Introduction of a semi-probabilistic moisture safety model for tall timber-based building shell – a risk based durability approach

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ABSTRACT: Recently several timber buildings are built as high-rise buildings. They challenge not only height but moisture safe conditions for mainly wood-based building envelopes under increased exposure. Compared to fire safety and structural demands, the risk of moisture damages today is underestimated in planning, construction and service life management. The main objective is to facilitate the confident design of durable and cost-effective component for tall timber facades by the blend of best-practice with a risk-based concept. Therefore the aim is to develop 'semi-probabilistic safety concepts'. The methodology encompasses a hygrothermal risk model with vulnerability of timber-based shell and the climate conditions for exposure. Risk assessment steps are combined with Life Cycle Costing and Life Cycle Assessment methods to a multi-disciplinary design optimization setting. For maintenance management and durability forecasting the accepted risk-level can be chosen due to the prediction of design alternatives and their life cycle costs for wood-based building shells.

1 INTRODUCTION

There are different categories of buildings or types of construction, which can be related to an increase use of wood, cf. Fig. 1. First category is multi-story timber buildings in which most parts of the load-bearing structure are built of wood. Above it there is another, even larger category of buildings, made of a so called hybrid construction. They consist of structures from reinforced concrete floor slabs and columns as skeleton or bookshelf configuration. Those building envelope consists of highly insulated timber-framed elements. This is a preferred setup, which allows slim wall thickness although high insulation properties are assured, even in passive house quality ($U < 0.15\ W/m^2K$). Finally yet importantly prefabricated timber-based wall elements are used in building retrofit where they are wrapped around the existing envelope like a second skin. In this category, similar to hybrid construction, highly insulating wall elements are placed in front of an existing load-bearing structure of buildings most of them between 4 and 8 levels high. Although latter category is quite young, their usage is steadily growing. The wall elements have to perform effective insulation, airtightness, durable weather proofing and modern visual appearance. A strong set of requirements but possible for wooden structures as several projects have shown in Ott et al. (2013). These are all applications that are unimaginable only a decade ago. On the one hand, massive effort in fire safety and a proofed equivalent performance have opened up the regulations for combustible construction products and then again, the environmental aspect of the lower greenhouse gas emissions during the life cycle convinces more and more investors or are explicitly subsidized from authorities.

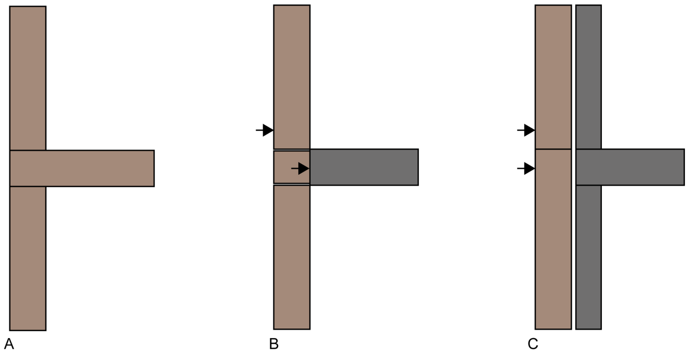


Figure 1. Façade sections show three different categories of exterior wooden walls A) entire wooden structure, B) hybrid wood-concrete structure, C) retrofitting existing mineral structures.

1.1 *Hypothesis & Research question*

Previous definition of the safety level based upon studies of single, specific structures under certain climatic conditions. The derived national building codes are applicable to most structures, for example in Germany that is the standard for the constructive wood protection, DIN 68800 Part 1 and Part 2. As for particular structures at risk (e.g. non-ventilated roofs), this standard requires a dynamic, hygrothermal detection with safety reserves dry out the construction. In addition to the evaluation and the selection of cost-effective measures to prevent damage studies on innovative, non-traditional structures, special customer requests with the changes in regulations or policy performance requirements or special constructions and effects are possible by probabilistic methods; cf. Foliente et al. (2002). In addition, one could be estimated through this approach using climate forecasts future actions and their consequences, cf. Bjarnadottir et al. (2011).

So far, the definition of economic security level of moisture is lacking with respect to:

- Stress related to exposure situations on the macro-level (climate & location, building height, surrounding, orientation) down to the micro level (facade, cladding and details)
- Resistance of the structure (which amount of moisture is present and how much reserve left), compared to
- Damage models (mold, rot, loss of strength)
- Consequences of any damage (human error during construction),
- Development of cost-effective measures (dimensioning, maintenance cycles).

The great variety in configurations of the building enclosure and the effects of the exterior and the interior climate require support in the correct selection of materials and design options as it is seen in Fig. 2. This results in the following central question. Which exterior wall constructions, details and special protection or maintenance is required so that the construction of a 'design life' of fifty years survives without damage? In contrast to similar models and existing results of Vanier et al. (1996), Cornick et al. (2003), Pietrzyk (2015) TallFacades focuses on the entire wall cross-section of highly insulated exterior walls and takes into account the effects of outdoor and indoor climate. For this purpose, a focus comes on risk areas on facades (corners, projections, window openings, etc.). In addition, the aspect of human error in the production is taken into account. The study will going to ask for the additional exposure from unexpected events or a decreased resistance due to weaknesses of the construction (neglect of maintenance, damage, etc.). A key point that leads beyond pure research and is essential for industrial applications is the risk assessment that puts the direct and indirect consequences and the cost of measures to the fore.

Figure 2. A six-storey wooden building of solid cross-laminated timber walls and slabs and articulated topography of the facade, NINA Trondheim.

1.1.1 *Damages & Resistance of exterior wall construction*

The look at accessible, historic data shows moisture damages for the entire construction sector and does not differentiate for steel, concrete or masonry works. An increase of timber constructions in the housing sector, from 5% at the millennium up to 15 % or even more nowadays, is strongly recognizable in the German speaking countries. These numbers cannot proof a causality of increased moisture damages, because continuous education and training of available rules for moisture safety as well as data from a questionnaire amongst engineering companies, experts and timber industry lead to other conclusions. The historic data shows an increase in moisture damages in the last ten years observed in a study of a German insurance company. This marks almost exactly a start of the increase of performance requirements in energy efficiency in the building sector. Simultaneous there is a stagnation or even a decrease of construction activity in Germany. Further reasons can be seen in the increasing complexity of joints accompanied by vulnerability to failure and damages in production due to human error.

1.1.2 *Climate exposure and Stress*

The hygrothermal behavior of building enclosures made from wood, primarily built as timber-framed constructions is discussed since more than 30 years. Improvements in heat protection and reduction in air leakage have been developed since that time. In earlier studies, one concentrated mainly on the convection in air spaces or cavities and deficiencies in vapor retardant layers of the wall cross section. The high moisture transport of diffusion and convection fluxes in cold seasons was identified, in most cases rightly, as main cause for damages within wall compositions. As improved methods for air tightness, forced by the need for more energy efficient buildings, are becoming standard in a way, the external loads are getting into focus. Meanwhile a few younger publications are dealing with the exterior climate and its impact on insulated walls of timber construction. Gudum (2003) recognizes the impact of ventilation behind outer claddings while Vinha & Käkelä (1999) studied various cladding systems. Nore (2009) observed driving rain on ventilated and unventilated coverings as two different moisture safety concepts. A non-ventilated structure of External Insulation System (EFIS) works reasonably well in dry climates, however, high moisture stress rising from the outside air, or bad workmanship, a ventilated facade shows better performance. This must be differentiated by exposure, wall construction, moisture protection and ventilation characteristics considered as Winter et al. (2006) have shown. Kehl & Künzel (2009) made computational studies using simulation of exposed outer shells based on the above-mentioned ventilated facades. Further, they recognize a high sensitivity of results depending on the specific material and construction properties of each of the examined exterior wall design. Apart from the Moisture Reference Year (MRY) paradigm introduced by Cornick et al. (2003). Later on Cornick & Lacasse (2006) extend this analysis, nor the investigation on specific influences of different risk areas at connections and penetrations of the façade, cf. Fig. 3, 4.

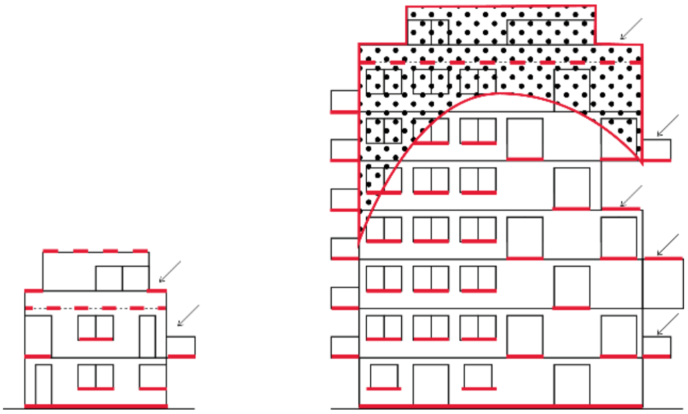


Figure 3. Risk areas (red) of building enclosures small houses (left) and tall houses (right) with high stress regard to wind-driven rain (dotted area).

1.2 *Performance based models for moisture safety*

Performance based concepts for the hazard protection of wooden building enclosures are developed since roughly 25 years and started with the moisture dimensioning of wooden constructions, cf. Nevander & Elmarsson (1991). Canadian and Australian researchers continued this, which took reference from risk-based concepts in structural engineering, cf. Vanier & Lacasse (1996) and Foliente et al. (2002). They do not only the exposure and resistance in mind, but also think about an integrated tool for product modelling, service life and durability exploration. Furthermore, the focus came to the exposure side by severe climate conditions. Meanwhile the construction specific perspective was treated by experience-based rules and wood damage models were developed independently. Rydock et al. (2005) and Kočí et al. (2014) provide MRY that are prepared statistically from historic climate data for simulation by which represent risk climate conditions for building envelopes, namely cold and rainy years. Construction independent MRY were not key, since individual, specific structures should be agreed with the investigated wide range of climate impacts from inside and outside. TallFacades decide on the construction-dependent approach to obtain more specifics about the wall structures and their detailed responses to a broad distribution of climates, thus resulting opportunities for cost-effective design of the wall cross-section can be derived. One result will be the determination of the probability of failure of each examined specific structure to a broad range of exposure. In sensitivity analyzes the sensitivity of the layers of a wall cross-section with respect to the different stresses, and their respective variation is investigated.

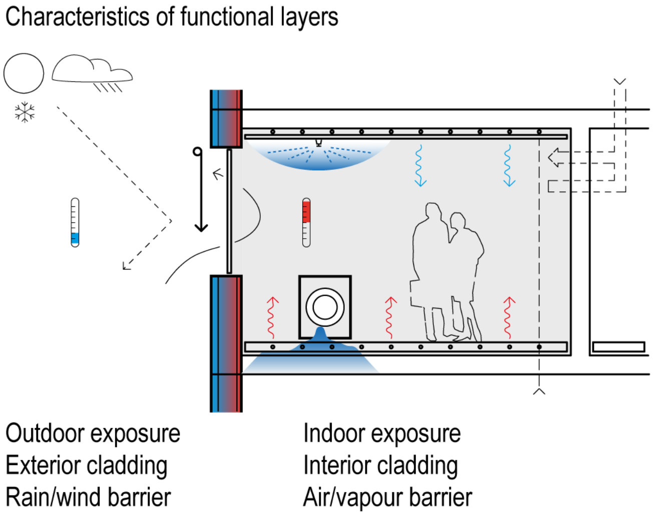
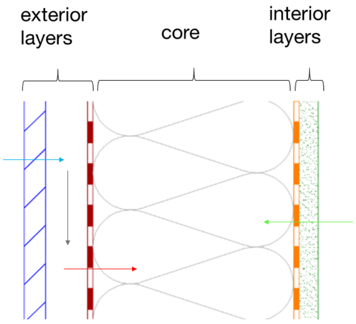


Figure 4. Hygrothermal exposure of a generic building envelope in tall timber condominium or offices.

2 MATERIALS & METHODS

2.1 *Exposure on wooden wall types*

Damage here is defined as the response of a structure to the overuse or their insufficient resistance to exposure. Based on excessive climate, exposure and reinforcing moisture accumulation in construction damage mechanisms are initiated and failure can happen. Defects in cladding or protective outer layer prior to exposure to outdoor climate are part of the experimental investigations, as errors of these layers have been rarely studied. These experiments (e.g. water run-off, WDR and façade aging) provide necessary input data for simulation calibration. Basic compositions like timber-framed walls, cross-laminated-timber (CLT) walls with different panelling and claddings on the exterior as well as the interior surface are chosen, cf. Fig. 5. It is a simple ventilated structure consisting of core (studs or CLT and insulation), exterior defence layers (cladding, air layer, wind barrier) and interior defence layers (the interior membrane works as vapour barrier and air barrier). The gypsum board functions as interior cladding and can be used as bracing. Each material is described and the physical properties used for hygrothermal WUFI simulations are given. WUFI is a transient hygrothermal finite element software for Heat And Moisture transport (HAM) control through different materials under various boundary conditions.



From exterior to interior

cladding – water shedding surface
air layer
membrane – (exterior) moisture barrier
core
membrane – vapor barrier
gypsum board – air barrier

Figure 5. Cross section of a generic timber-framed, insulated exterior wall with a ventilated rain screen as it is common in European wooden houses. Also showing three main functional layers of the undisturbed section.

2.2 *Risk assessment components*

There is foreseen a stochastic testing against a large number of simulations. Already at the level of climate impacts is started with a large number of variations of climatic data, which are applied against the basic construction, cf. Fig. 6. After the examination of the likelihood of failure due to high moisture content, the individual failure mechanisms are studied and used, the cost of repair or replacement of the structure based on consequences. The further consideration of different variations of the original construction, the improvements and their cost can be determined and thus efficient wall sections and any necessary action to optimize cost-expense ratio be determined.

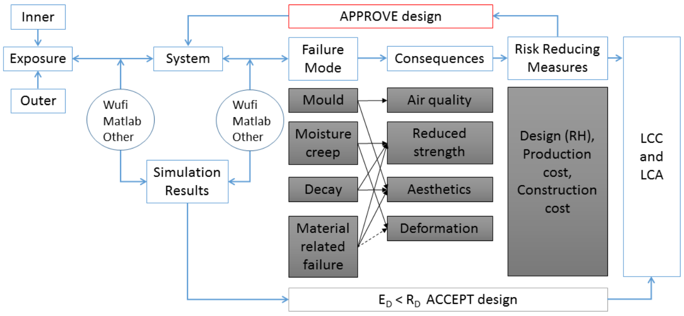


Figure 6. Risk assessment components and relationship to calculate the probability of failure. Consequences are matched with costs of repair. Further adjustment with risk reducing measures will show if additional measures are worthwhile.

3 RESULTS & DISCUSSION

3.1 *Results of system exposure and resistance*

A basic composition will be compared to several modifications. The modifications are more expensive and need more effort to be built than the basic composition. On the other hand, they have a better moisture behaviour and are not so sensitive on human error. Therefore, they will perform better during the lifetime of the building. The aim is to find the optimum solution with respect to both initial costs and lifetime costs.

Based on wall composition in Fig. 5, three modifications are developed. In number 1-1 an additional insulation layer is placed at the exterior side of the core, in number 1-2 an installation layer provides space for e.g. electrical boxes, and in number 1-3 the mineral wool insulation is exchanged by a moisture sensitive cellulose fibre insulation. The idea is to start each time anew from the basic wall composition and add each described measure step by step. A combination of these modifications might be possible in a subsequent step. WUFI-Bio is chosen as failure model for the first phase. It will add the fourth essential input parameter (nutrients) and create the output parameters for depicting mould germination.

The consideration of details like façade penetrations, horizontal barriers (windowsills) or influences of second water-bearing layer are another issue. In these cases, the risk of leakage is higher and failure mechanisms are based on multivariate impacts, cf. Fig. 4, 7. The direct consequences of moistening and the resulting damages can lead to varying extent of damage. From the nature of the information and extent of the damage then required repair is taken as the indirect consequences. For details, the optimisation workflow is similar as for the undisturbed wall. Sensitivity analysis is a problem here; due to high effort for simulation because the 2-dimensional version of WUFI has huge requirements for calculation time and resulting data amount. Weak constructions and harsh climate from sensitivity analysis of the undisturbed wall optimisation indicate simulation conditions. Selected risk area details from Fig. 8 are calculated with a focus on possible weak points and water intake, which can arise for them. Additional lab testing of these detail and variations will give supplemental information about the amount of moisture uptake related to design alternatives and for extend of damages.

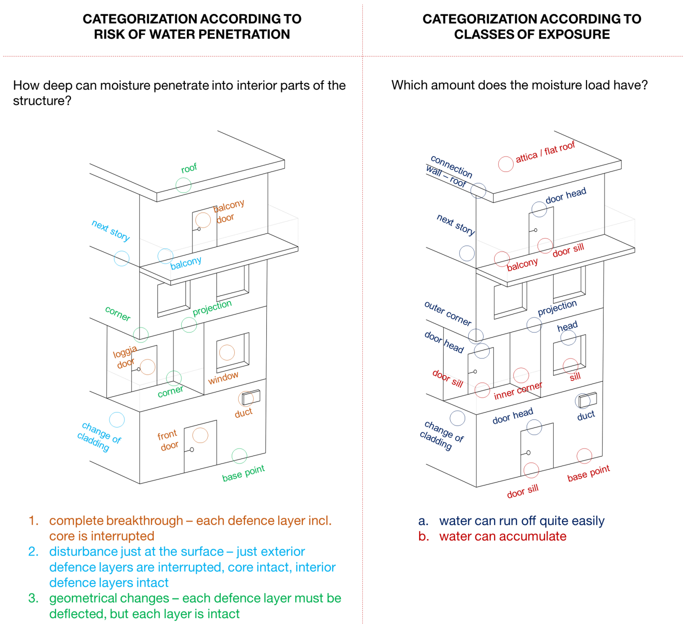
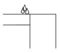
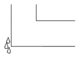
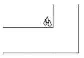
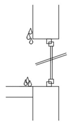


Figure 7. Categorization of façade details causing water run-off disturbance on exterior wall.

Cat.	Description	Pictogram Cross-Section	Details
1a	complete breakthrough + possibility of run-off		balcony door head, window head, loggia door head, duct, front door head
1b	complete breakthrough + possibilty of accumulation		balcony door sill, window sill, loggia door sill, front door sill, base point
2a	surface disturbance + possibility of run-off		next story, change of cladding
2b	surface disturbance + possibilty of accumulation		
3a	geometrical change + possibility of run-off		connection wall-roof, outer corner, projection
3b	geometrical change + possibilty of accumulation		attic / flat roof, inner corner, base point



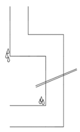


Figure 8. Systemized collection of façade details on exterior wall in regard to their exposure class.

3.2 *Damage models*

3.2.1 *Empirical and mathematical models*

Today there are a number of models for service-life prediction on timber structures. Developments in this area have led to different approaches for modelling service life, such as Scheffer-Index by Scheffer (1971). Dose-response models Brischke & Rapp (2010), Isaksson et.al (2012) were developed to deal with the long exposure time in field trials. Major types of wood bio deterioration are decay and discolorations. Mould and blue stain fungi are often called discoloration fungi and are often initial microbial colonizers of wood. Fungi that cause decay (rot) need free water to live and propagate i.e moisture content above fibre saturation point (FSP). Mould fungi on the other hand can develop when the moisture from the surrounded air is high and the moisture content in wood is below FSP. In FSP state, a Moisture Content (MC) of 28%–30% is generally assumed in the wood Siau (1984). Decay is undesirable but in many aboveground constructions, it is a slow process, especially if it is possible for the wood to dry out between wettings. If the conditions for the fungi's are right, the decay process can be fast. Generally, one could say that the optimal MC for wood-rotting fungi is between 40% and 80% in the wood, and the optimal temperature is between 25°C and 32°C, but they can withstand longer or shorter periods of dryness. However, there is a risk of biological decay through the whole MC range from about 20% to approximately 100% (depends on temperature and time).

Water also affects dimensional change through shrinking and swelling, which in turn influence crack formation and strength reduction. Weathering or degradation of the surface due to water, wind and Ultra Violet (UV) radiation are shown as visible aesthetical factors such as cracks, raised fibres, discoloration and mould. Facade deterioration is determined to the outer part of the envelope and the utmost surface. As identified by Zabel & Morrell (1992), degradation of wood is a complex process involving interaction between wood, the blend of microorganisms, climate and moisture content, exposure time, surrounding environment, irradiation, temperature, etc. Since the environmental requirements of fungi vary, fungal growth will vary depending on the limitations dictated by the prevalent environmental factors. An overview by Brischke & Rapp (2008) of potential inhibitory effects that might delay the start of fungal activity included competition, antagonism, inhibitory extractives, wood preservatives, insufficient permeability, hydrophobic behaviour, distance from sources of infection, adverse moisture conditions and UV light.

Five failure mode have been identified:

- moisture creep,
- decay,
- mould, and
- material related failure (MRF).

Their consequences related to material degradation are failure and deformation, reduction of strength, deformation, reduced insulation capacity; aesthetics value, air quality, and the indirect consequences related to monetary costs replacement, repair and asset, cf. Fig. 6.

3.2.2 *Experts knowledge & consequences*

Further examination of the consequences draw on expertise, as no systematic information on the local scale and the technical extent of damage to appropriate repairs and the costs are present. The uncertainty caused by human error (production in the factory, on-site installation) is determined on a qualitative basis, by expertise from industry and research. The selection of critical modes of construction (e.g. missing rain protection during assembly) and connection details (leaking breather membrane) will be based on expert assessments. Further information from damage evaluations, design catalogs and a comparison made of the mostly semi-empirical design rules for moisture protection add necessary information. This broad approach should help to fill the gap of knowledge, which comes right after the damage models.

Human error can be categorization in three groups of mistakes; design (e.g. missing ventilation layer), building (damage of rain barrier), and maintenance mistakes (leave blocked gutter). The frequency of occurrence of the three categories will be related to consequences.

The step from consequences to repair is also dependent on the qualitative scenarios based on experts guess. The indirect consequences scenarios are grouped into replacement, repair and asset. For each detail from one of the risk areas the cost of indirect consequences are advanced based on the extent, quality and necessary measures. The intake of moisture from planning or production deficiency is based on expert's assumptions. The cost of the consequences of different constructions in connection with yield scenarios for risk reduction, i.e. design change of constructions, declares which strategies are cost-effective. As one cover the uncertain input parameters through the many simulations, the human errors are handled similar to the probabilistic model of statics by application of safety factors, which represent drying out reserves.

3.3 *Semi-probabilistic Model*

The impact of the Wind Driven Rain (WDR) is the main subject, because uncertainties are particularly large here. While the temperature can be described with an average, a trend and seasonality and the relative humidity only very briefly changes during and after rainfall, but is otherwise closely linked to the seasonality of the air temperature. The average annual rainfall is in principle determined, however, the encounter with the wind and the phenomenon of WDR is highly uncertain the building enclosure. Facades have a wide distribution of the moisture entry, in terms of both WDR quantity as well as the influence of the height of the building on the rain amount cf. Briggen et al. (2009). Current data is usually poor because hourly measurement intervals and unweighted averaging normal rain and wind represent the micro-climatic stress insufficient. In contrast, what do advanced WDR models beyond the standard allow cf. Blocken (2004). For the probabilistic studies climate exposure data will be parameterized and evaluated regarding frequency, duration and extremes of precipitation events, and its correlation which is determined to moisture damage.

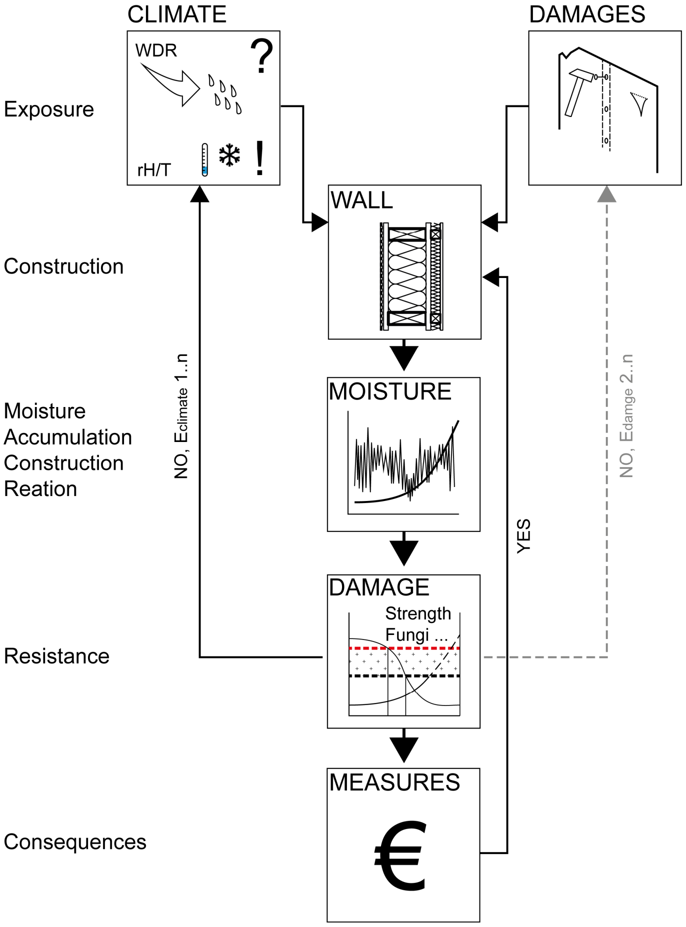


Figure 9. Risk model representation for the moisture management and durability assessment of tall timber facades.

The selected design must cover all conditions that can reasonably be expected during the execution and use of the structure, with sufficient accuracy. Since effects on a structure often occur in combinations with other (variable) impacts, different combinations with the account of occurrence probabilities must be applied to the outer wall, cf. Fig. 9. Using a probabilistic model the performance of facade constructions can be investigate. The model takes into account all uncertainties of climate and human error and expresses the accessibility of certain performance criteria in probabilities. The risk model represents the physical mechanisms of exposure of moisture on exterior wall components in a coupled model with probabilistic representation of the damage and degradation depending on the outdoor climate exposure from; i.e. starting from the understanding of failure modes, failure mechanisms and microclimate.

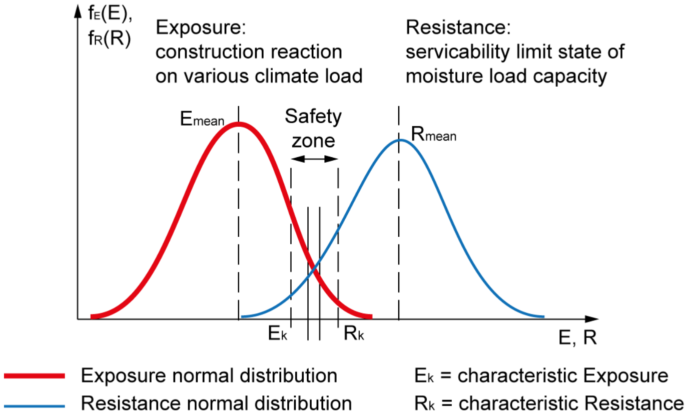


Figure 10. Normal distributions of Exposure and Resistance and the necessary safety zone between characteristic values of both.

4 DISCUSSION & CONCLUSIONS

In the first stage, a complex risk model is created for the simple cause-effect model, which differentiates the impact and consequences precisely. In this, physical phenomena and interaction between climate exposure and construction reaction are simulated and associated with the direct and indirect consequences. The boundary conditions for the moisture management model are derived from the data of outdoor and indoor climate. These stress a construction to be examined and for which preliminary damage might already be present e.g. by construction defects or increased building moisture. Based on specific construction details, failure and consequences lead to measures to increase the robustness. A specific construction can be optimized according to predefined target functions, see Fig. 10. The further selection of critical modes of construction and connection details will be based on expert assessments, damage evaluations, design catalogs and a comparison made of the mostly semi-empirical design rules for moisture protection. In the further course of the research project, TallFacades laboratory tests and experimental data are used to analyze uncertainties of design categories and damage classes of the facade.

As generally in civil engineering with specific risk theory and probabilistic methods a realistic framework for problem solving is given. The possible uncertainties are included in the system context and its influential imaging variables. In addition, the reliability theory is a framework for quality management, material selection and optimization to improve the robustness of the moisture protection of constructions. Some problems remain. There is a gap for in-service data of buildings and their components. The extent of damage is hard to grasp because there is no structured and even no generic data available and only conceivable by experts guess and development of qualitative scenarios. It is the same for the repair and for durability of materials used for facades. Finally, the appropriate combination of multivariate impacts like loads from permanent, temporarily, unusual situation, and human error exposure; how they are interrelating, is still open and has to be examined in detail.

5 ACKNOWLEDGEMENTS

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