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Durability-based design of timber structures – Guidelines for architects and planners

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ABSTRACT

Timber structures for bridges, buildings, claddings and decking are often an economically and sustainably feasible alternative to structures in other building materials. Predicting the performance (e.g. the service life) of building products made from timber and other bio-based building materials has become increasingly important. Performance data are requested by designers, planners, authorities and approval bodies, but rarely available. On the one hand, raw data on performance as well as reliable performance indicators are sparsely documented, on the other hand the number of reliable performance prediction models is limited.

The service life of a timber structure is influenced by degrading mechanisms such as mould fungi, decay fungi, insects, termites etc. Service life of timber structures in outdoor conditions is predominantly affected by the climatic conditions in terms of moisture and temperature over time. During recent years various modelling approaches were reported that can be used to predict performance of bio-based building materials, in particular wood and wood-based products. In first instance, the effect of climate (i.e. exposure) and the effect of the material resistance have been considered and were both found to be closely connected to the moisture performance of the material. Furthermore, the effect of design, constructive protection measures, microclimate, coatings, and maintenance schedules were set into perspective with the moisture-induced risk for decay.

Within the research projects ‘WoodExter’, ‘WoodBuild’, and ‘Durable Timber Bridges (DuraTB)’ engineering tools were presented to predict fungal decay of wood, both for commodities such as claddings and decking as well as for load-bearing structures such as timber bridges. The approach used in these tools is presented here and shown with an example.

The advantages of the new performance based prediction models are that they are scientifically based, with all factors being determined either by laboratory or field testing, modelling or expert opinions. As the approach is open, future research results can be easily implemented as well as the user might use own input factors. The tools promote a systematic approach to durability by design, they can function as a check list for the designer and can consider project specific conditions in a more precise manner.

INTRODUCTION

Timber structures for bridges, buildings, claddings and decking are often an economically and sustainably feasible alternative to structures in other building materials. Timber as a naturally renewable material has a beneficial carbon footprint and it is expected that building with timber increases due to the increased focus on life cycle analysis (LCA). However, when designing timber structures and commodities, the focus should not only be on meeting the load-carrying and aesthetic expectations, but also to design for a reasonable service life. For load-bearing timber structures, the demanded service life is described in Eurocode 1990 (2002) and should be e.g. 15 to 30 years for agricultural buildings, 50 years for building structures and 100 years for bridges. To reach the intended service life, the designer can choose between timber protection by design, use of naturally durable timber species or use of preservatives (or a combination of those methods). However, it has not really been possible to prove that a certain design leads to a certain intended service life with the information given in standards or earlier handbooks. Predicting the performance of building products made from timber and other bio-based building materials has become increasingly important. Performance data are requested by designers, planners, authorities and approval bodies, but rarely available (Brischke and Jones 2016). On the one hand, raw data on performance as well as reliable performance indicators are sparsely documented, on the other hand the number of reliable performance prediction models is limited. In the past, at least to some extent performance prediction was run against or at least only parallel to traditional durability testing of wood and wood preservatives, whereby the latter was focused on for decades due to its overwhelming market importance.

The service life of the structure is influenced by degrading mechanisms such as mould fungi (aesthetics), decay fungi, insects, termites etc. Service life of timber structures in outdoor conditions is predominantly affected by the climatic conditions in terms of moisture and temperature over time. On the one hand, the two parameters moisture content and temperature determine the exposure-induced dosage that can lead to fungal infestation and subsequent decay. On the other hand, the material resistance of wood stands in opposition to exposure and is itself affected by the inherent protective properties of wood and its ability to take up and release water in liquid or vaporous form (Meyer-Veltrup *et al.* 2017). Other factors such as design details, in-use conditions, and maintenance are only indirectly affecting the service life of wooden structures and can be accounted for through the aforementioned parameters.

During recent years various modelling approaches were reported (Brischke and Thelandersson 2014) that can be used to predict performance of bio-based building materials, in particular wood and wood-based products. In first instance, the effect of climate (i.e. exposure) and the effect of the material resistance have been considered and were both found to be closely connected to the moisture performance of the material. Furthermore, the effect of design, constructive protection measures, microclimate, coatings, and maintenance schedules were set into perspective with the moisture-induced risk for decay. Within the research projects 'WoodExter', 'WoodBuild' and 'Durable Timber Bridges (DuraTB)' tools are presented to predict fungal decay of wood, both for commodities as claddings and decking as well as for load-bearing structures as timber bridges. The tools have the potential to serve as instrument for design and service life prediction of timber structures. Several logistic decay models were applied and compared with respect to their feasibility to quantify direct and indirect decay influencing factors such as climate on macro, meso and micro level, topography, design details such as shelter through roof overhangs, end grain and side grain contact faces, and diverse metal joints.

To include all those factors, a factorization approach is used based on dose-response relationship between wood material climate and responding fungal decay, where onset of decay is defined as limit state (Brischke *et al.* 2017). The concept does also allow for quantifying the material resistance of untreated, modified and preservative treated wood using factors based on laboratory and field durability tests and short term tests for capillary water uptake, adsorption and desorption dynamics.

In the following an engineering approach is presented for service life prediction of timber structures and how this can be implemented in design guidelines and standards. The overall aim is to transport the rather complex and comprehensive knowledge achieved in various long term research projects to users such as architects, planners, engineers, and finally craftsmen and house owners. The way from a complicate backend based on bio-physical and engineering mathematical models to simple front-end tools with a user-friendly interface will be illustrated.

APPROACH FOR DETERMINATION OF SERVICE LIVES

Performance prediction of wooden structures is generally a three-step approach (Brischke and Thelandersson 2014, Brischke *et al.* 2015, Niklewski *et al.* 2016a). As illustrated in Figure 1, a design solution is considered successful if the exposure over time stays equal or below the resistance of the material in use. In other words and in analogy to structural engineering the load should never exceed the capacity. To quantify the dose on "both sides of the balance" at least three separate models are needed: exposure model, decay model and resistance model.

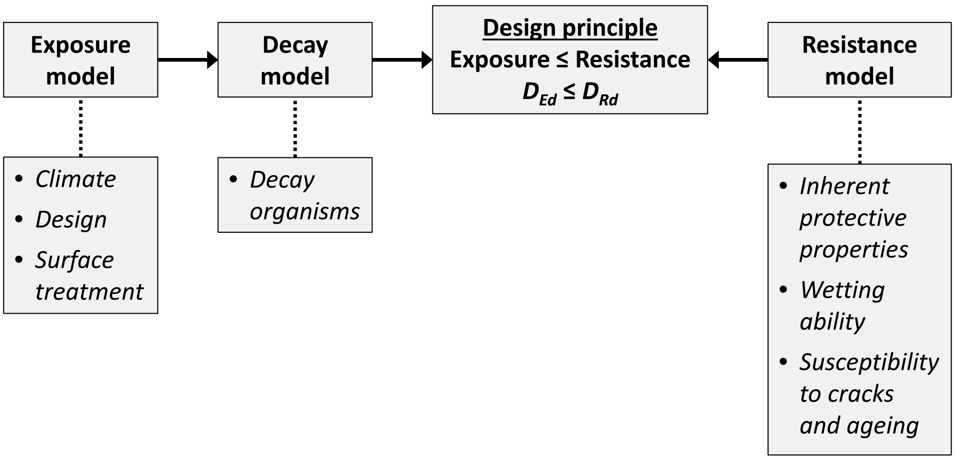


Figure 1: Performance modelling with three-step approach.

For components or details exposed to free water, the service life should be evaluated according to the approach presented in Figure 2. If members/details are protected from free water, then a risk analysis of the durability/service life of the protective part should be carried out.
The evaluation of a given component or detail exposed to free water should be made in the following steps as shown in the flowchart in Figure 2. The tool as presented in Figure 2 is the version developed for timber bridges (Pousette *et al.* 2017), however, the same general approach is also valid for cladding and decking. The differences between the bridge tool and the previous cladding/decking tool (according to Isaksson *et al.* 2014 and 2015) are pointed out later in this section.

A design solution (choice of design and material) is accepted if the exposure is less than the resistance (Eqn. 1):

$$D_{Ed} = D_{Ek} \cdot \gamma_d \leq D_{Rd} \quad (1)$$

where D_{Ek} is the characteristic exposure dose, D_{Ed} is the design exposure dose, and γ_d is a factor accounting for severity class. D_{Rd} is the design resistance of the chosen material. γ_d is chosen according to the consequences of non-performance and is determined to 0.6, 0.8 and 1.0 for low, medium and high consequences/risk respectively. For load-bearing bridge structures, γ_d=1.0.

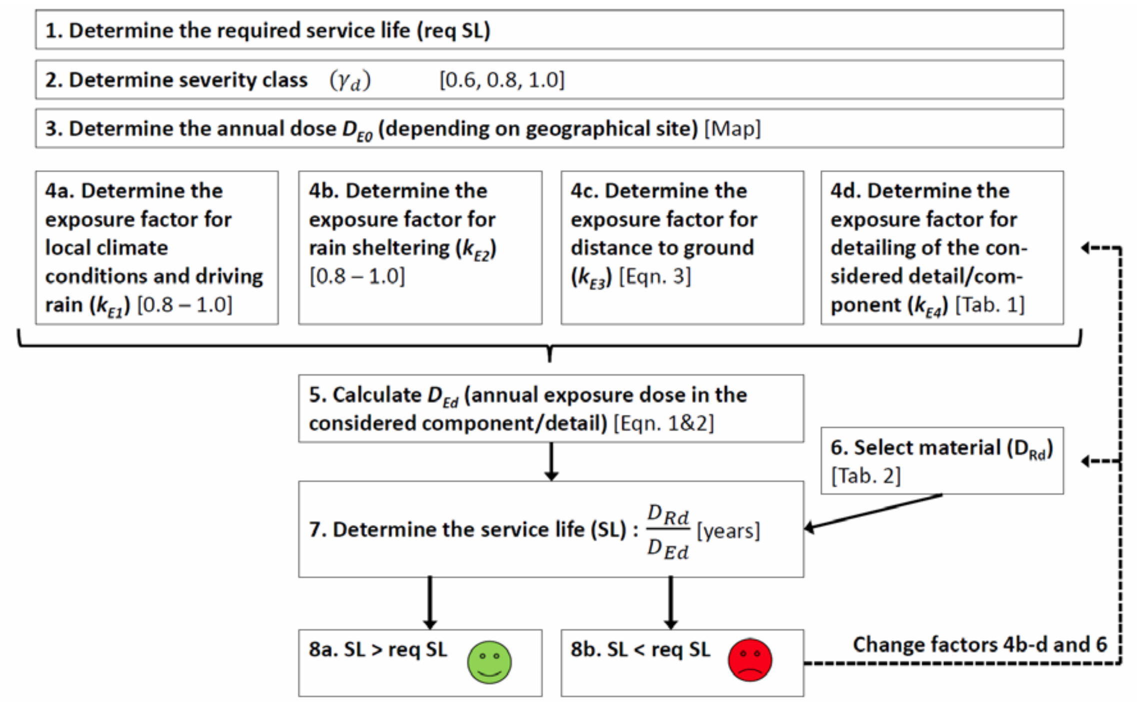


Figure 2: Evaluation of service life (SL) for a component or detail, after Pousette *et al.* 2017.

Determination of exposure

The exposure is calculated as follows (Eqn. 2):

$$D_{Ek} = D_{E0} \cdot k_{E1} \cdot k_{E2} \cdot k_{E3} \cdot k_{E4} \cdot k_{E5} \cdot c_a \qquad (2)$$

With the factors accounting for

- Local climate conditions and driving rain, k_{E1}
- Sheltering, k_{E2}
- Distance from ground, k_{E3} (Eq. 3)
- Detailed design (risk of water traps), k_{E4} (Table 1)
- Calibration factor c_a, to be taken as 1.4. The calibration factor was determined from reality checks, safety considerations and expert opinions.

In the tool for cladding and decking (Isaksson *et al.* 2014, 2015), factor k_{E1} is divided into two factors, one for local climate conditions and one for driving rain respectively. Also, the calibration factor is set to 1.0 instead of 1.4.

The *annual exposure dose D_{E0}* is dependent on the geographical location and takes into account the climatic effects. It is determined for a reference specimen on the basis of dose-response modelling and decay test results at different locations in Europe (Isaksson *et al.* 2013). To be able to present input data for D_{E0} for any place, modelled climate data

(Software Meteonorm) were used and the annual exposure doses were calculated for a large number of places in Europe and compiled in a map where eleven different zones were created by interpolating between the sites (Pousette *et al.* 2017). In general, the highest values for the exposure dose D_{E0} can be found along the western coast of Europe, and there is a trend of decreasing values from South to North in general. D_{E0} varies between 9 days per year in the lowest zone to 66 days per year in the highest zone. This means that depending on the regional climate, a factor of about 7 in service life can be found across Europe, with all other factors kept constant. A map showing the different climate zones and a table giving the annual dose D_{E0} are presented in Pousette *et al.* 2017. In the cladding and decking tool (Isaksson *et al.* 2014 and 2015), the annual exposure dose D_{E0} is presented for Sweden, with values between 15 and 32 days per year, thus showing a smaller variation than the variation over whole Europe.

Factor k_{E1} takes *local climate conditions and driving rain* into consideration. Local climate conditions can mean protection by adjacent buildings or topography, and just like driving rain (simultaneous rain and wind), it can usually not be affected by the designer. In Pousette *et al.* (2017), a map showing the free driving rain intensity is presented. The authors propose to include the effect of driving rain for high intensity regions, which in general can be found on the west coast of Europe, whereas driving rain could be neglected for the inner parts of Europe. For vertical surfaces, the factor k_{E1} should then be taken between 1.0 (driving rain, no sheltering) and 0.8 (no driving rain, but sheltering). For horizontal surfaces, $k_{E1}=1$. In cases, where the effect of driving rain or local sheltering by adjacent buildings are difficult to determine, it is recommended to use the conservative value $k_{E1}=1$. For comparison, in the claddings and decking tool (Isaksson *et al.* 2014, 2015), there are separate local climate conditions (sheltering) and driving rain factors, with the sheltering factor varying between 0.8 and 1.0 and the driving rain factor ranging between 0.85 and 1.05 (for Sweden).

The *effect of sheltering* located above the detail/component studied is based on field tests described by Bornemann *et al.* (2012), being included in the design by factor k_{E2}. The higher the overhang e and the smaller the vertical distance d (see Figure 3), the larger is the sheltering effect. Factor k_{E2} attains values between 0.8 ($e/d \geq 1$) and 1.0 ($e/d=0$), with a linear variation (Pousette *et al.* 2017, Isaksson *et al.* 2014, 2015).

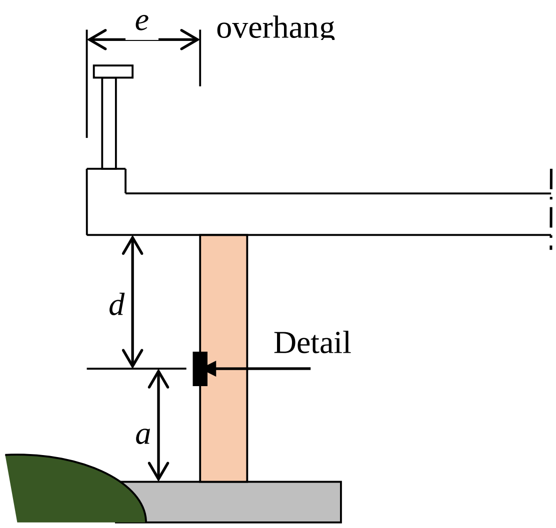


Figure 3: Definition of measures for overhang e and distance to ground a. From Pousette *et al.* (2017).

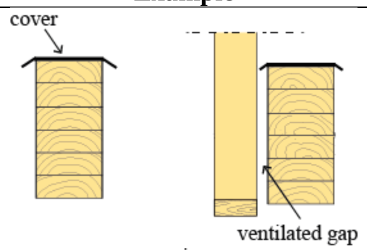
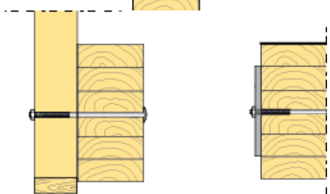
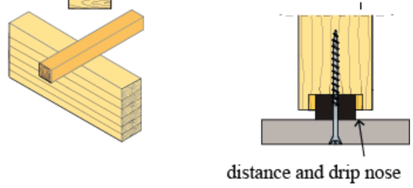
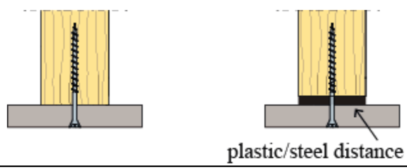
The *effect of distance from the ground* is considered by increasing the exposure for details/components located closer than 400 mm to the ground. Distances <100 mm should not be used due to splash effect and possible increased water uptake, resulting in decreased durability. The factor k_{E3} is determined by Eqn. 3 shown below, with distance a as described in Figure 3.

$$k_{E3} = \begin{cases} \dfrac{700 - a}{300} & if\ 100\,mm < a < 400\,mm \\ 1.0 & if\ a > 400\,mm \end{cases} \qquad (3)$$

The effect of sheltering above the detail/component in question and effect of distance to the ground are treated equally for both bridges and claddings/decking.

The *effect of detail design* (factor k_{E4}) is based on field test carried out by Niklewski *et al.* (2016b). Several typical timber bridge details were moisture monitored during two years. Post-processing with the simplified-logistic dose model (Isaksson *et al.* 2013) resulted in annual doses for the specimens and could be compared to a reference without moisture trap, resulting in relative annual doses. The details were grouped in five classes, depending on their water trapping behaviour, from excellent (group 1) to poor (group 5), see Table 1 for the factor k_{E4}.

Table 1: Rating of details with respect to exposure (factor k_{E4}). After Pousette et al. (2017).

Class	k_{E4}	Description	Example
Excellent	0.8	Design characterized by excellent ventilation (air gap >10 mm) and no standing water. Example: a vertical surface without connecting members or with sufficient gap between members[1]	
Good	1.0	Design characterized by excellent ventilation but standing water after rain events. Example: horizontal surface without connecting member	
Medium	1.25	Design characterized by poor ventilation but limited exposure to water. Example: vertical contact areas without sufficient air gap	
Fair	1.5	Design characterized by poor ventilation and high exposure to water *or* end-grain with good ventilation and limited exposure to water[1]. Example: horizontal contact areas and end-grain with sufficient air gap	
Poor	2.0	Design characterized by exposed end-grain with no ventilation and very high exposure to water. Example: end-grain contact area without air-gap	

[1] *It is assumed that the gap is kept completely free from dirt and vegetation.*

Also in the cladding and decking tool (Isaksson et al. 2014, 2015), details are grouped into five classes from excellent to poor. However, different descriptions and examples of details assigned to the classes are given for cladding and decking respectively due to the different types of exposure and especially the effect of ventilation. Here, the correction factor varies for claddings between 0.9 (excellent) and 4.0 (poor) and for decking between 0.9 (excellent) and 2.5 (poor).

Determination of wood material resistance

The resistance of different wood species or treated wood products, when exposed above ground, depends mainly on the material inherent resistance against fungal decay (e.g. toxic substances) and the wetting ability. Thus, the design resistance dose is defined as follows:

$$D_{Rd} = D_{crit} \cdot k_{wa} \cdot k_{inh} \qquad (4)$$

where D_{crit} is the critical dose, which corresponds to decay rating 1 (slight attack, according to EN252 (2015)), k_{wa} accounts for wetting ability of the tested material (relative to the reference Norway spruce) and k_{inh} accounts for the inherent protective properties against decay of the material (relative to the reference Norway spruce). D_{crit} was evaluated for Scots pine sapwood and Douglas fir heartwood and was about 325 days, and can be seen as constant for different wood species, if the differences between species are accounted for by the factors k_{wa} and k_{inh}. The factors k_{wa} and k_{inh} were estimated from testing and described in detail for a large number of wood species and treatment types by Meyer-Veltrup *et al.* (2017). The relative D_{Rd} in the right column (Table 2) expresses the ratio in service life (time to decay rating 1) between a certain species and Norway spruce, showing that the choice of right material is important. The material resistance dose D_{Rd} for a large number of wood species and treatments used in both bridge, cladding and decking applications can be found in Table 2. In determination of service life, the material resistance dose D_{Rd} (days) is compared with the design exposure dose according to Eqn. 1 and 2.

Table 2: Material resistance dose D_{Rd} (design value).
After Pousette et al. (2017) and Meyer-Veltrup et al. (2017).

Wood species	D_{Rd} [days]	Relative D_{Rd} (reference: Norway spruce)
Norway spruce *(Picea abies)*	325	1.0
Scots pine sapwood *(Pinus sylvestris)*	300	0.9
Scots pine heartwood *(Pinus sylvestris)*	850	2.6
European larch heartwood *(Larix decidua)*	1900	5.8
Douglas fir heartwood *(Pseudotsuga menziesii)*	1700	5.2
Western Red Cedar *(Thuja plicata)*	1050	3.2
Beech *(Fagus sylvatica)*	313	1.0
Oil-heat treated spruce *(Picea abies)*	2400	7.4
Thermally modified pine *(Pinus sylvestris)*	2400	7.4
Preservative-treated wood NTR AB[1]	1700	5.2
Preservative-treated wood NTR A[2]	2600	8.0

[1] *accepted for use class 3.2 according to EN 335 (2013)*
[2] *accepted for use class 4 according to EN 335 (2013)*

EXAMPLES

The possible use of the engineering tools described above and presented in detail in Pousette *et al.* (2017) and Isaksson *et al.* (2014, 2015) will be illustrated here with the help of two examples, one for a timber bridge detail and one for a cladding. As not all tables and figures from the tools are presented here in this paper, the reader is referred to the original sources for the additional information needed.

Example 1: Service life of a cladding

Consider a cladding with vertical boards on a single-family home in Stockholm, Sweden, and calculate the service life (SL) for the lower edge of the cladding according to the flowchart in Figure 2 and with help of the cladding and decking tool presented in Isaksson *et al.* (2014, 2015). The different factors and the resulting SL are shown in Table 3.

Table 3: Example of calculation of SL for the lower edge of vertical cladding in Stockholm, Sweden. Reference is made to tables (T), figures (F) and equations (Eq) in Isaksson et al. (2015).

Factor	Value	Source	Comments
Consequence class, γ_d	0.6	T2	Easy to change cladding
Annual exposure dose D_{E0}	28	F6, T4	
Factor for driving rain	0.91	T6	
Factor for sheltering by topography/buildings	0.9	T8	Assumed sheltering by adjacent buildings
Factor for rain sheltering	1.0	T14	Assumed no sheltering as lower edge is considered
Factor for distance to ground	1.7	F17	Distance to ground assumed to 200mm
Factor for detail design	0.9	T13	Assumed full ventilation and sealed end grain
Design exposure D_{Ed}	21 days	Eq 1+4	
Design resistance D_{Rd}	325 days	T20	Assumed Norway spruce
Service life $SL=D_{Rd}/D_{Ed}$	15.5 years		

<u>Comments and conclusions:</u>

- A SL of about 15 years for the lower edge of a cladding of a single family home is satisfactory. However, by changing the wood species, e.g. by using European larch heartwood, the SL could be increased to almost 90 years.
- This SL of about 15 years was obtained for the lower edge, which is close to the ground (200 mm distance). If the distance to ground is 400 mm, the SL increases to about 26 years which might be a cheaper solution than changing the wood material.
- If horizontal cladding is used instead of vertical cladding, the lowest cladding boards can easily be removed and substituted with new ones – for vertical cladding, maintenance of the lower ends of the cladding is much more complicated.

Example 2: Service life of timber bridge detail

Consider a bridge with a stress laminated timber deck of untreated spruce in Stockholm, Sweden and calculate the service life according to flow chart in Figure 2. The worst detail is assumed to be the connection between the pressure plates for pre-stressing rods and the timber deck, which is protected from rain. The different factors and the result are presented in Table 4.

Table 4: Example of calculation of SL for a timber bridge detail in Stockholm, Sweden. Reference is made to tables (T), figures (F) and equations (Eq) in Pousette et al. (2017).

Factor	Value	Source	Comments
Required service life, req SL	100 years	T2.1	
Consequence class, γ_d	1.0	T2.2	Bridge, load bearing
Annual exposure dose D_{E0}	32 days	F2.6	Zone g
Factor for driving rain and sheltering by topography/buildings	0.9	F2.7,T2.4	Low driving rain index → driving rain can be neglected; assumption of no sheltering
Factor for rain sheltering	1.0	F2.9	many bridges are subject to leaks at some point, effectively negating the effect of the cover[1] and it is thus assumed no sheltering
Factor for distance to ground	1.0	F2.10	Assumption: distance to ground >400mm
Factor for detail design	1.25	T2.5	
Design exposure D_{Ed}	50 days		
Design resistance D_{Rd}	325 days	T2.6	Assumed Norway spruce glulam
Service life $SL=D_{Rd}/D_{Ed}$	6.4 years		

[1] Pousette and Fjellström (2016)

Comments and conclusions:

- The service life (SL) of the detail in question is much lower than the required SL. This is not surprising, as it is difficult/impossible to reach long service life if untreated wood is exposed to moisture.
- The calculated SL of about 6 years should be used to determine inspection intervals (recommended 6 years) instead of being a real SL.
- By choosing a different material, e.g. preservative-treated wood NTR-AB or NTR-A (Table 2), the SL would increase to about 33 - 51 years. This might be a good strategy, especially if there is a risk for leakage.
- A good alternative would be to protect the load-bearing structure, e.g. by cladding. The cladding according to example 1 has a SL of 15-26 years, which would result in maintenance intervals of about 15 years. However, the inspection interval should still be around 6 years (due to risk of leakage (Pousette and Fjellström (2016)).
- The method can be used to determine inspection intervals so that more resources can be allocated to high-risk bridges. This in contrast to current practice where the condition of any bridge is checked every 6th year, regardless of the associated risks.

CONCLUSIONS

As shown for two examples, the engineering tools are quite easy to use, as the in-data are taken from tables and figures, i.e. the user can choose between several typical cases. The tools can be used both for prediction of service life and for prediction of necessary maintenance or inspection intervals, depending on the type of structure or element considered. The tools can also be used for parameter studies – in order to choose between different possible designs, and as a checklist for designers. The advantages of the new performance based prediction models are that they are scientifically based, with all factors being determined either by laboratory or field testing, modelling or expert opinions. As the approach is open, future research results can be easily implemented as well as the user might use own input factors. The tools will hopefully result in more durable and better timber structures and help architects, planners, builders, and craftsmen to build them.

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