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STUDIES ON HYGROTHERMAL PERFORMANCE OF WOOD ELEMENTS IN BUILDING CONSTRUCTIONS– REMARKS ON METHODOLOGY

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ABSTRACT

In general, building constructions containing wood elements are moisture sensitive. To increase the knowledge about their hygrothermal performance accompanied with assessments of risk of mold growth and other degradation mechanisms a set of analytical methods is typically used: standard calculation or more advanced mathematical models, laboratory measurements and field observations. Nevertheless, in some cases such approach seems not to be sufficient. Full size testing under controlled and long-time stable boundary conditions is needed in order to get more complex picture about the real performance and risks.

In the first part, the paper informs about hygrothermal problems and mold growth modelling. The key part of the paper deals with methodology and technique available at University Centre for Energy Efficient Buildings: Full size façade openings for placing different assemblies of building envelopes with wood elements and facility with crawl-space type foundations. Furthermore, laboratory experiments and measurements together with in-situ monitoring as example are presented. The paper discusses combinations of advanced modelling used for design of experiments on one hand with expected results from full size controlled testing on the other hand. Classification of mold growth risk can represent an efficient way of expression of overall quality in this respect. First results are presented here for illustration. Paper concludes that coordinated combination of different research techniques can bring new knowledge in understanding the processes leading to deterioration of wood elements in building construction.

KEYWORDS: Hygrothermal performance, moisture, mold growth, crawl space, cold roof, wood beams.

INTRODUCTION

General description

In general, building constructions containing wood elements are moisture sensitive (e.g. Trechsel 1994, Lstiburek and Carmody 1993). Wood is to high extend present in traditional buildings, which are very often the subject of a deep retrofit. Wood-based materials are used in modern buildings as well, but differently (platform frame systems, cross laminated timber systems, prefabricated modular systems etc.). Unfortunately, the moisture exposure directly determines service life of wood-based structures and must be though considered (Havířová and Kubů 2006, 2011).

Furthermore, the situation is changing from the building physics point of view. The required very low operation energy demand (EU 2010) for new buildings and for deep retrofit leads to different thermal performance compared to previous situation: A heat flow caused by heat losses is less present and constructions are much more air-tight (Novák 2009, Dimitroulopoulou 2012). Acceptance of interior side additional thermal insulation, which is in some cases the only solution, is still understood as a risky measure by the majority of stakeholders and engineers. This is especially the case if wooden beams of floor structures end in the walls (Ueno 2015, Guizzardi 2015, Kehl et al. 2013).

Wood-based materials are more often used now not only for structural purposes but also as thermal insulation (wood fibers). In the same time, application of several long-time proven preventive chemical treatments is prohibited in respect to health risks. A special task represents the use of biobased materials with non-domestic origin (bamboo, insulation made of marine algae, etc.) with respect to possible protection against biodegradation and the compatibility to other materials.

New, man-made wood based materials still carry more or less the original sensitivity of the natural wood. If exposed to unfavorable conditions, material properties change (Böhm 2009). Furthermore, the qualities can change during the lifetime. Therefore the wooden materials and structures must be tested to prove the desired qualities (Mirski et. al. 2015, Reinprecht et al. 2010, Volf et al. 2015).

To increase the knowledge about thermal and moisture performance of wood materials, accompanied by assessments of risk of mold growth and other degradation mechanisms, a set of analytical methods is typically used: standard calculations or more advanced mathematical models, laboratory measurements, and field observations. Nevertheless, in some cases such approach seems not to be sufficient (Ueno 2015). Full size testing under controlled and long-time stable boundary conditions (Janssens et al. 2011) is needed in order to get more complex picture about real performance and risks.

Situations with restricted or negligible air movement near to wood surfaces which are often seen as most critical are subjects of investigations presented in this paper:

- floor construction above crawl space type foundations,
- wood beam ends placed in pockets of brick walls,
- cold roofs made of wood.

Study of thermal and moisture performance

Moisture damage is one of the most important factors affecting service life of building structures. It especially applies for lightweight building envelopes containing natural organic materials (wood and wood-based products, hemp, flax, straw etc.), where increased moisture levels can lead to decay, mold growth and even hazards to human health (Tenwolde and Rose 1996, Adan and Samson 2011). Although current computational tools offer unprecedented possibilities to solve engineering tasks involving moisture transport in building structures, frequent disagreement between computed results and observed behavior still exists. It is often the case of structural details with two- or three-dimensional heat and moisture transport driven not only by temperature and humidity variations between the indoor and outdoor environment, but also by solar radiation, driving rain and air flow due to barometric pressure differences. A typical example here is the interstitial condensation in enclosures of modern wood-framed buildings in winter conditions due to air exfiltration caused by imperfections in air barriers. Condensation quantities related to exfiltration are up to three orders of magnitude higher than those transported by vapor diffusion (Tenwolde and Rose 1996, Janssens and Hens 2003, Langmans et al. 2012). In such cases where simultaneous moisture transport by diffusion, convection and capillary forces is involved, capabilities of numerical models are still limited. Also, any numerical model will always require measured input data (material properties, climatic data) and its reliability can be proved only by experimental validation (Kalamees and Vinha 2003).

Conditions for mold growth

Moisture safety of building constructions is usually related to risk of mold growth on its surfaces. Beside esthetical damages such as discoloration of interior finishes or moldy odor, mold fungi can also negatively influence health of the occupants (Sedlbauer 2001, Platt et al. 1989, Piecková and Jesenská 1999). An overview of interior mold species and possible diseases can be found in (Sedlbauer 2001).

Although mold fungi live on material surfaces and thus not cause any significant degradation to the material, they can prepare conditions for decay fungi (Johansson 2012, Neville and Webster 1995, Shigo 1975, Adan and Samson 2011). Therefore a visible mold growth on interior surfaces or on any biodegradable construction elements is a sign of improper moisture conditions and potential problems.

A common measure to avoid surface mold growth is keeping relative moisture content of ambient air below 75-80 % since this level is a minimal suitable moisture content level for mold growth (Rychtera et al. 1974, Adan 1994). In many cases this rule cannot be fulfilled throughout the whole year and then the situation calls for more detailed analysis using mold growth model.

In last two decades a couple of mold growth models were developed (Verrecken and Roels 2012). The original VTT mold growth model (Hukka and Viitanen 1999) and its improved version (Viitanen and Ojanen 2007) are most often used today. These models, developed in Technical Research Centre of Finland, are based on visual findings of mold growth in laboratory conditions. The original model is validated for spruce and pine sapwood only, while the improved model includes also other materials sorted in four sensitivity classes (Ojanen et al. 2010, Viitanen et al. 2015).

The input parameters are material, wood surface quality and courses of temperature and relative moisture content of ambient air (typically in one hour time step). The output is a course of mold index (M) ranging between 0 and 6. A recent mold index classification is shown in Tab. 1. Often a level of mold index equal to 1 is defined as the maximum tolerable value (germination of mold spores).

Tab. 1: Mold index classification (Viitanen et al. 2015).

Mold index (M)	Description of the growth rate
0	No growth
1	Small amounts of mold on surface (microscope), initial stages of local growth
2	Several local mold growth colonies on surface (microscope)
3	Visual findings of mold on surface, < 10 % coverage, or< 50 % coverage of mold (microscope)
4	Visual findings of mold on surface, 10 – 50 % coverage, or>50 % coverage of mold (microscope)
5	Plenty of growth on surface, > 50 % coverage (visual)
6	Heavy and tight growth, coverage about 100 %

MATERIAL AND METHODS

Experimental set-ups and observations

Several types of experiments and in-situ monitoring are continuously performed in the University Centre for Energy Efficient Buildings (UCEEB) for better understanding of thermal and moisture performance of constructions containing wood elements. The Centre is located near the city of Kladno, Czech Republic (50.15°N, 14.17°E).

Climatic room

The purpose of climatic room are the long-term measurements of hygrothermal properties of full scale samples of building envelopes and their key-parts under real climatic conditions. There are six openings in the façade („experimental windows“), 3.2 m high and 3.0 m wide each (Fig. 1).

Fig. 1: Climatic room a) interior of climatic room with HVAC systems, b) experimental façade with six "windows" for installation of fragments of building constructions.

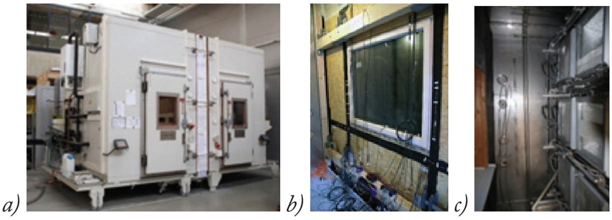


Fig. 2: Brick wall with embedded wooden beams. a) wooden beam end, b) air pocket, c) embedded wooden beam with sealed air gap.

Temperature and relative humidity inside the climatic room are kept stable and homogenous by an HVAC system, and both parameters are adjustable. The exterior side of the samples is facing natural outdoor environment of a western oriented façade. External climatic data are measured directly on the façade and data from the weather stations in neighborhood of the building are also available. Each opening can be divided into four smaller parts, so it is possible to measure up to 24 samples on the whole façade. Experiments can be focused on ageing, hygrothermal behavior, volumetric changes, deterioration mechanisms etc., and the measured data may serve as well for validation of mathematical models.

In contrast to measurements in climatic chambers, the façade enables real-lifeand long-time exposure. This is especially important for monitoring the moisture content transfer and biodeterioration processes in wood, which are, by nature, slow. Minimum test period here is one year, i.e. one annual climatic cycle, but even longer periods are planned (up to 3 – 5 years). And in contrast to in-situ monitoring campaigns, the samples here can be equipped with a large number of quality sensors. In each opening, up to 76 sensors can be placed to record air temperature, material temperature, relative humidity, moisture content, and heat flux.

Currently, there are running measurements on 6 types of modern wood constructions (building envelopes), on 300 mm brick walls with 4 typesof interior thermal insulations and with a different treatment of wooden beam pockets (Fig. 2), and the lightweight curtain wall made of wooden panels (Lupíšek et al. 2015).

Crawl space set-up

For hygrothermal and microbiological study of crawl spaces, a full-scale experimental house has been constructed (Fig. 3). It is a part of a long-term joint research project of the University Centre for Energy Efficient Buildings and Faculty of Civil Engineering, CTU in Prague. The main goal of the project is to determine basic rules for designing modern crawl spaces in Central European climate that would be moisture-safe, mold-free, with minimum maintenance requirements and cost effective (Richter and Staněk 2015).

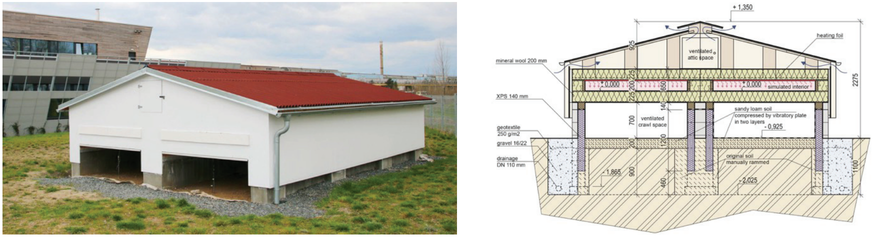


Fig. 3: Crawl space experimental set-up. Cross section in the design documentation and finished construction.

Experimental crawl space is composed of two symmetrical sub-floor spaces with west-east orientation. Each is 2.0 m wide, 7.5 m long and the height of the sub-floor cavity is 0.7 m. Crawl space is designed as cold, with the base floor U-value of 0.20 W·(m^{-2}·K^{-1}). Interior space above the base floor is simulated by a 20 cm high room. Thermostat-controlled heating foil provides temperature between 19-21°C during the heating season and automatically operated shutters are opened when the interior temperature exceeds 27°C to allow natural ventilation of the room. Side walls as well as partition wall are thermally insulated by XPS boards embedded 0.64 m under the ground in order to emphasize 2D character of the experiment. All structural connections are properly sealed to ensure airtightness of the experimental space. A proper drainage system with nearby seepage is made around the whole experimental crawl space.

Air, soil and surface of the base floor in both cavities are monitored using temperature, relative humidity and heat-flux sensors and anemometers. Climatic conditions are monitored by a nearby meteorological station (20 m from experimental house).

Pair of symmetrical sub-floor cavities allows direct comparison of different experimental set-ups under identical boundary conditions and in full size scale.

At first, the cavities will be monitored without any modification to verify whether they perform similarly. Then a set of measures will be consecutively implemented to one of the cavities to compare differences in their hygrothermal performance. Measures will be related to:

- implementation of different groundcovers to inhibit evaporation from the ground and/or suppress thermal accumulation in the soil under the crawl space,
- testing different sizes, positions and geometries of ventilation openings toprovide the best mixing and optimal (moisture safe) air change for each of all four seasons.

Parallel microbiological studies of mold growth on different sheeting materials and the effect of fungicides in real crawl space conditions will be performed.

Laboratory testing

Laboratory equipment at UCEEB allows multi-scale experimental testing of complex hygrothermal behavior of building envelopes. The key apparatus is the large climatic double-chamber, see Fig. 4a. The chamber enables full-scale testing of samples up to 3.0 x 3.0 m under wide range of precisely controlled boundary conditions, including temperature, relative humidity, solar irradiance, driving rain and barometric pressure difference, see Tab. 2 for details. Variety of testing procedures can be set and performed thanks to an integrated control system: long-term or short-term, steady or dynamic, complex or single-purpose. Additional equipment allows measurement of heat, moisture and air permeability of the sample. The sample can be equipped with a number of temperature, humidity and heat flux sensors and the sensor data as well as the course of the whole testing procedure are continuously stored for further evaluation.

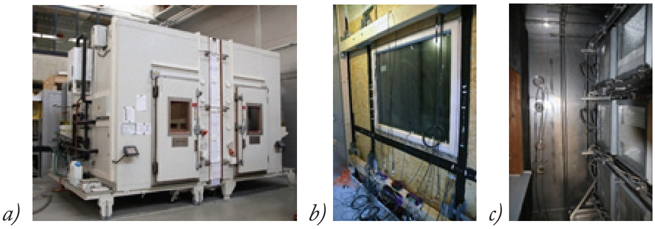


Fig. 4: Large climatic double-chamber with set-up of newly developed wood based curtain wall for retrofit purposes. a) overall view, b) picture from interior side with sensors and connections to data logger, c) picture from exterior side with removable solar and rain.

Tab. 2: Basic parameters of large climatic double-chamber.

Parameter	Chamber	
	Outdoor	**Indoor**
Temperature range	–20 to +80°C	–10 to +60°C
Relative humidity range	10 to 95 %	10 to 95 %
Pressure difference	up to +300 Pa	up to +300 Pa
Additional equipment	Solar simulator (500 – 1000 W.m^{-2}) Rain simulator (up to 17 l.min^{-1})	Guarded HotBox (U-value meas.) Water vapor diffusion meas.
	Air permeability meas.	Air permeability meas.

As an example, Figs. 4b, c show an experimental set-up to verify design and hygrothermal performance of structural connections of a newly developed wood based curtain wall for retrofit purposes (Lupíšek et al. 2015). The first round of experiments is aimed at risk of interstitial condensation under steady temperature and humidity gradients, with no barometric pressure gradient. In the second stage, barometric pressure gradient is applied to measure air in- and exfiltration of the sample under isothermal conditions. And finally, simultaneous effect of temperature, humidity and pressure gradients is studied. This gradual approach allows to distinguish between the individual effects and eliminates possible shortages in design or implementation.

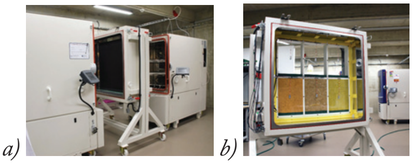


Fig. 5: Small climatic chambers a) double-chamber set-up, b) intermediate frame with samples.

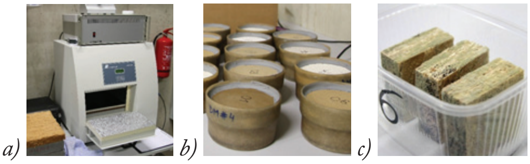


Fig. 6: Measurement of basic material properties. a) thermal conductivity, b) water vapor permeability, c) susceptibility to mold growth.

Experimental equipment available in the laboratory also includes two smaller climatic chambers that allows double-chamber set-up as well (Fig. 5a). They are intended for particular climatic tests of building materials and elements. As an example, Fig. 5b shows an intermediate frame (1.0 x 1.0 m) with samples of various hydrophobic and hydrophilic thermal insulations prepared for a test of interstitial condensation.

The laboratory also provides equipment for measurement of basic materials properties such as thermal conductivity, water vapor permeability, capillarity, sorption and retention curves, saturated moisture content and open porosity, and susceptibility to mold growth (Fig. 6).

Field observations

Field observations and measurements provide valuable experience and are necessary for identification of typical as well as critical situations in performance of buildings. Information from real buildings is also very often a starting point in defining requirements for particular experiments or advanced computational models, which can help to further explain and generalize the observed behavior. As an example, a long-term field measurement of hygrothermal behavior of a retrofitted cold deck flat roof is presented here.

Cold deck flat roofs were commonly used in Central Europe in 1970 and 1980s for multi-story slab block residential buildings based on industrialized building systems (Fig. 7a). The upper deck was often made up of assembled wooden elements (Fig. 7b). Nowadays, these roofs are being routinely retrofitted since their original insulation standard – most commonly 60 to 120 mm of mineral wool – does not meet current requirements. One of the common retrofitting techniques combines two measures: 1) blowing additional thermal insulation into the roof cavity (Fig. 7c) and 2) installing additional roof vents to strengthen ventilation of the air layer (Fig. 7d).

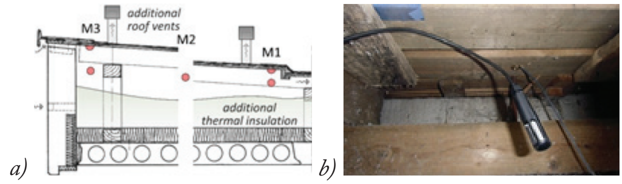

a) b) c) d)

Fig. 7: Cold deck flat roof of a multi-story slab block residential building before and after retrofit. a) overall view, b) upper deck made up of assembled wooden elements and original mineral wool thermal insulation, c) additional cellulose thermal insulation, d) finished roof with additional roof vents.

Thermal resistance of the lower deck typically increases from 2.3 before retrofit to 6.1 $m^2 \cdot K \cdot W^{-1}$ after retrofit. However, its diffusion resistance increases only little – from 5.9 to 6.4 m, expressed in terms of equivalent diffusion thickness. It means that during winter almost unchanged amount of water vapor reaches a significantly colder air layer. As a result, a risk of condensation on the lower surface of the upper deck increases. This has led to worries about moisture and microbiological safety of the wooden elements. Long-term in situ measurement showed to be the best option to evaluate the new situation here, for two reasons:

1. hygrothermal performance of the roof strongly depends on air change rate in the ventilated layer, which is difficult to predict,
2. any numerical model would have to be dynamic and two-dimensional at least to provide realistic information and suitable data for mold growth model.

A number of sensors were placed into the roof during retrofitting works to measure temperature and relative humidity in the air layer and on the lower surface of the upper deck (Fig. 8). Additional sensors were placed above the roof to measure temperature and relative humidity of the outdoor air. The measuring system was completed with data logger and GSM modem for its remote control. The measurement was started in 2013. An analysis of two-year data showed that although the relative humidity in the retrofitted roof increased compared to the original state, it remained on an acceptable level and condensation occured only rarely, mainly during sudden drops in outdoor temperature in winter months. Inserting the measured data into the VTT model also showed that the new hygrothermal regime did not constitute suitable conditions for mold growth on the wooden elements.

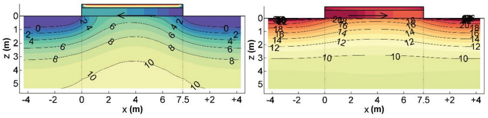


a) b)

Fig. 8: Measurement of hygrothermal performance of the retrofitted roof a) cross section of the roof and positions of measuring point M1–M3, b) sensors of temperature and relative moisture content in the air layer and on the lower surface of the upper deck, measuring point M3.

Mathematical models

Observation of reality improves understanding the complexity of physical phenomena in the world around us. However, there are few frequent limitations in practice. Relatively long-term measurement campaigns are needed to collect data about performance of building envelopes subjected to varying climatic loads. Also, number of sensors in experiments is limited and measurementsare affected by many uncertainties. Thus carefully calibrated mathematical model can introduce more complete pictureof a given problem, complementing the analysis of measured data. Moreover, mathematical models play an important role in designing new experiments.



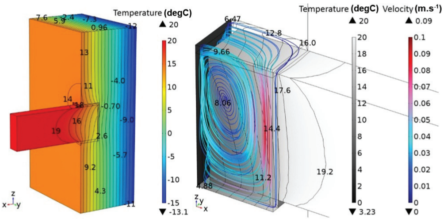


Fig. 9: 2D temperature field in the floor structure, ventilated air layer, and ground beneath a crawl space in mid-January (left) and mid-July (right) (illustration).

Fig. 10: 3D temperature field of a brick wall with embedded wooden beam (left) and a detail of air flow pattern in a closed cavity around the wooden beam end (right) (illustration).

Our research group developed several models for transient simulation of hygrothermal performance of layered building components, crawlspaces (Fig. 9), and ventilated attics. These models were developed in Matlab (Mathworks). Creating own models contributes to a better understanding of the problem. Such a process has also significant educational benefits. Software Comsol (Comsol) is used for more complex tasks involving three dimensional air flow (Fig. 10). The outputs from these models can be further coupled with mold growth model.

The outputs from simulation models have to be evaluated with care due to various modelling uncertainties. Models often suffer from incomplete knowledge of boundary conditions and material properties. Models also sometimes suffer from neglecting phenomena which are important in reality. A quantitative evaluation of results is often impossible. An experienced user with expert knowledge of physical principles is the key for correct analysis.

RESULTS AND DISCUSSION

The on-going experiments in climatic room described in 3.1 bring very first results. More than one year the hygrothermal performance of interior insulations made of wood fibers, vacuum insulation and mineral wool with a vapor barrier has been studied. The situation in the area of beam ends is presented here for illustration. To prevent the airflow from the interior to the beam pockets so called air-stop sticking tape was used in some cases (described here as "treated beam pockets"). The first results of the measurement of relative humidity and moisture content are shown in Figs. 11 and 12 for the sample with wood fiber insulation. Mold index calculated using the measured data is shown in Fig. 13.

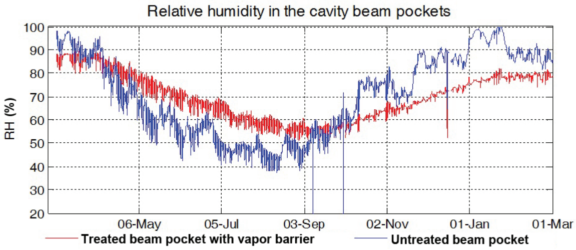


Fig. 11: Relative moisture content in the cavity of beam pockets- measured.

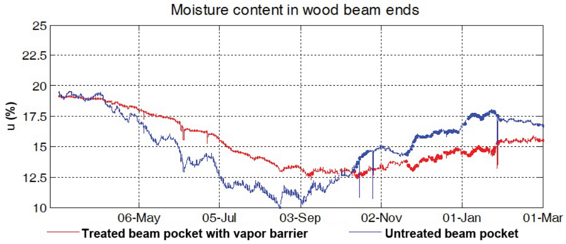


Fig. 12: Moisture content in wood beam ends – measured.

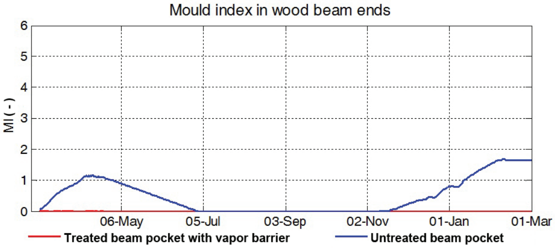


Fig. 13: Calculated mold index in wood beam ends – illustration.

From the measured values, it is obvious that the treated pockets have significantly lower amplitude of humidity throughout the year. The relative humidity in untreated pockets approaches to 100 % in winter time and the corresponding mold index reaches a maximum of 1.7 here. In contrast, the treated beam pockets reached practically zero mold index throughout the whole year.

It was demonstrated that the combination of different approaches and techniques can bring new knowledge in understanding the processes leading to unwanted deterioration of wood elements (Fig. 14): Observation of specific risk situations evaluated from the inspections of buildings or published information can be further studied in laboratory, by means of in-situ measurements under limited condition or by targeted full-size experiments. Some of these experiments can be efficiently designed by means of mathematical modelling in order to focus to real critical or typical situation.

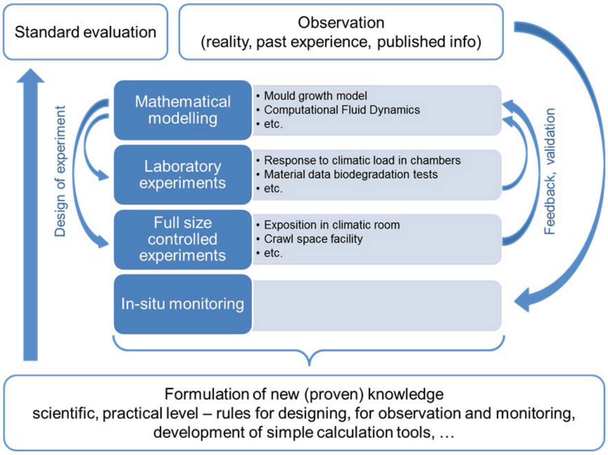


Fig. 14: General scheme of research activities.

On contrary, the results of carefully performed experiments can be used for validation of mathematical models or at least for discussions about their plausibility. All these studies can be performed to some extent in a coordinated way. All knowledge gained here should be interpreted not only as scientific findings but also transformed into practical usable knowledge. Based on that, simple calculation procedures serving as design supporting tools can be upgraded or newly developed.

CONCLUSIONS

Further research activities are needed in order to get more accurate and comprehensive information concerning very fine effects like mold growth and other deterioration mechanism. Intensive and long-time use of crawl-space facility is planned here focusing on selected situations evaluated from the practice.

Large climatic chamber will be further in use for detailed studies on building envelopes, especially on effects of water and water vapor penetration and moisture accumulation inside of construction. Exposition of samples to the barometric pressure difference represents other type of boundary conditions, which should be studied. Further development of mathematical modelling will be supported by confrontation to experimental results.

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