Outlining a methodology for assessing deterioration threshold criteria

Linked to retrofitting historical buildings with internal insulation

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Abstract – This paper describes a methodology for assessing damage threshold criteria as a part of the ongoing EU Horizon2020 project RIBuild. In RIBuild, effective, comprehensive decision guidelines are developed to support energy retrofitting of historical buildings with internal insulation without compromising their architectural and cultural values while maintaining an acceptable safety level against deterioration.

The methodology includes a survey and determination of threshold values for deterioration, which can then be used to evaluate the risk in specific structures of external walls. The work includes summarizing existing knowledge and adapting and developing models for failure modes based on field and laboratory testing.

Failure modes include frost damage of the exterior façade layer, rot and mould growth within the building envelope and adjoining structures, as well as discolouring of façade surfaces due to biological growth.

Keywords – internal thermal insulation; renovation; failure modes; historical buildings; energy retrofit

1. INTRODUCTION

1.1 ENERGY CONSUMPTION IN HISTORIC BUILDINGS

30 percent of the European building stock consists of historic buildings, which in the EU stand for more than one third of the total energy consumption from buildings [1]. It shows the importance of improving the energy efficiency of historic buildings.

It is possible to reduce the energy consumption in historic buildings by 15–20 percent [2]. One key action is to install internal insulation without impact on the outer façade. This is however followed by a risk of failures in the wall construction, related to the function, the aesthetics and possibly the indoor air quality – all associated with high costs. Therefore, there is a need of more knowledge and guidelines on how to, in an effective and secure way, install internal insulation in historic buildings.

1.2 RIBUILD PROJECT

The EU Horizon 2020 research project RIBuild stands for Robust Internal Thermal Insulation and revolves around developing guidelines on how to apply internal thermal insulation in historic buildings of masonry and stone without changing or affecting the outer architectural and cultural values.

The main purpose of the RIBuild project is to enable a reduction of the energy consumption in historic buildings to reach the EU 2020 climate and energy targets.

RIBuild is a five-year project and will be finalized in the end of 2019. The developed guidelines will include an assessment determining whether a building is suitable for internal insulation or not, based on identified failure modes and available damage models as defined below.

1.3 BUILDING ENVELOPES HEAT AND MOISTURE TRANSPORT

Internal insulation in historical buildings does not only decrease the transmission losses through the thermal envelope, it also changes the hygrothermal condition in the existing masonry wall. Depending on for instance the insulation thickness, heat conductivity, porosity and permeability of the added material, the existing hygrothermal conditions in the wall will be affected in different extent. The insulation generally lowers the temperature, reducing the drying of the wall, and hence increases its overall humidity. Using transient simulation models for assessing hygrothermal conditions over time, i.e. temperature and moisture inside the wall structures, the output can be directly used for evaluating the risk of the different failure modes described in this report.

To evaluate the risk of different failure modes, transient hygrothermal simulations, including solar radiation and rain, must be used. Results from the simplified steady-state Glaser method, which is not taking those into account, nor the capillary transport and the sorption capacity [3], is not giving results useful for a realistic evaluation of the failures.

1.4 IDENTIFIED FAILURE MODES AND BUILDING PARTS AT RISK

When additional insulation is put on the internal side of an outer wall of a building, the original wall structure will be colder and wetter. These changed conditions may also lead to higher risk of different failures. In the project we have identified four failure modes:

- mould growth on materials within the building structure;
- frost damage of the exterior façade layers;
- growth of algae and fungi on the façade surfaces;
- rot damage in wooden structures.

The first failure mode, mould growth, can affect the indoor environment and health of people in the building, while superficial growth on the façades primarily has aesthetic consequences. Initially, frost damage leads to aesthetical problems but may in a long term also give structural consequences. Rot damages affect the strength of the building, and the growth of the rot fungi may also affect the indoor air. The positions with high risk of failure in a wall that have been internally insulated, are illustrated in figure 1.

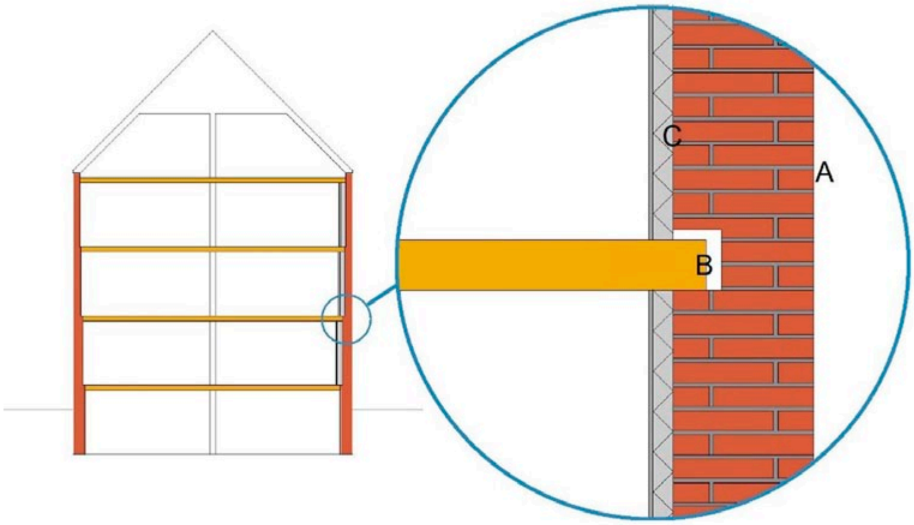

Figure 1. Parts of an exterior wall at risk of failure when installing internal insulation. (A) frost and discoloration of the façade surface, (B) rot in, and mould growth on, the beam ends, (C) mould and rot (if wood) on the interstitial materials surfaces and adjacent materials.

2. FAILURE MODES AND DAMAGE MODELS

2.1 DYNAMIC AND STATIC MODELS

Internal thermal insulation leads, as mentioned, to several risks of failures in the wall construction. To predict the failures, failure modes need to be known and different damage models should be used. Static models predict risk under constant conditions, while dynamic models also consider varying conditions present in buildings. These variations may affect the growth of algae, mould and rot fungi, as the growth rate is lower when conditions vary. Some species can survive dry periods and resume growth when conditions are favourable again. Frost damage is also highly dependent on varying conditions.

2.2 MOULD

Mould is a colloquialism for a range of microscopic fungi that share some common traits. They live on the surface of materials, produce airborne spores and use easy assimilated nutrients for growth. Mould acts as decomposers in the natural carbon cycle and their spores are found everywhere in the air and on various kinds of surfaces. When the right conditions are present, the spores germinate and grow to form a mycelium, and it is then that damage first occurs.

Conditions for mould growth include nutrient availability (primarily carbon sources), temperature, pH, moisture and duration of conditions. In general, the availability for water at the material surface is regarded as the crucial element for mould growth to occur. The susceptibility to mould growth of different building materials varies.

Growth inside a building is often not visible to the naked eye. Growth may also occur inside hidden parts of the building structure. Problems caused are therefore not always of an aesthetic kind. Neither does the growth affect the strength of the building structure. Instead, the negative effect of mould growth is linked to experienced indoor environment and possible negative health effects on people in the building.

There are several static and dynamic models for predicting mould growth, some are described and discussed in [4–6] from either measured data of RH and temperature or data from HAM-simulation (Heat, Air and Moisture) results. The results from the predicting models may be used to predict the extent of mould growth (e.g. as an index) or the possibility that there is risk for growth to appear at all. Each model has its pros and cons. In the project, prediction from different models will be compared to real outcomes in field studies.

2.3 FROST

Frost damage is mostly related to aesthetical problems when the frost is spalling the outer surface of the masonry wall. Where driving rain can infiltrate the masonry wall with internal insulation, the frost risk is moved further into the wall. The damage is due to a variety of mechanisms, including the volume increase of water when it changes to ice. The main parameters are the critical saturation degree and the critical freezing temperature. The temperature and saturation degree are both affected when internal insulation is added.

The models available for predicting frost damage together with results from a dynamic HAM-model, are listed below. It should be noted that the models only count the numbers of frost-thaw cycles or the time of exceedance of the two parameters mentioned above, hence not relating these solely hygrothermal indicators to the start or growth of the frost damage [7].

- – Modified Winter Index (1)
- – Amount of Frozen Water (2)
- – Time of Freezing (3)
- – Indicative Freeze/Thaw Cycles (4)

$$MWI = \sum_{i=1}^{8760} (T_L - T_i)(w_i - w_L) \qquad [T_i < T_L \;\&\; w_i > w_L\,] \tag{1}$$

$$AFW = \sum_{i=1}^{8760} w_i \qquad [T_i < T_L \;\&\; w_i > w_L\,] \tag{2}$$

$$TOF = \sum_{i=1}^{8760} \qquad [T_i < T_L \;\&\; w_i > w_L\,] \tag{3}$$

IFTC = number of freeze/thaw cycles $w_i > w_L$ (in which the freezing and thawing conditions hold at least 2 hours) (4)

w_I and w_L in the equations refer to the freezing temperature and the critical moisture content.

2.4 ROT FUNGI

A severe failure mechanism for wooden materials and constructions is rot or wood decay caused by fungal growth. This failure mode is closely linked to moisture as water activity is a prerequisite for fungal growth [8]. The most severe consequence of rot attack is the reduction of structural strength, but indoor air quality may also be affected.

The critical positions in the building envelope are where wood is present, and particularly where the moisture loads are high. In historic masonry façades, wood is mostly used for half-timbering in exterior walls. Wooden beam ends and supporting laths may be placed in the external walls, and are therefore in direct contact with bricks or stones. Also, if the building is internally insulated with systems that contain wooden materials, e.g. wooden framing, more wooden materials may become at risk of rot decay provided that the moisture level is high enough.

Rot fungal growth starts when the moisture content in wood exceeds a threshold value; this depends on different factors:

- duration of wetness, i.e. the time above the certain threshold value;
- condition of the wood; previously attacked wood has a lower threshold value; than non-affected wood;
- wood species;
- ambient temperature.

For most fungal species, the threshold value is in the over-hygroscopic range caused by condensation or liquid water sources from penetrating rain although there are some fungal species (dry rot) that can transport moisture over distances enabling rot attack far away from the moisture source. A prerequisite for dry rot is the presence of lime, which is often used in historic buildings and therefore present for the fungal growth. There are three types of rot fungi that can initiate decay in wood; brown rot, soft rot and white rot. Brown rot develops faster than other types of rot fungi, and is more likely to appear earlier than white and soft rot.

There are several mathematical models and assessment algorithms [9, 10] developed for predicting the risk of rot fungi and service life under dynamic conditions, all using governing environmental conditions such as moisture content and temperature for the wooden material as well as different material properties.

2.5 DISCOLORATION OF FAÇADES

When mould fungi grow on façades, they might cause discolouration. However, not all fungi cause this discolouration, only such species that contains dark pigmentation in their cells. In addition, algae and cyanobacteria growing on façades can cause discolouration. These microorganisms, like the fungi, need water to grow; in general, the lowest required moisture level for growth is higher. A big difference between the algae and cyanobacteria on one hand, and mould fungi on the other, is that the previous groups of microorganisms contain chlorophyll in their cells. In contrast, mould fungi lack this trait and are dependent on available nutrients within the material they grow on. Environmental factors are therefore more crucial than the nutrient content of the material for algae to grow [11], while the contents of façade material may also have an important impact on the establishment of fungi. However, other characteristics of the materials may affect also the growth of algae and cyanobacteria, such as surface structure and porosity [12, 13].

3. FAILURE MODE THRESHOLD VALUES

3.1 THRESHOLD VALUES IN DAMAGE MODELS

To use the failure prediction models mentioned above, for the different failure modes, specific threshold values are needed. However, thresholds values are not widely established for all failure modes and materials, which makes it difficult or even impossible to evaluate all possible solutions and failure criteria. Within RIBuild we are currently working on how to reach consensus on these criteria.

3.2 MOULD

As mentioned above, building materials differ in their susceptibility for mould growth. Some materials tolerate being exposed to air with relatively high RH (> 95 %) without mould growth occurring, while on the most susceptible materials mould growth can appear at a relative humidity as low as 75 % RH [14–16]. The lowest relative humidity at which mould growth can be expected in a material can be described as the critical moisture value. This material property can be evaluated in laboratory tests [17–18]. With this laboratory test, each product and mark of a material gets its specific critical moisture value, and it is therefore not possible to provide general threshold values for different groups of materials [15, 20]. The threshold value may differ within a specific group of materials, and change with the development of a product. “If the critical moisture level is not well-researched and documented, a relative humidity (RH) of 75 % shall be used as the critical moisture level” [22].

3.3 FROST

The literature presents no threshold values for the mentioned frost models. Instead the frost models are mostly used on a relative basis comparing different solutions. The models are based on the critical moisture content, derived from the critical saturation level. Therefore, the indexes from the models are useful only if the critical saturation level is known for the specific material.

3.4 ROT FUNGI

Threshold values for rot fungi vary significantly between different studies [8, 10, 22] but some typical threshold values can be derived. Absolute threshold limits for temperature and moisture content are difficult to present, as temperature and moisture content are closely interconnected for fungal growth, and vary between fungi species. However, at temperatures lower than 5 °C the fungi are considered to be dormant and will not initiate any rot fungi growth. Similarly, an upper threshold limit for temperatures above 40–45 °C has been shown, whereas the ideal temperature is around room temperature dependent on fungi species. Moisture content is of high importance, and sustained values close to or above wood fibre saturation can enable rot fungi to grow. Typically, such moisture contents are in the range of 25–30 weight-percent. Above certain moisture content (≥70 weight-percent) there is no rot fungi growth.

3.5 DISCOLORATION

As previously described, discoloration of façades can be caused by organisms such as mould fungi, algae and cyanobacteria. These have different threshold values for growth, but temperature and humidity are the most important environmental conditions, but exposures to pH and solar radiation also have an influence. The optimal temperature for algae and cyanobacteria lies between 10 °C and 40 °C. The organisms' resistance to high (above 50 °C) and low (below 0 °C) significantly varies from one organism to another. Optimum moisture conditions vary even more between different discoloration organisms. However, for green and blue algae, which are often the main cause of discoloration, liquid water is necessary. Algae and cyanobacteria can survive dry periods and growth continues when enough humidity is available again.

4. CONTROL ACTIONS

4.1 GENERAL CONTROL ACTIONS

An important control action is the pre-retrofit on-site investigation of the existing construction. Is there any pre-existing frost damage, ongoing leakage from driving rain, established mould or even rot? The choice of thermal insulation type and thickness must be considered when evaluating the proposed retrofitted construction.

General control actions to be considered:

- Estimating/calculating expected humidity and temperature conditions for the building material layers in the construction;
- Ensuring air tight mounting to circumvent additional moisture content leakage from the indoor air into the wall.

4.2 SPECIFIC CONTROL ACTIONS RELATED TO FAILURE MODES

- If possible, choose internal insulation materials and systems with higher threshold values for mould than the estimated conditions arising from the retrofit. Typical threshold values can be derived from laboratory testing and are already available for many materials;
- Possibly, a hydrophobic impregnation of the exterior surface can be beneficial to prevent moisture uptake, particularly concerning frost susceptible materials. A hydrophobic external surface may also inhibit certain algae species by reducing access to surface moisture;
- Choose clean, dry materials to eliminate additional building moisture. If storing material outdoors, use weather-proof covers to avoid excess moisture from precipitation.

5. DISCUSSION AND CONCLUSIONS

Part of the RIBuild project is to develop guidelines for assessing whether a building is suitable for internal insulation or not, based on identified failure modes and available damage models. Since many of the available damage models only give relative indications, evaluation must be carried out on a relative basis, particularly concerning failure modes such as frost damage and discoloration of façades. Consensus on acceptance levels for the different failure modes must be reached before serviceability limit state can be evaluated and the proposed measures assessed. For instance, is it possible to totally avoid mould growth in buildings? What would be an acceptable level of risk for different failure modes? If the mould is not too extensive and is not further growing, it may be accepted depending on the position in the building. Similar reasoning can be argued for the other failure modes.

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