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Consideration of driving rain penetration in hygrothermal simulations of half-timbered walls

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Abstract. This paper deals with the consideration of driving rain penetration in exposed half-timbered walls within hygrothermal simulations. On the basis of a real damage pattern, a model is created which forms the basis for a parameter study. The aim of this study is to find out how the penetration of driving rain can be represented in such a way that the damage can be explained by it. For this purpose, (i) a moisture source that depends on the wind-driven rain is increased in intensity according to the standard, (ii) pulses of increasing intensity as well as (iii) constant moisture sources again increased by a factor are implemented. The results show that with the assumptions made, a local moisture source has little effect on the overall water content of the structure. However, depending on the moisture source intensity, a local damage risk for the wood near the joint could be observed. The damage of the case study can be derived, at least in part, from these results. The approach of assuming 1% of the driving rain as the moisture source does not seem to be sufficiently dimensioned. Quantifying the moisture sources for an exposed truss wall is a task for further investigation.

Keywords – driving rain penetration, historic half-timbered wall, hygrothermal simulation, parameter study.

1. Introduction

When visible half-timbering became fashionable in Germany in the 1990s, this led to the uncovering of what was supposed to be visible half-timbering from the period of construction. But this way in many cases, trusses which had been deliberately plastered or clad in the origin, were exposed to the weather. In addition, there has been a strong increase in the demand for comfort, which requires the use of insulation and air-tightness of the structures. Lack of or wrong coordination of these measures led and often leads to serious damage to the wood structures [1]. In particular, on the one hand, sealing the joints between the wood and the panel often leads to damage, since the joints cannot be kept permanently tight [2]; on the other hand, it is necessary to minimize the penetration of driving rain or at least to prove that the penetrating water does not lead to consequential damage.

Existing regulations in Germany [3] specify that driving rain penetration due to unavoidable leakage can and should be specifically taken into account by implementing 1% of the driving rain water hitting the façade as a moisture source on the moisture-sensitive substructure (as a simplified substitute model for a flow simulation). This is justified with the fact that it can be assumed that even in building components designed according to the state of the art, small leakages can lead to an additional moisture input that can be significantly greater than that caused by vapor diffusion. If this is already true for new building components, how much more does the problem of driving rain penetration arise for exposed half-timbered structures?

In this paper, a half-timbered building in the Lower Franconian village of Birnfeld, which shows corresponding damage after improper renovation, is used as a case study to try to work out with a parameter study a plausible consideration of water penetrating through joints in hygrothermal simulations.

The variants discussed here represent an excerpt from the master's thesis [4], which considers more aspects in total. In figures, tables and diagrams the variants retain their original code.

2. Material and Methods

2.1. Case study building

The building under consideration is a former rectory, built in 1693. The house is partly of half-timbered construction. In the course of a renovation in 1992, the previously plastered half-timbering was exposed and provided with insulating plaster on the inside, windows were replaced, central heating and radiators were installed, and the top floor ceiling was insulated. In the course of planning a refurbishment of the building in 2019, gaps of up to 1cm were found between the new woodwork and the panels. After removal of the interior plaster, the client noticed flowing water on the inside of the north wall during rain events. During driving rain on the facade, spray water can be felt in the space next to the wall. Visual contact between the interior and exterior is possible at individual joints.

Figure 1. (a) significant loss of the wood cross-section, (b) remains of the fungus can still be seen

Cracking and moisture damage to the timber framing in the interior rooms may possibly be due to moisture penetration through these joints. A particularly damaged component is the sill on the north wall, which was newly installed in 1992 as part of the renovation. It shows damage due to wood-destroying fungi and pests, and the joint above the sill suggests that water penetration is a contributing factor to the damage to the wood. This detail will be used to test whether the damage can be explained based on the simulation with the driving rain penetration model.

2.2. Hygrothermal simulation model

For the investigation according to WTA Merkblatt 6.2 [5], a model is created with the simulation program Delphin of IBK Dresden [6], which considers heat transport, vapor diffusion and liquid water transport as well as the influence of short- and long-wave radiation and driving rain. The boundary condition inside is an adaptive indoor climate according to EN 15026 [7] and WTA [5] with standard internal moisture loads, the boundary condition outside is the weather file for Hof the Delphin database, which also provides data for wind and rain. Because of the damage described above, the calculation is performed for the north facade, for which the driving rain load is 11.81 l/m²a.

The simulated detail with the connection of the wooden beam and the compartment is shown in Figure 2 with discretization and the two selected analysis points. The wooden beam has a depth of 15 cm, and the compartment consists of 13cm of vertically perforated brick and 2 cm of lime-cement plaster. To the inside, 5 cm of insulating plaster and 3 cm of lime plaster are applied. The materials were selected from the Delphin database and are listed in Table 1 with their respective ID and characteristic properties.

Table 2. Materials from Delphin database with their ID and respective characteristic values (density ρ, specific heat capacity c_p, thermal conductivity λ, water vapour diffusion resistance μ, hygroscopic sorption value at 80% w_{80}, effective saturation w_{sat}, water uptake coefficient A_w)

	ρ	c_p	λ	μ	w_{80}	w_{sat}	A_w
	kg/m³	J/kgK	W/mK	---	kg/m³	kg/m³	$kg/m^2s^{0.5}$
710 Oak	580,7	1284	0,129/—	230,7	86,2	683,6	0,003
508 Perforated brick	1400	1000	0,350/—	18,8	11,4	319,4	0,177
718 Lime cement plaster	1739,2	1057	1,05/—	28,3	39	258,8	0,494
629 Lime plaster	1498,4	802,4	0,412/—	9,3	34,2	430	0,019
704 Insulation plaster	226,7	1090,5	0,058/0,066	27,6	8,6	301	0,008

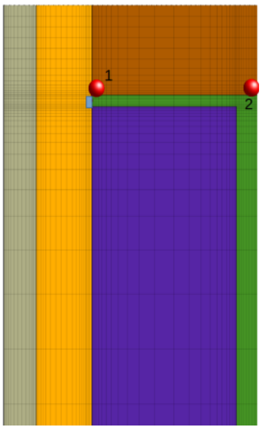

Figure 2. Geometric model from inside (left) to outside (right). Colors: Oak: brown, brick: blue, lime cement plaster: green, lime plaster: yellow, insulation plaster: grey.

2.3. Evaluation criteria

As described in [8], the following criteria are applied to evaluate the situation of wood in the results: The pore air moisture content of wood components must not exceed 95% at 0◦C and 86% at 30◦C as a daily average. The intermediate values can be interpolated linearly. Over the course of the year, 85% should not be exceeded in the long term. Furthermore, the relative mass content should not exceed 20% for wooden components. For the material used [710] with a density ρ of 581 kg/m³, this corresponds approximately to a water content of 116 kg/m³. Therefore, the color scales of the water content profiles are shown with a maximum of 116 kg/m³ - making thus visible any area exceeding this limit.

2.4. Rain penetration model

The penetrating driving rain quantity shall be considered as a moisture source within the model. For this purpose, the amount of driving rain hitting the facade, RainFluxNormalToSurface, is calculated in an upstream simulation using the weather dataset and North orientation of a vertical wall.

It is assumed that not only the water hitting the joint penetrates it, but also water running off the facade. Therefore, the percentages of water entering the joint from driving rain are increased stepwise with respect to a source width of 1cm. To define the moisture source value *s*, the values of the driving rain hitting the north facade *r* are multiplied by the corresponding factors *p* according to equation (1).

$$s = r * p \quad (1)$$

The moisture source is attributed to a section of 10 per 5 mm in the insulation mortar right next to Analysis point 1.

2.5. Parameter study

A base case (G) without any additional moisture source, i.e. assuming perfect execution of work and driving rain protection is simulated for comparison.

2.5.1. Variant package I: moisture source related to driving rain

In a first step the above described method is applied by creating 6 moisture source files (I.2 to I.6), increasing the percentages stepwise from 1% over 5%, 10%, 20% and 50% to 100% and applying it to the hourly driving rain values with respect to a source width of 1cm. Since the total driving rain quantity for the north façade is 11.81 l/m²a, the variants from 1% to 100% result in water quantities between 1.18 ml/a and 118.14 ml/a for a joint of 1 m length.

The distribution of driving rain and thus moisture penetration events over the year corresponds to the weather file of Hof and includes a big variety of long and short, intensive and shallow events.

2.5.2. Variant package III: archetypal moisture sources (pulse and continuous)

To allow a better understanding of how different kinds of rain events influence the moisture distribution in the wall and whether a critical moisture quantity for the moisture source modelling the driving rain penetration can be determined, two kinds of archetypal moisture sources have been defined.

First, a pulse source of one hour, which is applied to the construction and the reaction of the model is observed. The respective intensity is increased from 1,8 ml/h (III.1) in factor ten steps to 18 l/h (III.5).

In a further step, constant moisture sources of different sizes are implemented over the whole year in order to see what amount of moisture the construction can continuously remove, and at which point the construction starts wetting up.

Table 2. Variants considered in this paper

Moisture source based on weather		Pulse source		Continuous source	
	Considered parameters		Considered parameters		Considered parameters
Variant	increasing the percentages of moisture source [%]	Variant	Pulse intensity	Variant	Constant value
I.1	1	III.1	E-3	III.6	E-17
I.2	5	III.2	E-2	III.7	E-10
I.3	10	III.3	E-1	III.8	E-5
I.4	20	III.4	E-0	III.9	E-4
I.5	50	III.5	E+1	III.10	E-3
I.6	100			III.11	E-2

3. Results and discussion

In the basic case G, the water content fluctuates between approx. 3.2 kg and 6 kg over the course of the year, see Figure 3 (a). The water content is dependent on the vapor pressure gradient of the dew period. In April, May, July, September and January, dependencies of the water content on the driving rain can be observed. The annual maximum of water content in September is concentrated on the outside of the structure.

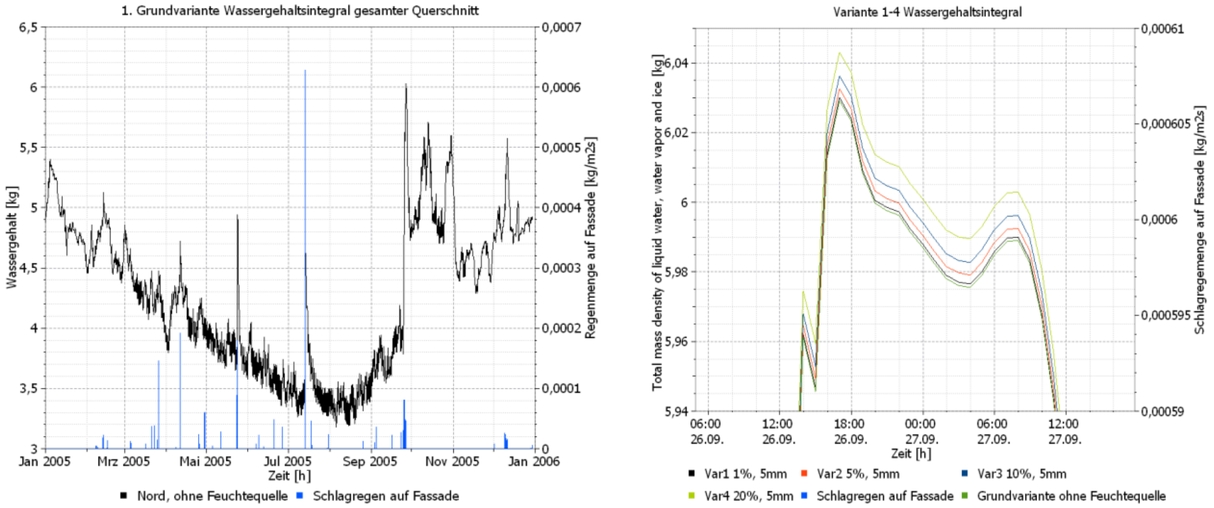

Figure 3. (a) water content integral over the whole modelled section, (b) 48h detail of water content integral over the whole modelled section for Variant package I

3.1. Variant package I: moisture source related to driving rain

In the comparison of the variants with different penetrated driving rain content I.1 to I.6 and the base case G without driving rain, hardly any differences in the water content can be seen in the output values (see detail in Figure 3 (b). For the total water content of the construction, the moisture sources thus have only a minor influence. The decisive factor here is the water absorption over the surface of the construction.

However, at analysis point 1, directly next to the moisture source, Figure 4 shows clearly a growing influence of the increasing moisture source on the relative humidity: While the mean course of relative humidity for variants G and I.1 to I.3 increases from values in August of approx. 69 - 70% relative humidity to values in February of approx. 84 - 85%, variants I.4 to I.5 show also in their mean course several percentage points higher relative humidity. In the course of the year, there are five extreme values, where relative humidity increases up to 22% in a short period of time. It can be seen that with larger source of humidity the maximum values of the graphs become higher, i.e. the influence on analysis point 1 increases. After a rain event the relative humidity drops again, however with different time pace depending on the intensity of the moisture source:

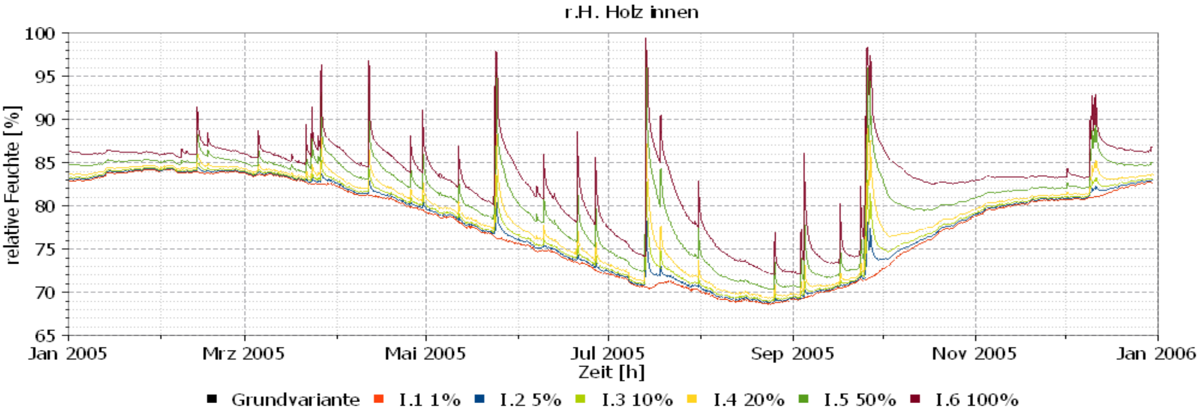

Figure 4. Relative Humidity at analysis point 1 for base case (G) and variants I.1 to I.6 with different % of driving rain penetration.

- In variant I.1 almost no difference to the basic variant can be observed. The annual amount of water introduced can be absorbed and removed by the surrounding materials.
- In variant I.2 with 5% of the impinging driving rain quantity, an influence of the moisture source on the relative humidity at the analysis point of the wood can be seen. The effect increases with increasing water input.
- In the case of variants I.2-I.4, the relative humidity almost reaches its initial moisture content again after about one month,
- whereas this does not happen in the case of variants I.5 and I.6. This means, that a quantity of water is added which the adjacent materials cannot completely remove.

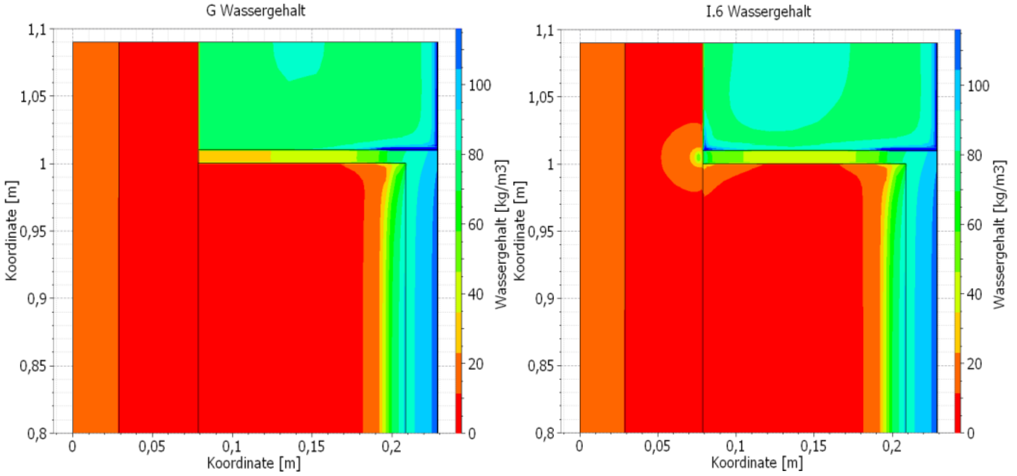

Figure 5. Profile of the water content for base case G (left) and I.6 (right) for 28.09. 12 o'clock.

The influence of the modelled penetrating driving rain on the water content is concentrated in an area around the moisture source. In the case of joints in the framework, therefore, on a position on the wood. The most critical variant I.6 exceeds the critical value as described in [5] in 131 hours over a year. The relative humidity of 85% is exceeded in 32% of the hours of the year.

Figure 5 compares the water flow profiles of September 28 at 12:00 p.m. for the base case G and Variant I.6. In the profile, one can see the effects of a previous rain event. The influence of the moisture source is mainly limited to areas in its immediate vicinity. At analysis point 1, the saturation limit is reached and exceeded. An increased water content can be observed in the insulation plaster with a radius of 2.5cm.

The wood shows increased values in the area by 1 - 4kg/m³. The water content integrals, as well as the water saturation of the wood averaged over the surface, show that the moisture source hardly changes the moisture behavior of the overall construction. If the analysis is limited to analysis point 1, it is shown that the relative humidity remains elevated for moisture sources of higher intensity (20 - 100%). Under the assumptions made here, the limit values of the WTA are exceeded for variants I.5 and I.6.

The assumed water quantities of approx. 60 ml/a per meter for variant I.5 and approx. 120ml/a per meter for I.6 do not appear to be unrealistically high – considering that also driving rain running down the façade will run into joints, especially horizontal ones. I.5 and I.6 already show overshooting of critical values and related damage risk due to penetrating driving rain – which would not be predicted with the 1% source over the whole surface proposed by [3]. In order to further understand the behavior of the simulated model, its reactions to pulse and constant moisture sources will be investigated in further variants.

3.2. Variant package III: archetypal moisture sources (pulse and continuous)

Figure 6 depicts the relative humidity response at analysis point 1 to a one hour pulse source. Variant III.1 reaches a maximum relative humidity of 91.8% relative humidity, Variant III.2 reaches 95.2% and III.3 reaches 99.4%. The time for the area of the humidity source needs to settle back to "normal" (defined as time until 0.1% difference to the basic variant is reached) is 13h for III.1. For the tenfold increase of the moisture quantity in variant III.2, the re-swing time is extended from 13 h to 110 h by a factor of 8. The hundredfold increase as in III.3 leads to a time of 901 h, which corresponds to a factor of 69.

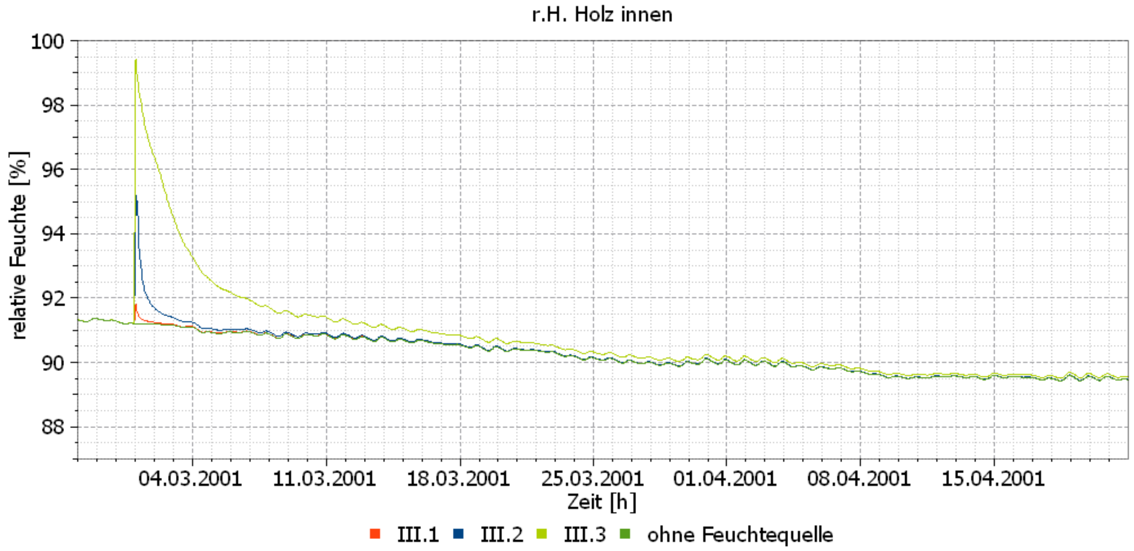

Figure 6. Relative humidity at analysis point 1 for variants III.1 to III.3 – 1h pulse moisture sources with increasing intensity

As regards the other "archetypal" moisture source – the continuous sources of moisture in variants – Figure 7 presents the influence on the saturation over the wood section: variants III.6-III.9 add an amount of water to the system that can dry out during the year. The amount of moisture added in variant III.10 and particularly in III.11 would cause the structure to become damp, getting worse over time. While III.10 however still meets the saturation limits, III.11 goes clearly beyond the 20% already at the end of the second year.

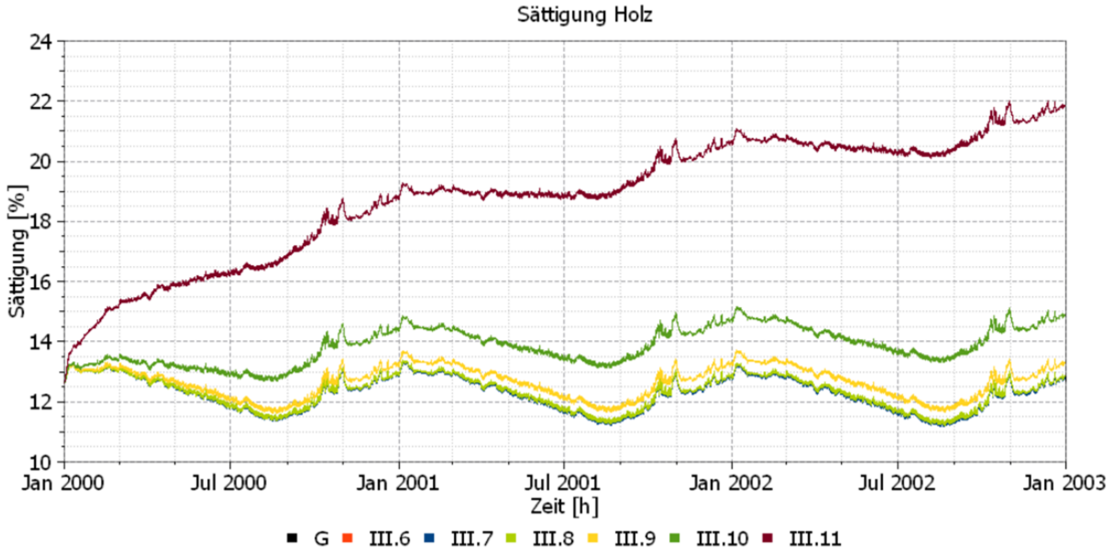

Figure 7. Saturation of wooden section (whole section) mass-% for variants III.6 to III.11.

The maximum value of 85% of relative humidity in analysis point 1 is not transgressed in variants III.6- III.8, as can be seen in Figure 8. In variant III.9 the limit value is exceeded for 60% of the hours of the year, and in variants III.10 and III.11 for the whole year.

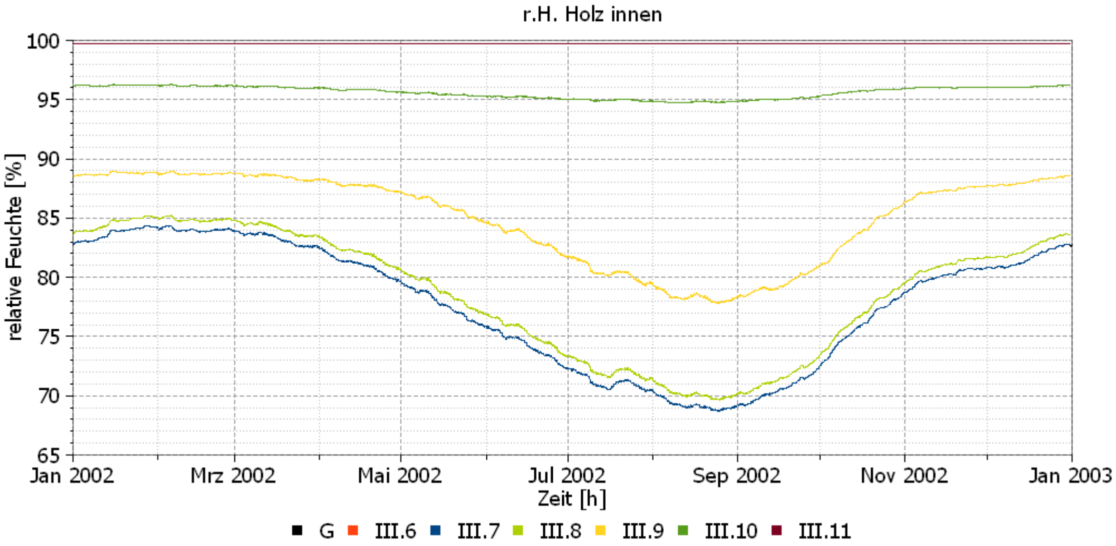

Figure 8. Relative Humidity at analysis point 1 for variants III.6 to III.11 – continuous moisture sources with increasing intensity.

In which order of magnitude were now the rain penetration events due to real weather compared with the above analyzed archetypal moisture sources? The maximum value in the shortest time results at annual hours 4689 and 4690 with driving rain of 2.2 l/m² over these two hours. The highest rain density results within 81h from annual hour 6424 to 6505 with a total of 3.1 l/m² over the whole period in terms of driving rain, corresponding to an average of 38,54 ml/hm². Table 3 reports the resulting water quantities for the single modelled variants and shows that (i) as regards short heavy rain events I.5 and I.6 can be compared to III.2, that (ii) I.6 is in the same order of magnitude of ml/h as III.8 and thus actually at the limit of what the structure can bear long term and (iii) in terms of overall yearly water amount I.6 would correspond to III.9.

Table 3. Comparison of the annual sum of different moisture source variants

	Moisture source based on weather				Pulse source		Continuous source		
	2h	82h							
Variant	ml	ml	ml/h	ml/a	Variant	ml	Variant	ml/h	ml/a
I.1	0.227	0.316	0.0038	1.181	III.1	1.8	III.6	4.32 E-14	1.58E-11
I.2	1.131	1.531	0.0192	5.907	III.2	18	III.7	4.32 E-6	1.58E-4
I.3	2.269	3.160	0.0385	11.814	III.3	180	III.8	0.432	15.8
I.4	4.537	6.321	0.0770	23.628	III.4	1800	III.9	4.32	158
I.5	11.342	15.801	0.1927	59.070	III.5	18000	III.10	43.2	1580
I.6	22.686	31.603	0.3854	118.140			III.11	432	15800

4. Conclusion

Under the assumptions made here, moisture is concentrated around the moisture sources also for the variants with the highest values. The moisture sources have only a small influence on the overall construction, but If leakages at the woods lead to the penetration of driving rain, the water ingress leads to a higher water content especially in the area of the wood. Depending on the dimensions of the moisture source, this can lead to unacceptably high moisture contents in the wood.

On the one hand side, on the basis of these results, influences on the sill of the case study can be deduced, which are partly responsible for the existing damage.

On the other hand side, the observed local damage risk suggests that a "distributed" approach of 1% over the whole area would not reveal all risky situations.

How to quantify the moisture source for a wall, for specific joints is a task to be investigated also with experimental studies.

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