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A Risk-Based Approach for Quantifying Durability and Life-Expectancy of the Wall-Foundation Construction Detail in Timber Buildings

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Abstract. *Understanding and predicting the durability of timber structural components of buildings can lead to a more reliable and efficient use of this material in constructions. The work described herein presents a methodology to assess the life-expectancy of wall-foundation details in timber buildings based on the estimation of the durability of the timber structural element. Risk classes were defined starting from the inputs from the most relevant standards addressing the durability of timber available in Europe. The attribution of a risk class to the wall-foundation detail requires decision trees that consider the key aspects that affect the durability of this construction detail in the case of fungal attack. The methodology was then applied to three case studies and the results were compared to the observations from onsite inspections carried out on the decayed structural timber elements. The present work represents the first step towards the development of a tool capable of predicting the durability of timber components within the building structure. The work reported herein was carried out within the framework of the TSafe project.*

Keywords: *Timber Buildings, Wall-Foundation Detail, Durability, Risk-Based Approach, TSafe Project.*

1 Introduction

Understanding and predicting the durability of timber is of paramount importance for a more reliable, extensive and efficient use of this material in constructions. Furthermore, quantifying the durability will also allow for a more precise quantification of the carbon stocks stored into the wood products (Profft *et al.,* 2009).

Because decay caused by biotic attack is one of the most critical concerns in the long-term performance of wood, durability at the material level has been deeply investigated. In-ground and above-ground behaviour of wood has been studied through field and laboratory testing (*e.g.*: Meyer *et al.,* 2016; Meyer *et al.,* 2017). Prediction models have been also developed to predict decay caused by fungal attack or to predict mould grow (Brischke *et al.,* 2014).

The prediction of timber decay in building structural components has instead been investigated by only but a few researchers. The Australian project, reported in Leicester *et al.* (2008), is an interesting example of a comprehensive project that examines the decay of timber and the corrosion of the metal fasteners. Decay functions have been developed within the framework of the aforementioned project to predict the depth of the fungal attack on timber structural elements inside the building envelope.

The functions have been calibrated through an extensive field test campaign and on opinions of experts (Wang *et al.,* 2008c). Strong assumptions have been made by the researchers to keep these functions simple and straightforward. Moreover, a limited set of Australian structural typologies have been considered in the project.

Recently, the increasing availability of timber-based products for a diverse range of building solutions has stimulated researchers into approaching more sophisticated tools to map timber moisture distribution over time. The Heat, Air and Moisture (HAM) analysis is one of the tools adopted to predict timber moisture content with precision (*e.g.*: Carbonez *et al.*, 2015 and Chung *et al.*, 2019).

The Wall-Foundation Detail (WFD) in timber buildings can have quite different geometries, materials, wall stratigraphies and boundary conditions. The combination of these characteristics can create a very large number of possible configurations that escalates the effort of performing HAM analyses. With reference to the durability of this construction detail, finding the most critical combinations can be very important to approach this problem effectively. Another key issue to be solved when studying this detail is how to model water intrusion. Guidelines for modelling water intrusion in walls where the problem can be schematized as one-dimensional can be found in Lstiburek *et al.* (2016a-b). An equivalent of the above-mentioned guidelines for the two-dimensional problem is not available yet and because the WFD is essentially a two-dimensional problem, its study demands bigger efforts in order to run numerical analyses and perform experimental tests.

The paper presents a methodology to categorise the WFD of timber structures in relation with the durability of the timber structural element. This method permits to assign a risk class to the detail, based on decision trees that considers the most significant issues related to timber durability accounting for fungal attack. Risk classes are used both to identify the most critical configurations and to associate to them a decay estimation function that at this preliminary stage was taken from literature. Three case studies (Gaspari *et al.*, 2020) are then introduced to compare the results of this preliminary decay prediction.

The methodology proposed herein is part of the TSafe project where reliable strategies for the risk assessment of timber structures are used to create decision-making tools useful to every party involved in the construction of timber structures. The purpose of the TSafe project is to combine numerical simulations, such as HAM analyses, with artificial intelligence and machine learning algorithms to extract simple and applicable rules from complex problems solved numerically (see for example Glavind *et al.*, 2019 and Freire *et al.*, 2017).

Risk classes are defined in section 2. Then, the decision trees necessary to assign a risk class and the parameters for the quantification of the decay are presented in section 3. The results obtained are compared to three case studies in section 4. Finally, section 5 outlines the conclusions and future work.

2 Risk Classes

Risk classes were defined according to the provisions contained in the main European standards that deal with the durability of timber from the material point of view (*i.e.*: ÖNORM B 3802-1:2015, EN 335:2013 and DIN 68800-1:2019-06) and from that of a building detail (*i.e.*: ÖNORM B 2320:2017 and DIN 68800-2:2012-02). Risk classes identify a general behaviour of the construction detail in terms of protection against water intrusion, condensation, and water permanence and of timber drying performance. Moreover, the risk classes group together different building details that show similar behaviour. A definition of the risk classes for the WFD, considering the standards cited above, is reported in the following (Gaspari *et al.*, 2020).

- Risk class 1 (R1): timber is protected against outdoor weather (direct rain, bounce water, wind-driven rain and external rain accumulation) and against rising damp. Moreover, presence of condensation is possible, but a rapid drying is ensured.

- Risk class 2 (R2): timber is protected against outdoor weather (direct rain, bounce water, wind-driven rain and external rain accumulation) and against rising damp. Presence and permanence of condensation is possible.
- Risk class 3 (R3.1 and R3.2): timber can get wet, due to outdoor weather (direct rain, bounce water, wind-driven rain and external rain accumulation) or to condensation caused by non-efficient airtightness. The class R3 is divided into the two subclasses R3.1 e R3.2 considering, respectively, the possibility of timber to dry or not.
- Risk class 4 (R4): timber can get wet due to outdoor weather (direct rain, bounce water, wind-driven rain and external rain accumulation) or to condensation. Timber is in direct contact with a porous material that can absorb water. Timber cannot dry rapidly.
- Risk class 5 (R5): timber can get wet due to outdoor weather (direct rain, bounce water, wind-driven rain and external rain accumulation) or to condensation. Timber is prevented from drying and water that comes in contact with timber cannot run out.

As a preliminary approach, a fast and straightforward evaluation of the decay is assessed through functions available in literature that estimate the depth of the fungal attack (Leicester *et al.*, 2008). According to Wang *et al.* (2008c), the decay depth d_t is evaluated through equation (1) as a function of the time *t* and the slope *r*

$$d_t = \begin{cases} 0 & , \quad t < lag \\ (t - lag)r, & \quad t \geq lag \end{cases} \tag{1}$$

where $r = k_{wood} k_{geometry} k_{climate}$ and lag is a function of *r*. The parameters k_{wood} and $k_{geometry}$ are constant values that depend on the wood species, on the location of timber within the detail and on the interaction between timber and the other elements (as defined in Wang *et al.*, 2008c). The parameter $k_{climate}$ depends on the amount of water (from precipitation) penetrating the detail and on such water can dry off.

In order to consider the contribution of condensation, equation (2) is proposed, where the term $t_{wet,cond}$ is added to the equation proposed by Wang *et al.* (2008c).

$$k_{climate} = 0.03(t_{wet,rain} + t_{wet,cond})^{0.4} \tag{2}$$

$$\begin{cases} t_{wet,rain} = \sum_{i=1}^{12} (t_{rain} - t_{drying})_i \ , & (t_{rain} - t_{drying})_i \geq 0 \\ t_{wet,cond} = \sum_{i=1}^{12} (t_{cond} - t_{drying})_i \ , & (t_{cond} - t_{drying})_i \geq 0 \end{cases} \tag{3}$$

The “duration parameters” t_{cond}, t_{drying} and t_{rain} in equation (3), must be evaluated based on the assigned risk class. The relation between the risk classes and these parameters is reported in Table 1.

Table 1. Relations between the duration parameters and the risk classes.

R	t_{rain} [hour/month]	t_{cond} [hour/month]	t_{drying} [hour/month]
1	0	0	∞
2	0	To be evaluated	To be evaluated
3.1	To be evaluated	To be evaluated	To be evaluated
3.2	To be evaluated	To be evaluated	To be evaluated

4	720	To be evaluated	To be evaluated
5	720	To be evaluated	0

In the cases where t_{rain} and t_{drying} must be evaluated, suitable methods can be found in Wang *et al.* (2008c). The t_{cond} indicates the number of hours per month in which timber is wet because of condensation and it can be calculated by referring to well-established methods for the hygrothermal analysis of buildings. Leakage coming from the inside of a building was not considered in the present study for the sake of simplicity, but suitable approaches can be found in Wang *et al.* (2008c).

3 Decision Trees

The WFD in timber buildings can be classified through decision trees whose branches account for the various conditions which may occur and affect the durability of the timber structural components. For brevity, only the decision trees related to the three case studies selected to compare the results are presented.

The background material for developing the decision tree included prominent European standards in the field of durability of timber structures such as ÖNORM B 2320:2017 and DIN 68800-2:2012-02.

The most relevant parameter is the distance of the base-surface of the timber element from the ground surface. This distance H is positive when the position of the timber base-surface is higher than the ground surface, negative otherwise.

In the three case studies selected, H was always less than 10 centimetres, so two conditions were considered in the following: (a) H greater or equal to 0 cm, but lower than 10 cm, and (b) H lower than 0 cm. A decision tree was defined only for the first scenario since risk class R5 was always assigned to the second one. Figure 1 shows the two decision trees defined for the $0\ cm \leq H < 10\ cm$ (Gaspari *et al.*, 2020).

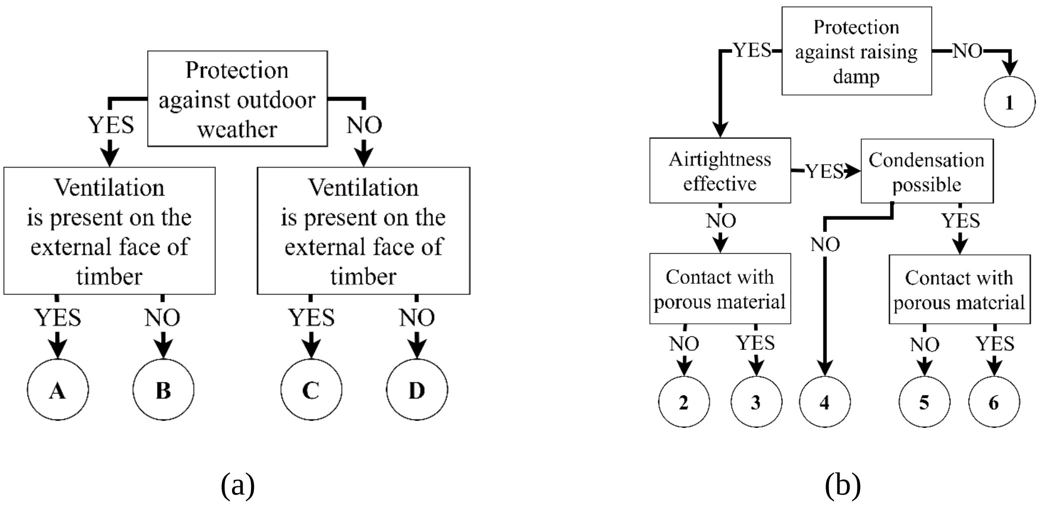

Figure 1. Decision tree (a) DT1 and (b) DT2 for $\mathbf{0\ cm \leq H < 10\ cm}$.

The decision tree DT1 shown in Figure 1 (a) considers outdoor weather (direct rain, bounce water, wind-driven rain and external rain accumulation) and the possibility of timber drying off due to ventilation. This tree results in 4 different conditions, from A to D. Decision tree DT2, reported in Figure 1 (b), takes into account the rising damp issue, the building airtightness and whether timber is in contact with porous material or not. This second tree leads to 6 conditions. These two trees are independent from one another, but both must be used for the evaluation of the detail. All combinations of the results from the two trees are shown in Table 2 (Gaspari *et al.,* 2020).

Table 2. Risk classes definition for the combination of DT1 and DT2.

	DT1			
DT2	**A**	**B**	**C**	**D**
1	4	4	4	5
2	3.1	3.2	3.1	5
3	4	4	4	5
4	1	4	3.1	5
5	2	2	3.1	5
6	4	4	4	5

In the preliminary procedure for the decay estimation, additional aspects must be specified in order to assess the decay estimation properly. In fact, decay estimation functions are typically defined for a single face of the timber element. However, depending on the geometry of the WFD and on the contact between timber and other materials, multiple faces can be affected by decay. These additional aspects are provided in Table 3.

Table 3. Additional aspects for the combination of DT1 and DT2.

	DT1			
DT2	**A**	**B**	**C**	**D**
1	A3	A4	A3	A3
2	A2	A4	A2	A3
3	A2	A4	A2	A3
4	A1	A4	A2	A3
5	A2	A4	A2	A3
6	A2	A4	A2	A3

The aspects reported in Table 3 are defined as follows, considering the internal and external faces of timber.

- A1: decay due to leakage must be evaluated solely on the internal face.
- A2: decay must be evaluated on the external face and eventually on the internal face due to leakage.
- A3: decay must be evaluated on both faces.
- A4: decay must be evaluated on the external face and eventually on the internal face due to leakage. Moreover, if the internal face of timber is in contact with a scarcely permeable material or $H_{int} < 0\ cm$, R5 risk class must be selected.

Considering a linear element (for example a post or a beam), if decay is present on both internal and external faces, the same depth of the fungal attack must be considered on the lateral faces. The same must be done if decay is present on one face and a porous insulation is in contact with timber.

Finally, the leakage contribution must be considered only if $H_{int} \leq 5\ cm$.

4 Results

In this section the WFD of three case studies is analysed by applying the decision trees. Then, the preliminary procedure for the estimation of the decay is applied to the case studies and a final comparison is reported.

The case studies have been described in detail in Gaspari *et al.* (2020), while just a brief description is provided herein. Table 4 gives an overview on these case studies.

Table 4. Overview of the case studies.

Case study	**Structural typology**	**Year of construction**	**Year of inspection**	**Element analysed**	**Dimensions [mm]**	
					Thickness	Width
A	Light-frame	2007	2018	Post	140	80
B	Light-frame	2009	2018	Post	160	180
C	CLT	2015	2017	CLT	160	200

For case study C where the timber component is a CLT panel, a reference width of 200 mm corresponding to the width of a single wood-board of the CLT panel was selected.

In case study A, the distance of the base-surface of the post from the ground is set to *H = 0 cm*. In fact, in this case the base-surface of the timber element is at the same level of the ground surface. There are no waterproof membranes; protection against outdoor weather and ventilation are also absent. These conditions lead to path D in DT1 and to path 1 in DT2. The combination of paths D and 1 determines a risk class R5 with the additional condition A3. In case study A the element studied is a post and because both external and internal faces must be evaluated, then all four faces must be evaluated.

In case study C, the base of the post is set to *H = -23 cm* and consequently a risk class R5 was assigned to the detail. All faces of the post must be evaluated.

Case study C presents a CLT wall with *H = 0 cm.* The CLT wall is not properly protected against outdoor weather and ventilation is absent. Moreover, a hygro-thermal analysis verified the absence of accumulation of condensation. These conditions lead to path D in DT1 and path 4 in DT2. The combination of paths D and 1 results in assigning risk class R5 with the additional condition A3.

In order to evaluate correctly the decay of the CLT panel, the lateral faces of the board were considered. In fact, cracks and long-term effects on CLT boards usually lead to preferential paths for water to penetrate into the CLT.

Case studies A, B and C were inspected after 11, 9 and 3 years after construction, respectively. Case studies A and B showed 0 % of residual timber cross-section, where the residual cross-section is the ratio between the timber cross-section area in sound conditions at the time of the inspection and the original timber cross-section at the time of construction. Case study C showed a residual cross-section of approximately 60 %. The comparison between the outcomes of the inspections and the results of the model has been reported in Figure 2.

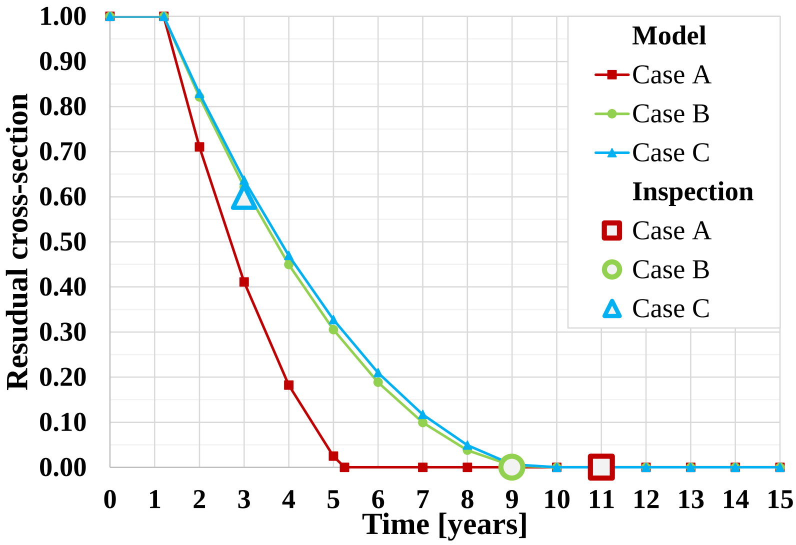

Figure 2. Comparison between the observations from the case-study inspections and the results of the analytical model.

5 Conclusions

This paper proposes a methodology to categorise the Wall-Foundation Detail (WFD) of timber structures in relation with the durability of the timber structural element. Risk classes were defined looking at the prominent standards that treat the topic of the durability of timber. The risk classes can be assigned to the WFD via decision trees designed to consider the main aspects that can affect the durability of this construction detail in relation with fungal attack. This was the first step to develop a reliable method capable of predicting the life-expectancy of timber construction details. Future research steps, as a part of the TSafe project, will involve more sophisticated tools such as Heat, Air and Moisture analysis, machine learning and a combination of both. For a preliminary validation of the overall analysis approach, three case studies were selected and studied using the methodology proposed herein. A good correspondence was observed from the comparison between the results of the proposed methodology and the onsite inspections.

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