GmbH, DE).

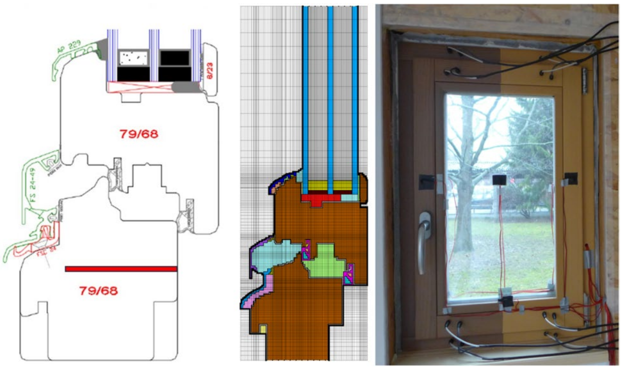

Fig. 1 Design of the considered profile (left)—red horizontal line is the location of the measuring electrode; numerical model of the considered profile (middle)—adopted from Vidmar and Jukić (2022), photo of experimental window setup (right): window profile made of spruce—left part and TM spruce—right part

We used climate data for Ljubljana in our research. We decided to do this because Ljubljana has been shown in a previous study to be one of the more threatening environments for wood decay and mould growth in outdoor applications. A relative Sheffer climatic index was similar to that for Hannover, while the relative dose was highest in Ljubljana (Ugovšek et al. 2019).

The problem is considered as two dimensional, thus the size of the crack in the third dimension is infinite here, such is then also the third dimension (length) of the surface damage (cracks).

2.2 Methodology

The simulations were performed following the standards EN 15026:2023, EN ISO 10211:2017 and the German guideline WTA Guideline 6-2 (2014) using the program Delphin 6.1. 5-year (2017–2021) half-hourly climatic data from the website http://meteo.arso.gov.si/ for the location Ljubljana Bežigrad (Lat.: 46°4′; Long.: 14°31′; Alt.: 299 m; Slovenia, Cfb climate—temperate, no dry season, warm summer) were used: temperature, relative humidity, short-wave solar radiation, cloud covering (used for long-wave radiation), wind direction and velocity, and rain on horizontal plane.

In Fig. 1 (middle plot), the model of the considered window profile from Fig. 1 (left plot) is shown. As already discussed in Vidmar and Jukić (2022), due to the convergence problems it was impossible to simulate the whole model. From two simplified models already considered in Vidmar and Jukić (2022), we decided to consider here a simplified 2D model of the bottom part of the frame, because its outer part is most problematic concerning problems due to the high MC. Therefore in the paper, only this model is considered.

2.2.1 Considered phenomena in modelling

We considered heat transfer through the wood and air, short-wave radiation absorption, long-wave radiation absorption and emission on/from the surface and in the (only) air cavity, water vapour transfer and condensation, wind-driven rain absorption by the surface (taken into account a factor 0.3 of the splashing) and conduction of water through the material. In a non-ventilated cavity, long-wave radiation is considered using the equivalent thermal conductivity of the air. The boundary conditions used in the simulations are listed in Supplementary information (see Table S1).

An absorption coefficient of 0.6 for short-wave radiation was taken from EN 15026:2023 for grey or medium-shielded surfaces. Surface emission of 0.9 was adopted for long-wave radiation. Due to different possible types of grounds and different possible installation heights of the windows, in the study, the radiation exchange with the ground was neglected.

2.2.2 Parameters in modelling

Material properties used are presented in Supplementary Information (see Table S2; Figure S1). The surface coating layer is about 0.1 mm thick. To avoid mesh-related problems, it was modelled with a 1-mm-thick layer. The applied surface material properties are presented in Supplementary Information (see Table S3). The upper and lower horizontal planes in the model are adiabatic. We considered the most unfavourable north orientation of the profile of the window.

VTT, isopleth and biohygrothermal mould growth models were used. Their parameters are presented in Supplementary Information.

2.2.3 Models

The considered physical model with undamaged coating is shown in Fig. 2 (left plot). The inner and outer shelves are impermeable to water and water vapour. There is a 1-mm-thick air layer between the outer shelf and the wooden tooth of the profile, which captures a probable disconnection between the shelf and the wooden tooth. Shelves were modelled using environmental temperature and adapting zero moisture flow conditions at the shelf contact with the profile. The possible damage from the liquid water, which could enter and stay between the shelve and the tooth was not considered. Technically, the edges of window frames are rounded nowadays, but due to the finite difference type of modelling approach, it is not possible to take it into account here.

Short and long-wave radiation, temperature, relative humidity and wind-driven rain were adapted on the whole outer vertical surface of the model (red area in Fig. 2, left plot). On all remaining outer surfaces, (only) temperature and relative humidity boundary conditions were adopted. In this paper, we focused on the less favourable case without shading and rain protection. At the tooth and its closest neighbourhood highest MC values are obtained.

The damage of the surface coating was introduced by removing its part from the middle of the vertical outer exposed surface. The size, i.e. height, of the removed part corresponds to the height of the crack in the coating. Different crack heights, 1 mm, 3 mm, 5 mm, 7 mm and 9 mm were considered. The model with the 9 mm high crack size is shown in Fig. 2 (right plot). The considered cell in the calculation of MC contents and mould growth models is marked with a green ellipse.

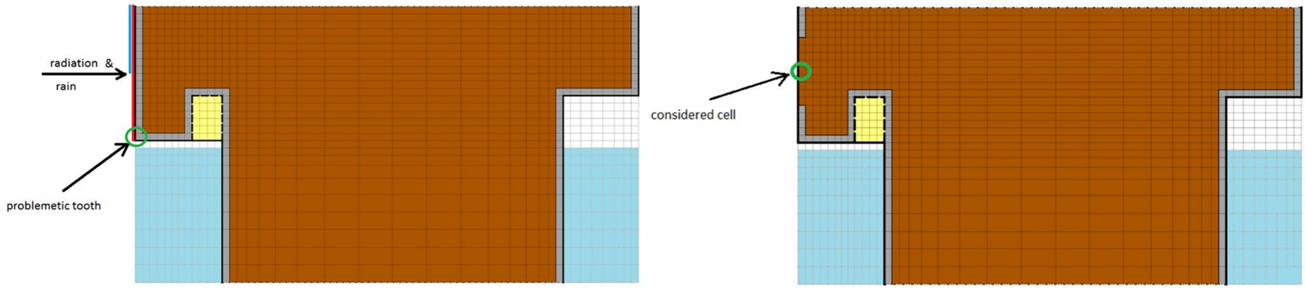

Fig. 2 Model of the lower part of the frame with surface coatings (grey), small air cavity (yellow) and shelves (light blue). The area exposed to wind-driven rain and radiation in the model is marked with red. The area in the alternative ("more favourable", not considered here) model is marked with dark blue. The problematic tooth is marked with a green ellipse. The model with surface coating damage in the height of 9 mm (right)

2.2.4 Experimental moisture content inside wooden frames

Wood moisture content (MC) was determined through measurements of electrical resistance (see Fig. 1, right plot). Electrodes were applied approximately 50 mm deep (from the inside surface) and linked to electrical resistance measuring equipment (Gigamodule, Scanntronik Mugrauer GmbH, DE). The method was validated with samples that were preconditioned at various RH and temperatures to achieve various target concentrations. This equipment enables accurate wood MC measurements between 6 ± 0.1% and 60 ± 0.1%. MC was logged twice per day, at midnight and noon, at the same time as temperature. Transfer electrical resistance measured inside the wood, wood species-specific resistance characteristics were developed based on the methodology described by Otten et al. (2017). The measured quantities are locally averaged values detected from 2 mm thick electrodes, which have a measuring field from approximately 10 mm to approximately 50 mm into the depth of the wooden profile from the inside of the room, thus they reach about 18 mm below the outer surface. The measured values represent the average MC of the wood through the entire measurement field.

3 Results and discussion

The degradation of wood develops if the combination of optimal temperature and wood moisture content exceeds 325 days with optimal conditions (Isaksson et al. 2013). Therefore, in parallel to long-lasting field testing, various types of models are utilised to assess the performance of wood in outdoor conditions (Brischke and Thelandersson 2014), as simulation of the window's performance and comparison with the field test were the goal of the present research.

After the first year of the simulation period, the effect of constant initial conditions used (temperature of 20 °C and relative humidity of 80%) is considered to have almost vanished. The graphs, except those for the VTT and biohygrothermal mould growth models, thus only show the results from the beginning of the second year up to the end of the 5th year of the simulation period. It is not a problem to take such high moisture initial conditions in the VTT model, we tried lower ones (14% MC in spruce and 9% in TM spruce), but without the difference. The reason is that the VTT mould growth index does not start to grow before the beginning of the autumn of the first year. Due to the almost zero value of the mould growth rate of the biohygrothermal model in the first half year of the simulation period, also in biohygrothermal modelling, the whole first year of the simulation was taken into account.

3.1 Experimental moisture content and validation of numerical models

To be able to evaluate the moisture content (MC) of native spruce and TM spruce, the simulation results were first compared with the results of MC measurements in the real environment (Fig. 3), as it is known that weathering of the wood has a significant influence on moisture performance of wood (Žlahtič-Zupanc et al. 2018). The window frame used for simulations and modelling was exposed in the field of the Biotechnical Faculty in Ljubljana (for the description see clause 2.2.4). The MC measurements over the 4 years are similar to the simulation results (Fig. 3). The average difference in MC over 4 years is (only) 0.21% [kg/kg] for native spruce and 0.40% [kg/kg] for TM spruce, which validates the numerical model. However, Sandberg (1999) and Sjökvist et al. (2019) have shown that density has a significant effect on the wetting of Norway spruce wood in outdoor conditions, regardless of the permeability of surface coatings used, wetting is much faster in lower-density wood than in higher-density wood. This results in a higher presence of cracks in lower-density wood. The lower-density wood had a higher portion of early wood, with its higher porosity and lower cell wall thickness and is more susceptible to degradation (Kropat et al. 2020). On exposed tangential surfaces, the frequency and size of cracks in spruce are up to 6 times greater than on radial surfaces (Sandberg 1999).

3.2 Models with undamaged coating

Coatings on wooden frames have multiple roles, from aesthetic to protective. Figure 4 shows the calculated weekly-averaged locally maximum MCs in the native spruce (left plot) and TM spruce (right plot) in the models with coating 1 and coating 2 as well as the borders, 18% (the maximum daily-averaged acceptable MC in wood, according to the WTA Guideline 6-8 (2016)) and 25% and 30% (the minimal MC for fungal decay (Johansson 2014)). The maximum MCs in the critical wintertime period are always reached at or around the outermost wooden tooth cell of the exposed profile side. The maximum values in the winter time, which are on the safe side as far as their problematic nature is concerned, are, of course, not always reached at the same location. It might not be clearly evident from Fig. 4, but the data show that larger crack induces larger MC.

Maximum MCs in both models with the TM spruce are always below 12% [kg/kg], thus far below critical 18%, whereas for native spruce with coating 1, this value is 15.3% (at day 1501). Therefore the systems which fit these models are suitable for installation at the considered location as far as maximum MC is concerned. On average coating 2 offers slightly worse protection than coating 1 in both models. The average difference in both comparisons

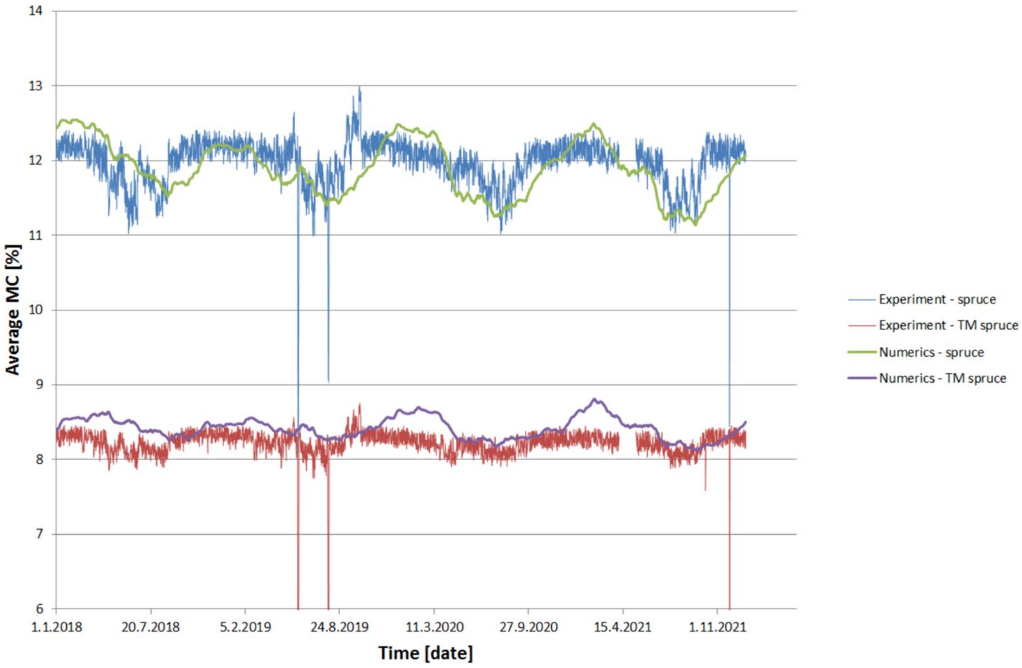

Fig. 3 Experimental and numerical average MCs in both wooden types (window frame measured in the installed model house). The data are from 1.1.2018 to 31.12.2021

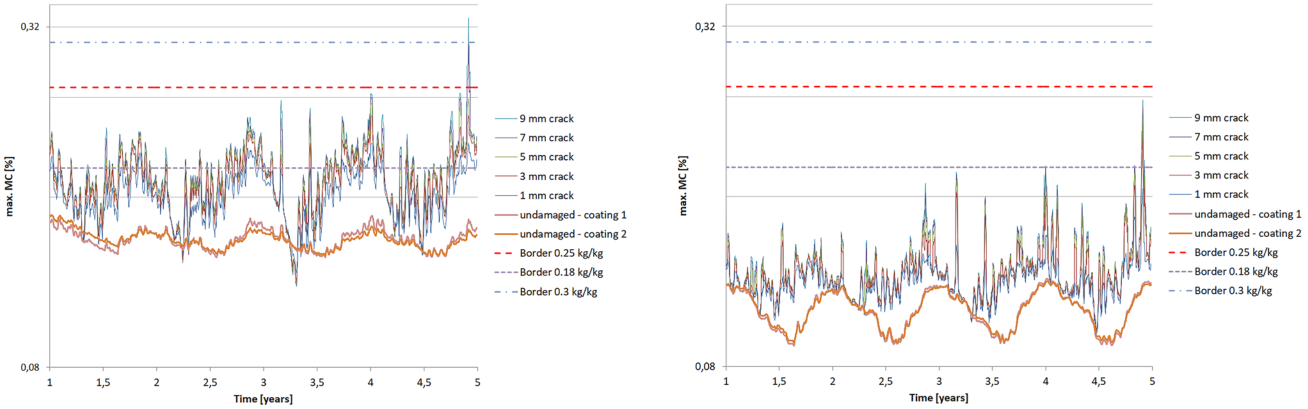

Fig. 4 Weekly-averaged locally maximum MCs in the models with native spruce (left plots) and TM spruce (right plots). Results with the damaged region (crack) in the height of 1 mm, 3 mm, 5 mm, 7 mm, and 9 mm for coating 1 as well as results with the undamaged coating 1 and coating 2 together with the border lines are shown in the logarithmic scale

is +0.02% [kg/kg] in native spruce and −0.02% [kg/kg] in TM spruce. It is of no significance, therefore from here on only coating 1 will be considered. When comparing the results for native Norway spruce and TM spruce, the main conclusion is that in TM spruce the maximal MC values are about 4% lower than in native spruce. This is in line with findings from Humar et al. (2020c), who reported a similar difference of 5.6% in the MC between TM spruce and native Norway spruce exposed outside as facade elements.

We also tested the case without rain and radiation (i.e. with shading) and got the MC for day 1501 (the day with the time maximum of the local maximum MC value in native spruce over the entire simulation time) for about 3% [kg/kg] lower than for the case without shading. It confirms that the case with radiation and rain is more unfavourable.

Calculation uncertainties were determined in a simpler way, variating each parameter from Table S4 (except porosity) for ±10% in the model without surface damage. The variation of the climatic data was not considered. Results show that the wood density and its sorption curve are the most influential parameters in case of wood MC. Especially the increase of the sorption curve by 10% means a high change in the results of the MC. Uncertainty of other material parameters has a much lower influence (detailed results are shown in Supplementary Information).

According to the isopleth model (results are shown in Supplementary Information—see Figure S2), the limit for germination is not exceeded for the frame made of native spruce (left plot), but for the frame made of TM spruce (right plot) it is exceeded for short time intervals, thus the 9 days of the germination risk are obtained with the longest period of more than 4 days. The limit for germination in 16 days is not exceeded in any of the models in 4 years of simulation. There are higher contents of the water in native spruce as shown in Fig. 4 (left plot), but the isopleth model takes only into account temperatures and relative humidities—and the latter are higher in the model with TM spruce. The reason is the lower sorption isotherm curve of TM spruce in comparison to native spruce, which enforces higher relative humidity values in the material of the outer part of the frame in wintertime.

The VTT mould growth model, biohygrothermal mould growth model, as well as VTT and WTA wood degradation models show no growth and no degradation, respectively. Nor for native nor TM spruce.

3.3 Models with damaged coatings

Coating damage could potentially result in water accumulation that enables fungal development under the coating (MacKenzie et al. 2007). Figure 4 shows also the calculated weekly-averaged local maximum MCs in the native spruce (left plot) and TM spruce (right plot) of the damaged models with surface coating 1 with crack sizes of 1 mm, 3 mm, 5 mm, 7 mm and 9 mm (plots are in logarithmic scale). Maximum MCs in the damaged models in the critical winter periods are located at the centre of the crack (marked with a green ellipse in Fig. 2, right plot). This location was chosen because of the higher moisture contents in the models with the crack, than around the exposed tooth.

The problems arise sooner, i.e. at a smaller crack height with native spruce, which is presented in more detail in Fig. 5. Its left plot shows the number of days in 4 years of simulation (the first year is not taken into account), where the maximal MC is above 18% for native spruce (red) and TM spruce (blue). Its right plot shows the maximum length of such consecutive days for native (red) as well as for TM spruce (blue). Note, that in both plots logarithmic scales are used.

In the model with a 3 mm high damaged region with coating 1, the longest interval of MCs above 18% for TM spruce has a duration of 2 days (from the day 1156 to the day 1157), whereas for native spruce this interval is 35 days long (from the day 1782 to the day 1816). In the corresponding model with a 9 mm high crack size, there is a similar interval of 3 days for TM spruce, whereas for native spruce this interval is of length 44 days (probably longer because on the last day of the simulation, whose maximum MC value is part of the sequence, the value is still above 18%). It means that for native spruce the crack height of 3 mm can already be problematic, whereas for TM spruce it is not the case. Due to the very complex nature of the considered phenomena, the sharp border between acceptable and non-acceptable crack size is practically impossible to determine. However, according to the results, it is between 1 and 3 mm for native spruce and greater than 9 mm for TM spruce.

Figure 6 shows that a 3 mm high crack in native spruce means a big difference in MC in the most critical period compared to the model with the TM spruce (a collection

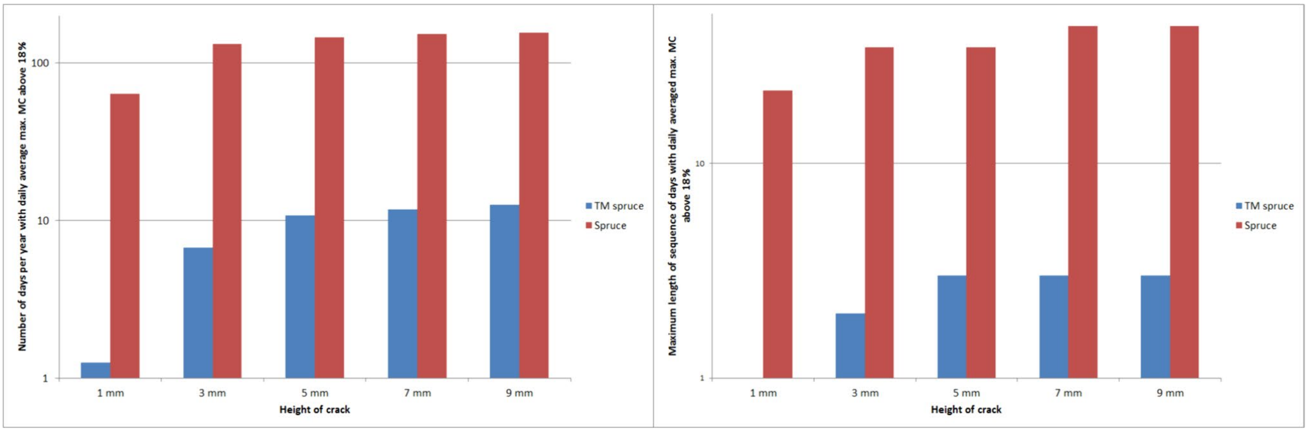

Fig. 5 Number of days per year in 4 years of simulations in each of the model configurations with damaged coating 1, where the average daily maximum MC of 18% is exceeded (left): maximum length of the sequence of days in 4 years of simulations in each of the model configurations with damaged coating 1, where the average daily maximum MC of 18% is exceeded (right)

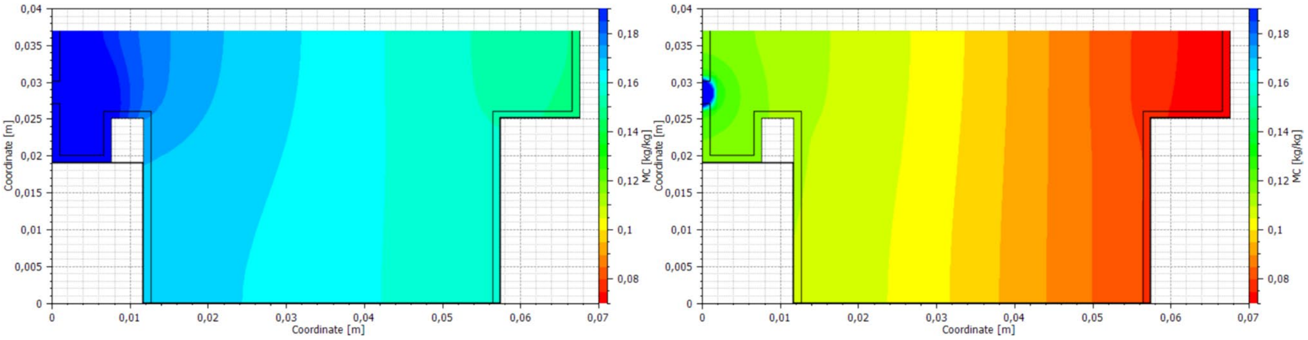

Fig. 6 MC profile in the model with native spruce (left) and TM spruce (right) with surface coating 1 at day 1795.5 after the start (5th winter) of simulations: models with the damaged region in the height of 3 mm. The problematic (critical) regions are shown in blue. The day 1796 is the day of the maximum local maximum MC in native and TM spruce during the whole simulation time

of such plots for cases without cracks and all considered crack sizes is presented in Supplementary Information—see Figure S3).

The results of biohygrothermal and VTT modelling for different configurations of the damaged physical model are shown in Supplementary Information (Figures S4 and S5). Both plots clearly show that the mould growth rate increases with the increase of the crack size. As for the isopleth modelling on the physical models without damage, also here models with TM spruce are more unfavourable than the models with the native spruce. The reason is the same as in the models without damage. Even if we changed the substrate class for TM spruce from I to II, which could be justified due to its thermalisation processing, the native spruce would be less critical.

For the same parameters of both models also the VTT mould growth model prefers the native spruce against the TM spruce (parameters are presented in clause 3.1). Only if we choose the "very sensitive" material option for the native spruce and the "medium resistant" material option for TM spruce, the resulting mould growth index for TM spruce models for some crack sizes is lower than for the native spruce (see Figure S5 in Supplementary Information).

We also tried the isopleth model for the damaged surfaces, where both wooden types were considered with the same substrate class I. The results are presented in Supplementary Information (see Figure S6). Also there the comparison between results of smaller and bigger crack sizes shows that with the increase of the crack size mould growth is more probable. But a comparison between spruce and TM spruce favours spruce again. Therefore we conclude that the biohygrothermal, VTT and isopleth models would need some improvements to correctly capture the differences between the native and TM spruce material. Thus all the mould growth models, which do take into account only T and RH for the input parameters, would favour native spruce in comparison to TM spruce if the same material class was taken into account. The reason is as follows: due to the lower sorption curve of the TM spruce, higher surface relative humidity values should be reached in the material when higher MC contents must be transported. Due to the lower MC in TM spruce in comparison to native spruce, we do not believe the results of the presented three mould growth models reflect the real situation. A mould growth model, which would take into account also the water content in the material (not only in the spore as does the biohygrothermal model), should be tried.

Based on the experimental data we believe that the blue stain fungi will appear on the surface of native wood within 12 weeks of exposure, additionally, the development of blue staining is dependent on climate. Staining is faster in warm and humid months in late spring and slow in cold winter and dry early spring months (Kržišnik et al. 2018).

An additional problem is that all the mould growth models used here were developed for the inside of the buildings because the UV radiation and rain can remove or at least decline the rate of mould growth. Thus, one has to be careful to apply them outside as done here. However, the comparison of the results of the models with the same wood type and with the increasing height of the crack shows that with the increase of the crack size the possibility of mould growth increases. Thus at least the comparative value of the presented mould growth modelling concerning different size cracks is of benefit here.

4 Conclusion

This study investigates heat and moisture transfer through window profiles made of thermally modified (TM) and native spruce using hygrothermal simulations in Delphin 6.1, focusing on climate data from Ljubljana-Bežigrad. Key factors include the impact of surface coatings and cracks on moisture accumulation and mould growth. The simulations combined experimental data for TM spruce's desorption curve with Delphin's spruce data for higher relative humidity. Liquid water conductivities were fine-tuned using experimental water absorption data. Simulations were simplified due to convergence issues, the most unfavourable case was considered and the results were validated. The two surface coatings tested (M SORA 03-08 and M SORA DB703) showed negligible differences when undamaged. However, cracks in the coating led to significant differences between native and TM spruce. A 3 mm crack in native spruce led to 35 consecutive days of moisture content (MC) above 18%, while TM spruce saw only 2 days. Even with a 9 mm crack, TM spruce limited MC above 18% to 3 days, highlighting its superior moisture resistance. Three mould growth models—Isopleth, VTT, and Biohygrothermal—demonstrated increasing mould risks with larger cracks. However, these models inaccurately favoured native spruce over TM spruce, as they did not fully account for wood moisture content or external factors. The study suggests that mould growth models need improvements to represent wooden materials better or at least more data are needed to feed the existing models. The research was conducted under specific climatic conditions and used a biocide-coated coating system. While the results are location-specific and more statistically significant values for the most influential material parameters density and sorption curve as well as liquid water conductivity of TM spruce would improve the quality of the results, they indicate that TM spruce reduces moisture risks compared to native spruce, especially when surfaces are cracked.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00107-024-02149-0.

Acknowledgements We thank Gregor Strmljan for performing experimental work on water vapour diffusion and water absorption. We thank Miha Jukić for the help in the simulations. We thank Barbara Šubic from MSora d.d. for the documentation and information about their wooden profile configuration and manufacturing of the test window, where moisture logging was performed. Then, we thank Heiko Fechner from Bauklimatik Dresden Software GmbH for helping with the Delphin software. Gregor Vidmar thanks Katja Malovrh Rebec for fruitful discussions. Part of the research presented was supported by the Slovenian Ministry of Education, Science and Sport and by the European Regional Development Fund, European Commission (project WOOLF, grant number 5441–2/2017/241). In addition, this project was supported by the Slovenian Research and Innovation Agency ARIS in the frame of the programmes P2-0273, P4-0015, and IO-0032 as well as infrastructure centre IC LES PST 0481-09.

Author contributions Conceptualization: GV; Data curation: GV; Formal analysis: GV, RR, MH, BL; Funding acquisition: MH, BL; Investigation: GV, RR, HM, BL; Methodology: GV, MH; Project administration: GV; Resources: GV; Supervision: MH; Validation: GV, MH, BL, RR; Visualisation: GV, MH; Writing—original draft: GV; Writing—review & editing: GV, RR, MH, BL.

Data availability The data are deposited at Slovenian National Building and Civil Engineering Institute, Ljubljana, Slovenia. They can be obtained/looked into by writing an email to one of the authors.

Declarations

Conflict of interest The authors declare no competing interests.

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