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# Engineering Failure Analysis

journal homepage: [www.elsevier.com/locate/engfailanal](http://www.elsevier.com/locate/engfailanal)

## General durability criteria for exposed timber structures based on the analysis and inspection of bridges and observation towers

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### A B S T R A C T

This article analyses 14 timber bridges and 5 observation towers, all located in Switzerland and constructed between 1990 and 2020. The study aims to organize and formalize a comprehensive set of durability criteria and associated operational sub-criteria to describe the longevity of exposed timber structures. The inspected case studies include a variety of structural systems and durability design approaches. The bridges span from arch to complex truss systems, while the towers range from traditional log-based structures to modern CLT constructions. The investigations included historical research, visual inspections and the cataloguing of construction details most relevant to durability. To improve the understanding of decay mechanisms, a condition index was developed, which considers the presence, extent and timing of decay. Explanatory details and photographs of the case studies are also presented, illustrating the influence of moisture design on observed decay patterns. Based on the results, three general durability criteria for exposed timber structures are proposed: (i) intrinsic element and environmental risks, (ii) water and moisture input, and (iii) long-term quality and care, with related operational sub-criteria. Future research will focus on developing a quantitative framework to assign relative weights to each durability principle, allowing a systematic prioritization based on their actual impact on timber longevity, and on providing a methodological tool to support informed decisions in the evaluation, design, and management of timber structures.

### 1. Introduction

The renewed popularity of exposed timber structures in modern engineering, driven by their sustainability [1] and favourable engineering properties, makes ensuring durability and the full-service life a fundamental and ongoing challenge. This issue is mainly related to the interaction between the physical properties of wood and moisture or water [2], which triggers various phenomena in the material and leads to inevitable biodegradation, primarily caused by biological agents such as fungi [3]. Several studies [4,5], confirm that damage and decay caused by moisture are among the most frequent causes of problems in timber structures. According to [6], 21% of decayed timber structures show damage caused by design flaws within the first year of service, with the average onset of damage occurring around the seventh year. This aspect is particularly critical for exposed structures, which are more vulnerable to environmental conditions and therefore require careful design and detailing to prevent accelerated deterioration. For this reason, best practices in timber construction are essential throughout the project, as durability depends on proper design, accurate execution [7], regular monitoring [8], and ordinary maintenance in order to avoid costly and disruptive repairs [9,10]. In this context, several laboratory and in-situ tests have been conducted over the years to evaluate the moisture behaviour of above-ground timber, as

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<https://doi.org/10.1016/j.engfailanal.2026.110986>

Received 18 February 2026; Received in revised form 4 April 2026; Accepted 12 May 2026

Available online 14 May 2026

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summarised in [11]. Although specific literature exist for moisture-related design, such as the 4Ds principle [12] and technical documents providing practical recommendations [13], comprehensive and general design criteria for exposed timber structures remain lacking. The growing focus on timber durability is clearly reflected in the second generation of Eurocodes, with the official release expected in 2027. Durability, previously addressed in only two pages (Section 4 of Part 1–1 and Part 2 for bridges [14]), will now be covered more extensively, with twelve pages equally split between the general and bridge parts [15]. The revised bridge section will introduce a new Annex D “Durability: Construction Measures and Detailing Examples”, which provides clear strategies and detailed design solutions to enhance the long-term performance of exposed timber structures [16]. In the new EC5 part 2, a 100-year design service life is confirmed for protected timber bridges, with unprotected elements requiring replacement or shorter lifespans, as described in [17]. The present paper analyses a selection of representative exposed timber structures through on-site inspections and condition assessments. The aim is to identify common decay mechanisms, evaluate critical design and construction details, and propose general durability criteria. The following sections present an overview of the case studies, including key information for each structure, along with representative photographs. This is followed by the development of an assessment methodology and a description of the main observed issues, as well as the solutions adopted to ensure durability, illustrated through construction details and explanatory illustrations. Finally, the durability criteria and their associated operational sub-criteria are presented.

## 2. Overview of inspected case studies

### 2.1. Selection criteria

To develop a representative portfolio of case studies and capture a wide range of real-world conditions, this research focuses on structurally critical and highly exposed timber structures, bridges and observation towers. Bridges are chosen not only for their widespread presence but also because they exemplify complex engineering challenges and detailing required ensuring structural service life. Towers, on the other hand, represent extreme cases of timber structures exposed to adverse condition. Often located in highly exposed natural environments and designed to provide panoramic views, towers are frequently “open and transparent” constructions with large openings, which inevitably limits their lifespan. All inspected structures are located in Switzerland, a country with a long tradition of using timber for exposed structural applications [18,19]. To ensure an assessment of the factors that most affect durability, the selected case studies are highly heterogeneous in terms of:

- Environmental factors: Variations in solar exposure, orientation, ambient humidity, natural ventilation and altitude
- Structural configurations: Arches, beams and trusses for bridges and various design concepts for towers
- Construction technologies: Solid timber, GLT, CLT and log construction.
- Wood species: Spruce, larch and ash.
- Protection strategies: Protected and unprotected elements.
- Structural dimensions: Various spans for bridges and heights for towers
- Age: Structures from 5 to 35 years old

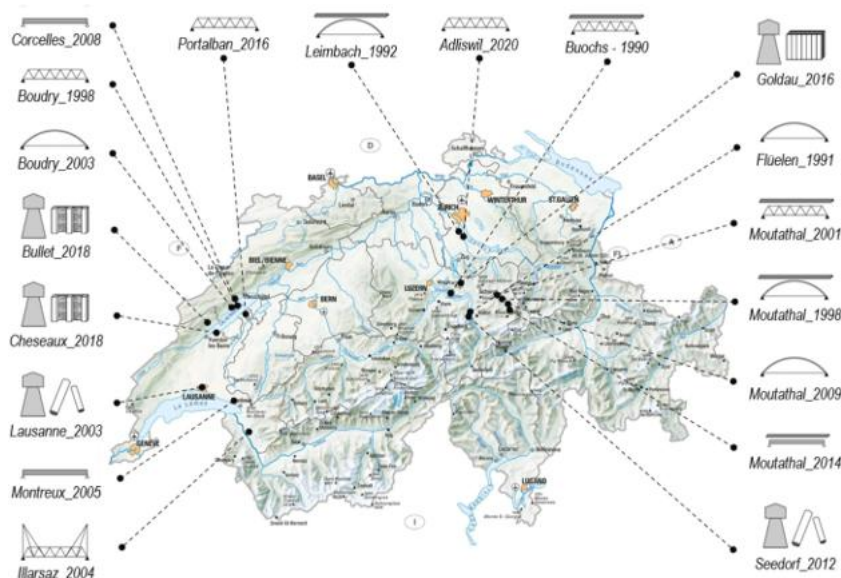


Fig. 1. Geographical location of inspected structures.

## 2.2. Case study summary

This chapter presents all the selected case studies, comprising a total of 14 bridges and 5 observation towers. Specifically, Fig. 1 shows their geographical distribution in Switzerland and Table 1. Selected Bridges and Towers presents short description for each case, including representative photographs. For clarity and consistency throughout the study, each structure has been labelled using a standardized format based on its location and year of construction (*Place\_Year*).

## 3. Inspection and analysis methodology

### 3.1. Visual assessment and data Acquisition

The assessment of timber elements and construction details was primarily based on visual and non-invasive methods, aiming to establish durability criteria and practical criteria grounded in observable and measurable parameters such as dimensions, contact points, spacing and the presence or absence of specific features. Each timber bridge and tower included in the study underwent a structured three-phase inspection procedure. The first phase involved a preliminary study to understand the structure's history and context. This included identifying the construction techniques and wood species used, determining the year of construction or any major restorations and gathering available technical documentation such as drawings, reports and bibliographic references. The second phase involved on-site inspections, during which the durability and decay conditions were directly assessed. Particular attention was given to mapping construction details that were either decayed or in good condition. Explanatory sketches were created, and photographic documentation was collected to support the inspection. In the final phase, all the data collected was examined and analysed. The information was reorganised to support the development of clear and illustrative construction details, with particular attention to the elements most critical to the durability of the structure.

### 3.2. Definition of the condition Index

To generalize the assessment of timber components, a Condition Index  $I_c$  was developed. Various approaches exist in the literature to describe the state of timber elements, assigning a decay class based on visual inspection. For example, EN 252 [20] uses five classes to assess biological attack on timber in ground contact, based on penetration depth. The Mould Index [21] originally includes seven classes, but two require microscopic observations and are therefore not applicable here, effectively reducing the usable levels to five. Similarly, Lepage's deterioration index [22] evaluates the natural durability of wood species exposed to decay, using five categories on a descending scale from 100 (no attack) to 0 (failure) [23]. Other approaches can also be found in the literature. For instance, [24] developed a visual inspection procedure for the Italian railway bridge management system, defining a condition function for each component that sums defects weighted by importance, element type, intensity, extent, and urgency. Likewise, [25] proposed a method for reinforced concrete bridges in Sri Lanka, where the condition index includes visual and type factors, an element significance factor, and a casual factor accounting for bridge age, environment, traffic conditions, and inspection quality. In this study, the Condition Index  $I_c$  considers both the observed decay and its timing. The observed decay is evaluated using the Visual Decay Rating ( $D_V$ ), classified on a five-class scale consistent with the above-mentioned references. The corresponding scores are defined by scaling and inverting Lepage's index into an increasing range (1–10), as reported in Table 2. The assignment of the Visual Decay Rating ( $D_V$ ) is based on qualitative visual inspection criteria considering the extent and depth of decay. In particular, "superficial decay" refers to degradation affecting only the outer layers of the material without significant loss of cross-section, while "deep decay" involves a reduction in the effective cross-section or mechanical integrity. The distinction between 'Localized' and 'Widespread' decay is based on the spatial distribution of damage: localized decay is limited in area, whereas widespread decay affects a significant portion of the element, in accordance with the UNI EN 252 [26] classification for attack grades 2 (moderate) and 3 (severe). These criteria are intended to support consistent and repeatable classification during inspections.

The timing of decay is accounted for through the Early Decay Factor ( $ED_f$ ), defined as:

$$ED_f = \max\left\{1; 1 + \frac{SL - Age}{SL}\right\} \quad (1)$$

where  $SL$  is the expected Service Life of the component (Table 3) and  $Age$  is its age at the time of inspection.

The purpose of this factor is to weigh the severity of the observed decay based on the bridge's life cycle. While  $ED_f$  remains 1 for structures that have reached their design life, it acts as a multiplier (up to 2) for elements experiencing decay at an early age. This highlights premature decay, which often indicates significant design or construction deficiencies and tends to progress more rapidly [27]. Based on these considerations, the Condition Index  $I_c$  is expressed as in equation (2). It ranges from 0, indicating no decay, to 20, corresponding to extensive and deep decay observed in the early years of the component's life (Table 4).





$$I_c = D_V \times ED_f \quad (2)$$

Where:

- $I_c$  = Condition Index
- $D_V$  = Visual Decay Rating
- $ED_f$  = Early Decay Factor





**Table 1**

Selected Bridges and Towers.





No.	Name	Photo	Description
1	Fluelen_1991		40-m span larch glulam arch footbridge built in 1991, unprotected. Deck supported by cables and composed of timber beams and timber planking
2	Leimbach_1992		40-m span fir glulam arch footbridge built in 1992, protected. Deck supported by steel ties and composed of timber beams, timber planking, and asphalt. Roof supported by timber pillars
3	Muotathal_1998		28.5-m span spruce glulam arch vehicular bridge built in 1998, protected. Deck supported by timber pillars and composed of timber beams and timber planking. Roof supported by timber pillars
4	Boudry_2003		49-m span larch glulam arch footbridge built in 2003, unprotected. Deck supported by cables and composed of steel beams (including arch tie-rod), timber planking, and timber parapet

(continued on next page)

**Table 1** (continued)

No.	Name	Photo	Description
5	Muotathal_2009		34-m span spruce glulam arch vehicular bridge built in 2009, unprotected. Deck supported by cables and composed of mixed steel-CLT structure and asphalt
6	Montreux_2005		31-m span larch glulam beam footbridge built in 2005, unprotected. Deck composed of timber beams, timber planking, and upper finishes
7	Corcelles_2008		26.5-m span larch glulam beam footbridge built in 2008, unprotected. Deck composed of timber beams, timber planking, and upper finishes
8	Muotathal_2014		26.2-m span glulam beam footbridge built in 2014, protected. Deck composed of mixed steel-CLT structure and asphalt. Roof supported by timber pillars
9	Bouchs_1990		24-m span fir glulam truss footbridge built in 1990, protected. Deck composed of steel beams, and timber planking. Roof supported by truss

**Table 1** (continued)

No.	Name	Photo	Description
10	Boudry_1998		25-m span larch glulam truss footbridge built in 1998, unprotected. Deck composed of timber beams, and timber planking
11	Muotathal_2001		36.8-m span spruce truss vehicular bridge built in 2001, protected. Deck composed of glulam truss, glulam floor, and asphalt. Roof supported by truss
12	Illarsaz_2004		81-m span larch glulam cable-stayed (truss) footbridge built in 2005, unprotected. Deck composed of timber beams, and timber planking
13	Portalban_2016		30-m span larch glulam truss footbridge built in 2016, unprotected. Deck composed of timber beams, steel bracing, and timber planking


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**Table 1** (continued)

No.	Name	Photo	Description
14	Adliswil_2020		45-m span beech glulam truss footbridge built in 2020, unprotected. Deck composed of timber beams, steel bracing, and timber planking
15	Lausanne_2003		35-m high timber tower built in 2003. Self-supporting spiral structure made of local Douglas fir and spruce. The flat roof partially protects the structure
16	Seedorf_2012		11.2 m high white fir wood tower built in 2012. Tower composed of 48 logs arranged in four groups with a central spiral staircase. The flat roof partially protects the structure
17	Goldau_2016		29.6-m high timber tower built in 2016. Two inclined bodies converge toward the top, with primary load-bearing structure in CLT and glulam, supported by a reinforced concrete base. Cladding of vertically arranged sawn white fir boards
18	Cheseaux_2018		Timber tower built in 2018. Three-storey frame structure predominantly of spruce and white fir, with oak staircase; external cladding of horizontal boards

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**Table 1** (continued)

No.	Name	Photo	Description
19	Bullet_2018		13.4-m high timber tower built in 2018. Load-bearing frame predominantly of local ash, completely enclosed with diagonal board cladding; CLT interior stairs and floors

**Table 2**

Observed Condition and Visual Decay Rating.

Observed condition	$D_V$	Assessment criteria
No decay	0	No visible degradation; surface resists light scraping with a fingernail, coin, or small knife; no affected area. Admitted colour change
Superficial localized decay	1	Outer wood layer easily removed with light scraping affecting < 10% of the examined surface segment*
Superficial widespread decay	4	Outer wood layer easily removed with light scraping affecting > 10% of the examined surface segment*
Deep localized decay	6	Wood that can be pierced with a pointed probe or a screwdriver with penetration not exceeding ~ 10% of the cross-section on an area less than ~ 10% of the examined surface segment*
Deep widespread decay	10	Wood that can be pierced with a pointed probe or a screwdriver, with penetration exceeding ~ 10% of the cross-section on an area more than ~ 10% of the examined surface segment *

\*Segment: minimum distance between two parallel edges of the inspected surface, used as reference to calculate degraded area.

**Table 3**

Component type and Service Life in accordance with Eurocode 5 [14].

Component type	SL(Years)
Structural	50
Non-structural	10

## 4. Durability and decay assessment of inspected bridges

### 4.1. Influence of structural Typology on durability

This section discusses how different timber bridge typologies influence durability, with reference to recent studies on decay mechanisms and protection strategies ([28,29]), and highlights significant differences between bridge typologies such as arch, beam, and truss structures. The curved shape of the arch does not present flat horizontal surfaces, thus facilitate rainwater runoff and reduce water accumulation. In these bridges, the deck is structurally separated from the arch, which minimizes the number of critical joints, contacts and exposed connections. Moreover, the hangers supporting the deck are often located on the intermediate parts of the arch, providing indirect protection of the connections. However, attention must still be paid to the deck beams, which are often exposed at the ends where they are connected to the hangers. In contrast, beam bridges often have a flat extrados surface, which requires protection through metal sheets, timber coverings or other indirect systems. In these bridges, the design of connections between the main beams and the deck is crucial to prevent moisture retention and potential decay. Truss structures are generally more vulnerable to decay due to the high number of structural members and connections. In particular, joints such as those between the lower chord and vertical or diagonal members, as well as the numerous other connections between elements, can become critical points for water accumulation if not properly protected or exposed, increasing the risk of decay.

### 4.2. Observed condition and common durability aspects

To provide a comprehensive assessment across all bridge typologies cited in Section 4.1, the Condition Index developed in Section

**Table 4**  
Condition index classification.

Range	Condition state	Description
$0 < I_c \leq 1$	Excellent	Elements showing no visible signs of decay or superficial localised decay
$1 < I_c \leq 4$	Good	Elements showing early superficial localised decay
$4 < I_c \leq 6$	Fair	Elements showing early superficial widespread decay and/or deep localised decay
$6 < I_c \leq 10$	Poor	Elements showing very early superficial widespread decay and/or early deep localised decay
$10 < I_c \leq 15$	Critical	Elements showing very early deep localised decay and/or early deep widespread decay
$I_c > 15$	Severe	Elements showing very early deep widespread decay

3.2 was applied to the most representative construction details and elements (as summarized in Fig. 6). This analysis focuses on the recurring durability challenges identified during inspections, which are consolidated in Table 5. This summary table includes technical schemes and photographs for each scenario, systematically cross-referenced in the text using the notation D + n° (sequential number). During the inspections, cases of visible and widespread deterioration were observed after only a few years since construction, with a condition index equal to or greater than 10. Among these cases, it is possible to identify recurring patterns, namely common aspects that appear in similar situations. One of such common aspects concerns conceptual errors in the protection system, particularly when the protection is only partial. This occurs, for example, when only the surfaces considered most exposed to risk are protected, such as horizontal surfaces without proper water drainage. It has been observed that ineffective protection can have a boomerang effect, promoting water accumulation and humidity peaks that compromise the entire element, not just the protected surface. In the Montreux\_2005 (No. 6, Table 1) and Corcelles\_2008 (No. 7, Table 1) beam bridges, as well as in the Boudry\_1998 truss bridge (No. 10, Table 1), horizontal surfaces are protected using metal flashings without overhangs and with an interface spacing smaller than 1 cm, insufficient to allow proper ventilation and drying of the timber surface. In all these cases, the  $I_c$  is very high, around 15, reflecting diffuse decay along the horizontal faces of the timber immediately below the joints between successive metal plates, which act as localized points for moisture accumulation and water stagnation. In the Corcelles\_2008 (No. 7, Table 1) and Boudry\_1998 (No. 10, Table 1) bridges, for instance, the joints have a gap, probably originally sealed with silicone, between the two metal plates, with a lower support element that promotes water stagnation, as shown in Fig. 2 and detail D1 in Table 5. In the Montreux\_2005 bridge (No. 6, Table 1), the joints were welded, leading to micro-cracks from thermal expansion of the plates and subsequent water ingress (D2, Table 5). The same behaviour resulting from the welding of metal plates was observed in the more recent Portalban\_2016 bridge (No. 13, Table 1) (D3, Table 5).

As described in detail in D4, Table 5, protection issues were also observed at the ends of the deck beams of the Fluelen\_1991 bridge (No. 1, Table 1), where the upper timber protection was already decayed. This is due both to direct wood-to-wood contact and insufficient maintenance, resulting in decay. A similar situation occurs in the protective board on the extrados of the same bridge's arch, although the effects on the structure are smaller thanks to a wide ventilation gap of about 4 cm at the interface (D5, Table 5). Lack of maintenance often also affects non-structural, so-called "sacrificial" elements directly exposed to the weather, such as the lateral protective battens of the Muotathal\_2001 tunnel bridge (No. 11, Table 1) or various parapets. A particularly significant case is the arch of the Boudry\_2003 bridge (No. 4, Table 1) (D6, Table 5), whose lateral face shows a very extensive decay zone ( $I_c = 15.6$ ). Comparing this arch with that of the Fluelen\_1991 bridge (No. 1, Table 1) (D5, Table 5), twelve years older but with  $I_c$  equal to 5.28, it appears that despite similar construction methods, both larch arches, inclined to facilitate runoff on the vertical faces and protect the inner face, the difference in decay is mainly due to the environmental context. The Fluelen\_1991 bridge (No. 1, Table 1) is positioned perpendicularly to a highly ventilated valley, promoting rapid drying, while Boudry\_2003 (No. 4, Table 1) is in a particularly humid area near a dam, where the microclimate accentuates decay. Not only microclimate, but also solar exposure seems to play a role, as observed on the two sides of the Corcelles\_2008 bridge (No. 7, Table 1): the east side shows a grey coloration typical of photolytic aesthetic decay, while the west side exhibits a brown colour typical of superficial material decay, as illustrated in the Fig. 3.

Another crucial aspect concerns the ends of structural elements. End-grain decay can be very aggressive, as observed in the Boudry\_1998 bridge (No. 10, Table 1). In this bridge, the truss beams rest on two metal supports embedded in a reinforced concrete box. The small gap between the beam end and the concrete, combined with leaf accumulation due to lack of cleaning, created a preferential path for moisture, causing intense end-grain decay (D7, Table 5). Similar phenomena are observed in the more recent Portalban\_2016 bridge (No. 13, Table 1), where the gap between the beam end and the concrete wall, still too narrow, is clogged with debris, resulting in decay (D3, Table 5). Joints and connections between elements are also critical for ensuring adequate service life. In beam bridges, the joint between the beam and deck joists is crucial, especially when a gap exists between the deck and beams. Protecting these joints is essential, as shown by comparing an unprotected case, Corcelles\_2008 bridge (No. 7, Table 1), and a protected one using an angle bracket, such as Montreux\_2005 bridge (No. 5, Table 1) (D8 and D9, Table 5). Joint vulnerability is also relevant in truss structures. In the Illarsaz\_2004 bridge (No. 12, Table 1), for example, the inward slope of the truss and the direct contact between the deck end stop and the lower chord create a water stagnation point. Fig. 4 below shows that within a few years, decay developed rapidly and extensively, necessitating significant repairs using consolidating resins and metal covers to protect the joint, as detailed in D10, Table 5. Joint design is therefore fundamental.

As shown in D11, Table 5, in the Bouchs\_1990 truss bridge (No. 9, Table 1), joints were designed as "open," leaving a gap between elements to prevent water accumulation. Additionally, grooves for interposed plate connections are provided on the protected face of the element and are not visible on the exposed face. The bridge, despite being 35 years old, is currently in good condition ( $I_c = 1.3$ ), thanks to both correct detail design and the presence of a roof, as well as the inclined trusses that reduce exposure to weather [30]. A

**Table 5**  
Representative Details and Photos from the Inspected Timber Bridges.

n°	Bridge	Description	Detail	Photo
D1	Corcelles_2008 (a) & Boudry_1998 (b)	Detail of the upper surface protection with metal flashings. Decay at the gap between adjacent flashings due to water ponding		
D2	Montreux_2005	Detail of the upper surface protection with welded metal flashings. Decay at flashing joints and railing connectors due to water ingress through weld cracks and anchorage details		
D3	Portalban_2016	Detail of the beam support area. Decay at flashing joints and near the beam end due to weld cracks and insufficient spacing at the beam-concrete interface		
D4	Fluelen_1991	Detail of the bridge deck section. Decay due to direct wood-to-wood contact between the capping and the beam end		

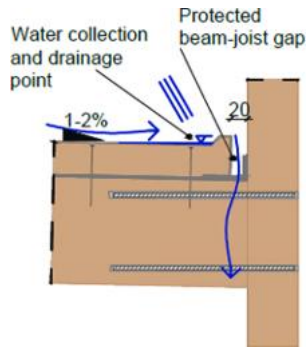

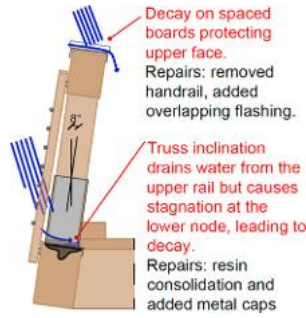

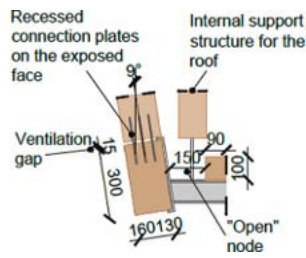

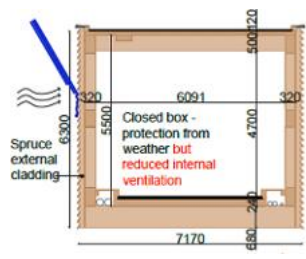

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Table 5 (continued)

n°	Bridge	Description	Detail	Photo
D5	Fluelen_1991	Section of the arch. Beam slope and wide gap between beam and top protection ensure proper drainage. Decay at the lower face due to the absence of a drip groove		
D6	Boudry_2003	Section of the arch. Beam slope promotes water drainage, but an unfavourable microclimate causes decay		
D7	Boudry_1998	Detail of the beam support area. Deep decay at the beam end due to reduced gap from the ground and debris accumulation which retains moisture		
D8	Corcelles_2008	Detail of the main beam-joist joint. Decay at the gap between deck and main beam due to the lack of protection for the joist		

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Table 5 (continued)

n°	Bridge	Description	Detail	Photo
D9	Montreux_2005	Detail of the main beam-joist joint. Good condition at the gap between deck and main beam due to the presence of joist protection	 <p>Water collection and drainage point</p> <p>Protected beam-joist gap</p> <p>1-2%</p> <p>20</p>	
D1	Illarsaz_2004	Detail of the beam-deck joint. Decay due to water ponding caused by improper slope at the beam-deck contact area	 <p>Decay on spaced boards protecting upper face. Repairs: removed handrail, added overlapping flashing.</p> <p>Truss inclination drains water from the upper rail but causes stagnation at the lower node, leading to decay. Repairs: resin consolidation and added metal caps</p>	
D1	Bouchs_1990	Detail of the beam-deck joint. Good condition due to an open joint design that promotes water drainage	 <p>Recessed connection plates on the exposed face</p> <p>Internal support structure for the roof</p> <p>Ventilation gap</p> <p>9°</p> <p>15</p> <p>300</p> <p>160130</p> <p>150</p> <p>90</p> <p>100</p> <p>"Open" node</p>	
D1	Muotathal_2001	Section of the tunnel bridge. Slight decay due to poor internal ventilation	 <p>Spruce external cladding</p> <p>Closed box - protection from weather but reduced internal ventilation</p> <p>6300</p> <p>320</p> <p>5000</p> <p>6091</p> <p>320</p> <p>4700</p> <p>240</p> <p>7170</p> <p>5000/120</p>	

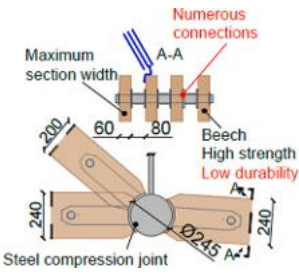

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Table 5 (continued)

n°	Bridge	Description	Detail	Photo
D1	Muotathal_2009	Section of the arch. Good condition due to full protection of the beam		
D1	Muotathal_2014	Section of the main beam. Good condition due to full protection of the beam and the presence of roofing		
D1	Boudry_1998	Detail of the beam-deck joint. Good overall condition due to the slope of the vertical posts and the protection of the joists with top caps		
D1	Portalban_2016	Detail of the beam-deck joint. Decay of the joists due to misplacement of the protective membranes		

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Table 5 (continued)

n°	Bridge	Description	Detail	Photo
D1	Adliswil_2020	Detail of the truss joint. Slight decay near the connectors		



(a)



(b)

Fig. 2. Details of the metal plate joints in the Corcelles\_2008 (a) and Boudry\_1998 (b) bridges, showing the gaps between plates and the lower support elements that lead to water stagnation.

top protection, such as a roof, does not completely prevent wetting of the elements, but in many cases, it limits the occurrence of water contact to exceptional events. The long interval between wetting events allows drying, thus reducing the risk of fungal development. In support of the previous statement, the Leimbach\_1992 (No. 2, Table 1), Muotathal\_1998 (No. 3, Table 1), and Muotathal\_2014 (No. 8, Table 1) bridges, which have upper covering structures, are in excellent condition, with an  $I_c = 0$ , without signs of decay. An extension of the lateral protection can also be adopted, as in the Muotathal\_2001 bridge (No. 11, Table 1) (D12, Table 5), which features a closed tunnel-like cross-section. This solution provides greater protection against rainfall, but the reduced ventilation typical of closed sections leads to moisture phenomena, as evidenced by the stains visible on the bridge ceiling. In addition, it is possible to protect the structural element directly through complete protection systems. Protected sections were observed in the Muotathal\_2009 bridge arch (No. 5, Table 1) (D13, Table 5), cited in [31], and the Muotathal\_2014 beam (No. 8, Table 1) (D14, Table 5). In both cases, protection includes not only an upper cover but also lateral face protection using timber battens, as well as intrados protection with drip grooves. These drip grooves are essential to ensure proper water drainage along vertical and inclined faces, preventing the natural flow of water towards the corners, which could otherwise cause infiltration on the underside and subsequent decay, as observed in the intrados of Fluelen\_1991 (No. 1, Table 1). Transverse beams under the deck also require careful design, as gaps between deck boards allow water passage. As shown in D15, Table 5, a good example of joist protection is in the Boudry\_1998 bridge (No. 10, Table 1), using a top timber cap. In the Illarsaz\_2004 (No. 12, Table 1) and Portalban\_2016 (No. 13, Table 1) bridges, joist membranes are either non-overlapping (Fig. 5) or not protruding (D16, Table 5), resulting in joist decay.

A particularly interesting case is the most recent Adliswil\_2020 bridge (No. 14, Table 1), built using timber obtained from beech. As described in [32], to compensate for the low natural durability of this wood species, the timber was impregnated, thin sections (maximum 6 cm) were adopted to facilitate drying of inner layers, and all joints are metallic (D17, Table 5). Despite the young age of the structure, the numerous exposed connections remain localized points of decay, currently only superficial. The following illustrates the results for the inspected bridges by applying the condition index to the structural elements, non-structural components, and construction details discussed in this section. This visualization enables a direct comparison of durability performance across the

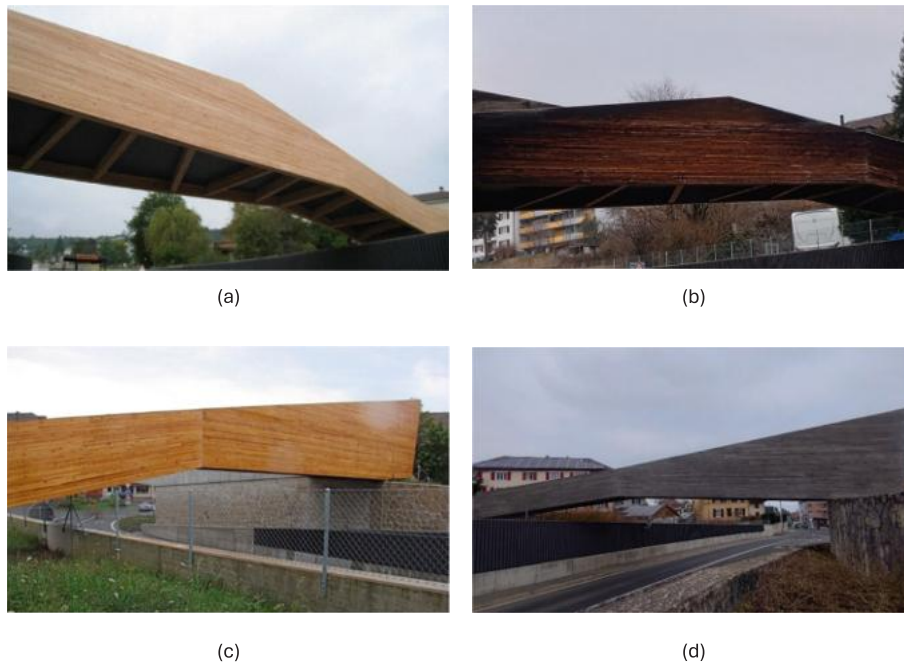


Fig. 3. Corcelles\_2008 Bridge – West facade: (a) as new and (b) in 2025; East facade: (c) as new and (d) in 2025.

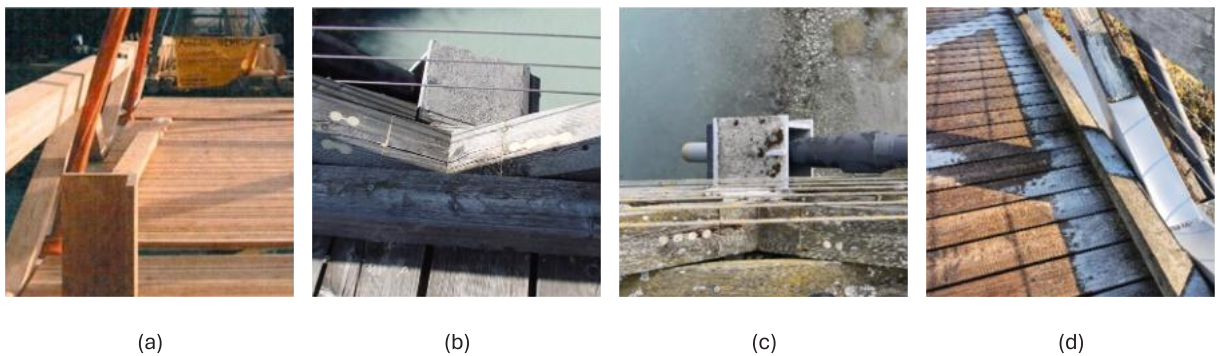
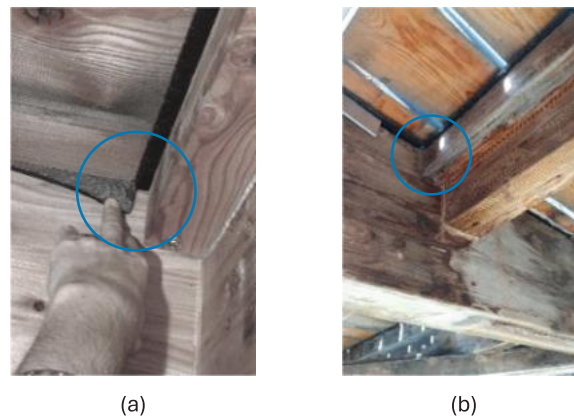


Fig. 4. Illarsaz\_2004 bridge: detail of the truss-deck joint – (a) right after construction (photo from 2005); (b) first signs of decay (photo from 2008); (c) widespread decay (photo from 2021); (d) after retrofit (photo from 2024).

different analysed scenarios.

## 5. Durability and decay assessment of inspected observation towers

By following the procedure adopted for the bridges, a condition index was assigned to the main structural and non-structural components and details of the towers, as well as to the joints most relevant in terms of durability, following detailed on-site inspections. All illustrative schematics and photographs corresponding to the analysed scenarios are systematically catalogued as D + n in the final summary Table 6. The towers under investigation present different structural typologies: log structures, Lausanne\_2003 (No. 15, Table 1) and Seedorf\_2012 (No. 16, Table 1), a cross-laminated timber (CLT) wall system, Goldau\_2016 (No. 17, Table 1), and frame structures such as Cheseaux\_2018 (No. 18, Table 1) and Bullet\_2018 (No. 19, Table 1). As highlighted in section 2.1, observation towers are representative examples of “extreme” timber structures. Their function requires panoramic visibility, which entails large openings, while their exposure to unfavourable environmental conditions further challenges timber durability. Similarly to bridges, the type of structural system significantly influences the decay mechanisms observed. Log structures represent an archetype of “transparent” architecture, with minimal wall protection and direct exposure of the structural core, but they also ensure excellent natural ventilation. During the inspection of the 32-meter-high tower in Lausanne (No. 15, Table 1), described in [33], widespread decay was observed on the external logs, particularly within longitudinal shrinkage cracks (D18, Table 6). This issue, common in log construction, has been mitigated with good results in Seedorf\_2012 (No. 16, Table 1) through anti-crack grooves on the inner log face



**Fig. 5.** Illarsaz\_2004 bridge: joist with non-overlapping membrane as observed in 2006 (a) and the resulting decay in 2024 (b). The circles indicate the same location in both images, highlighting the membrane discontinuity and the subsequent timber decay (b).

(D18, Table 6). It is worth mentioning that Seedorf\_2012 (No. 16, Table 1) is located in close proximity to the Fluelen\_1991 bridge (No. 1, Table 1), in an area characterized by a favourable microclimate, as previously described in 4.2, which may have had a positive impact on the good condition of the tower logs. In Lausanne\_2003 (No. 15, Table 1), the tower height required stacked log segments and the log-to-log joint, after almost 25 years, still shows very good performance ( $I_c = 0$ ) thanks to partial protective measures and adequate spacing between elements (D19, Table 6). By contrast, CLT and frame wall systems tend to exhibit high internal moisture levels, most likely due to insufficient ventilation, resulting in staining and surface decay (average  $I_c \approx 7$ ), as shown in Fig. 7.

In all towers, horizontal surfaces such as floors and stairs proved particularly vulnerable, as they are directly exposed to rainwater and drainage is often insufficient. In Lausanne\_2003 (No. 15, Table 1), although a naturally durable species such as Douglas fir was used, maintenance works were required about a decade after construction (specifically between 2012 and 2017) to replace the decayed stair ends [33]. The CLT tower in Goldau\_2016 (No. 17, Table 1), 29.6 m tall and described in [34], offers another significant case. The structure consists of two inclined volumes converging towards the top, entirely constructed from CLT and glued-laminated timber, supported on a reinforced concrete slab at the base. The tower has openings only on the outward-sloping facades inward-sloping facades ( $11^\circ$ ), but during the inspection, snow accumulation was observed near the edges of the floor beneath the openings, highlighting the limited effectiveness of these design precautions and the lack of a protective upper overhang (D20, Table 6). Ground connection is another critical detail for tower durability. Unlike bridges, towers are directly supported on the ground. In Lausanne\_2003 (No. 15, Table 1) and Seedorf\_2012 (No. 16, Table 1) (D21, Table 6), a high condition index was associated with decay at the log bases. In Lausanne (No. 15, Table 1), despite a 15 cm clearance from the ground, the absence of a drip groove has compromised the lower log ends. In Seedorf (No. 16, Table 1), rain rebounding off the concrete foundation slab damaged the logs positioned too close to the ground. The situation is even more severe in Cheseaux\_2018 (No. 18, Table 1), where foundation posts are submerged in swamp water and show advanced decay. A durable alternative was implemented in Goldau\_2016 (No. 17, Table 1), where the CLT base is completely protected and complemented by a ventilated wall solution (D22, Table 6). Finally, as already emphasized for timber bridges, protective and sacrificial elements, especially if made of wood, must be periodically maintained to ensure long-term durability. Consistent with the bridge analysis, the graph in Fig. 8 presents the condition index values of the tower elements, enabling a direct assessment of their durability trends.

## 6. Validation of the condition Index

The Condition Index  $I_c$  includes the Visual Decay Rating  $D_V$ , a parameter derived from existing timber-specific approaches (e.g., EN 252 [20], Mould Index [21], Lepage [22]), which prevents these methods from being considered as independent validation tools. Therefore, the proposed Condition Index  $I_c$  was evaluated through comparison with established condition rating systems. In particular, the National Bridge Inventory (NBI) [35] rating system was selected as a reference, as it is widely adopted in engineering practice and is based on general condition descriptors such as section loss, extent of decay, and structural relevance. The NBI system uses a scale from 0 to 9, where 9 corresponds to excellent conditions and 0 to a state of collapse, and can be applied to deck, superstructure, and substructure. For some bridges, whose superstructure has been analysed in the previous sections using the Condition Index  $I_c$ , a direct comparison with the NBI rating system was performed based on the observed decay characteristics, as summarised in Table 7 below.

The results show a consistent correspondence between increasing values of  $I_c$  and decreasing NBI ratings, indicating a progressive transition from good to critical conditions. This agreement supports the coherence of the proposed index with established engineering practice. It can also be observed that the proposed Condition Index tends to be slightly more conservative in the assigned condition state compared to the NBI rating. This is mainly due to the inclusion of the Early Decay Factor  $ED_f$ , which introduces a temporal dimension, enabling the identification of premature decay, often particularly aggressive, that is not explicitly captured by conventional classification systems. Furthermore, the proposed Condition Index, specific to timber structures, allows for a more detailed assessment at both the component level and the level of individual structural elements and construction details.

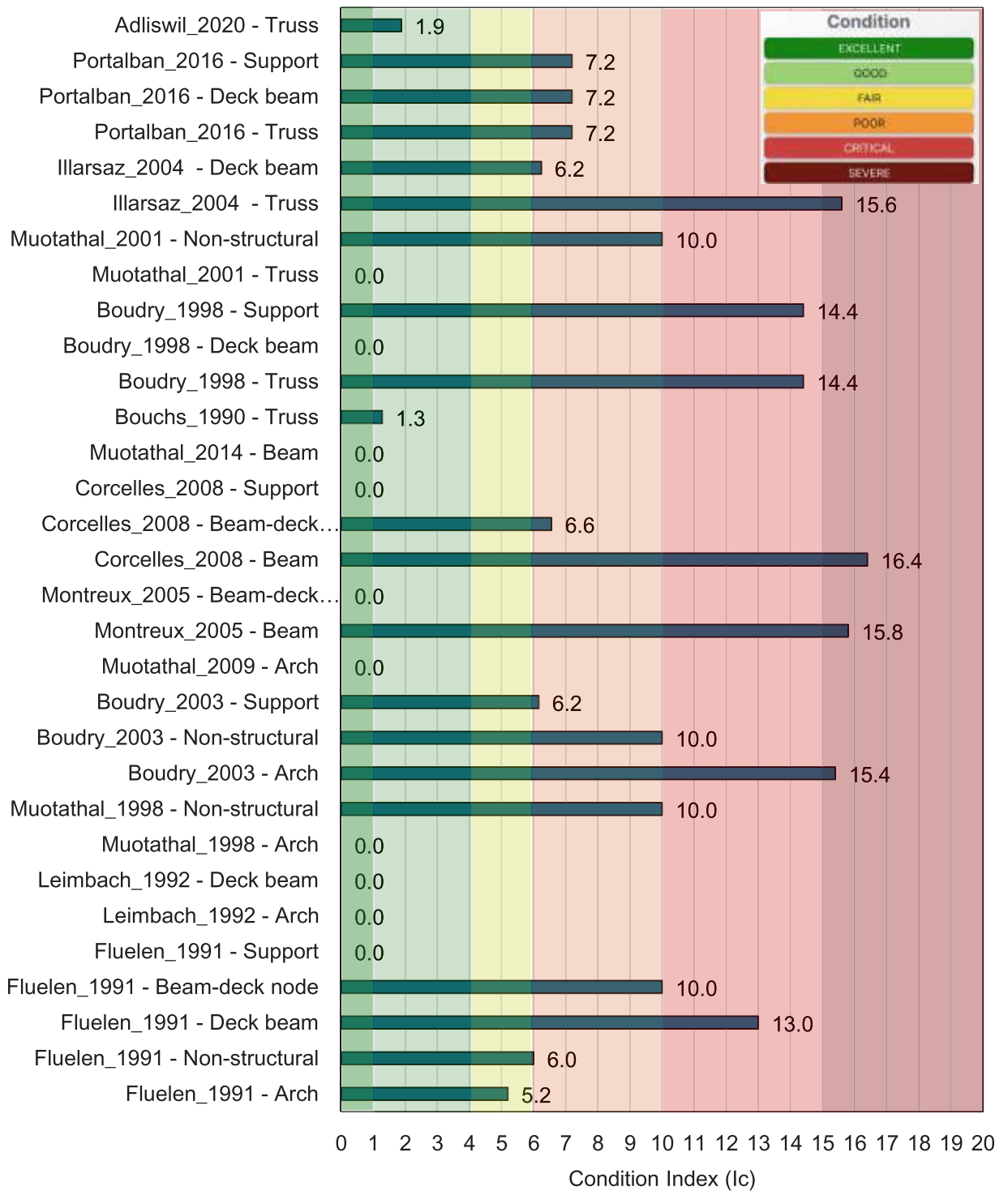


Fig. 6. Condition Index  $I_c$  of the Inspected Timber Bridges.

### 7. General durability criteria of exposed timber structures

#### 7.1. Three general durability criteria

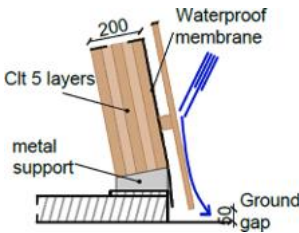

Based on the inspection of bridges and observation towers, as well as a critical review of the literature, three general criteria have been identified that are decisive for the long-term performance of exposed timber structures in service classes 2 and 3:

**Table 6**  
Representative Details and Photos from the Inspected Timber Towers.

n°	Tower	Description	Detail	Photo
D1	Lausanne_2003 (a) & Seedorf_2012 (b)	Detail of two different log sections. Decay (a) and good condition (b) respectively due to the absence and presence of anti-cracking grooves		
D1	Lausanne_2003	Detail of the log-to-log joint. Good condition due to proper spacing and a protruding metal flashing		
D2	Goldau_2016	Detail of the tower wall opening section. Decay due to water ingress in internal areas from driving rain, caused by insufficient wall slope and the absence of a protective overhang		
D2	Lausanne_2003 (a) & Seedorf_2012 (b)	Detail of two different log-to-ground connections. Decay at the log ends respectively due to insufficient gap from the ground (a) and the absence of a drip groove (b)		

(continued on next page)

Table 6 (continued)

n°	Tower	Description	Detail	Photo
D2	Goldau_2016	Detail of the tower wall-to-ground connection. Good condition due to proper clearance from the ground and protection of the CLT from weathering		

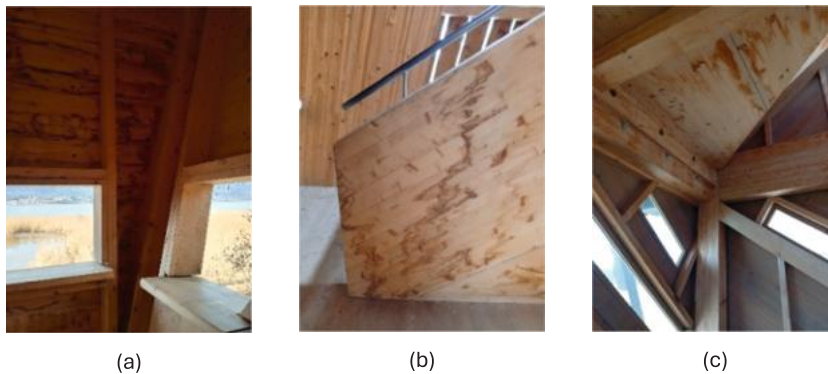


Fig. 7. Moisture stains on timber – Towers of (a) Cheseaux\_2018, (b) Goldau\_2016 and (c) Bullet\_2018.

- *Intrinsic Element and Environmental Risks*

This principle refers to the natural durability of wood species, the characteristics of individual components, their geometry and specific environmental exposure conditions. These factors determine the intrinsic vulnerability of the structure, even before protective measures are applied.

- *Water and Moisture Input*

The second principle highlights the risk associated with wetting of components, regardless of the source. Direct rainfall, indirect water paths, rebound water, capillary rise, high ambient humidity, snow accumulation or condensation can all contribute to an increase in the moisture content of wood. Critical conditions for biological decay occur when drying between one wetting event and the next is insufficient.

- *Long-Term Quality and Care*

This aspect considers the effectiveness over time of the protective measures, the quality of the construction details, the drainage and ventilation strategies, and the maintenance carried out over time. Even excellent design solutions can fail if their performance declines during the life of the structure.

Taken together, these criteria form the basis for understanding and improving the durability of exposed timber structures. It is not a single factor that determines the longevity of a structure, but rather the interaction and balance between the intrinsic properties of the

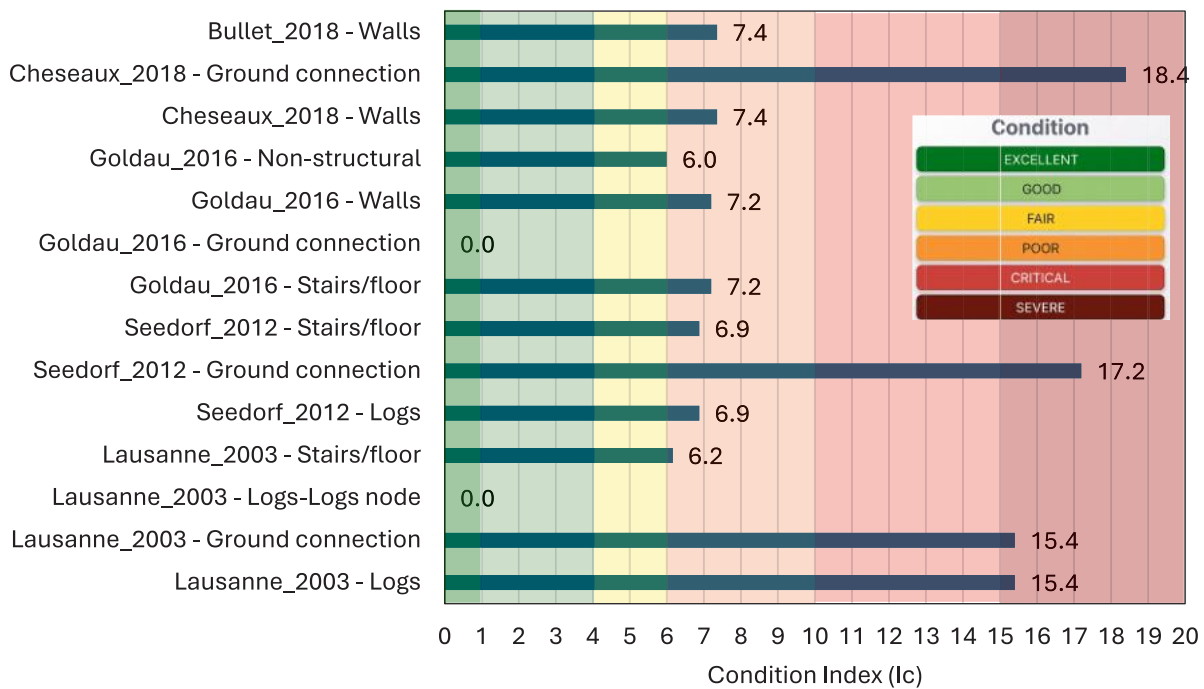


Fig. 8. Condition Index  $I_c$  of Inspected Timber Towers.

Table 7

Comparison between the proposed Condition Index  $I_c$  and NBI ratings for selected timber bridges.

Bridge	Element	Age	$I_c$	$I_c$ Condition state	NBI	NBI Condition state
Fluelen_1991	Arch	35	5.2	Fair	6	Satisfactory
Leimbach_1992	Arch	34	0	Excellent	8	Very Good
Muotathal_1998	Arch	28	0	Excellent	8	Very Good
Boudry_2003	Arch	23	15.4	Severe	5	Fair
Muotathal_2009	Arch	17	0	Excellent	9	Excellent
Montreux_2005	Beam	21	15.8	Severe	5	Fair
Corcelles_2008	Beam	18	16.4	Severe	4	Poor
Muotathal_2014	Beam	12	0	Excellent	9	Excellent
Bouchs_1990	Truss	36	1.28	Good	6	Satisfactory
Boudry_1998	Truss	28	14.4	Critical	5	Fair
Muotathal_2001	Truss	25	0	Excellent	8	Very Good
Illarsaz_2004	Truss	22	15.6	Severe	4	Poor
Portalban_2016	Truss	10	7.2	Poor	6	Satisfactory
Adliswil_2020	Truss	6	1.88	Good	7	Good

material, moisture management and the effectiveness of construction solutions over time. Fig. 9 summarizes the three general durability criteria together with their related operational sub-criteria. These criteria are briefly discussed in the following sections.

## 7.2. Intrinsic element and environmental risks

### 7.2.1. Exposed surface characteristics

A timber surface is considered exposed if it is directly subject to weathering without protection from the building envelope or other elements. The associated risk depends on the type of surface, whether it is a side-grain or an end-grain surface, as well as its inclination and geometry, which affect water runoff. End-grain absorption at member ends can be up to ten times higher than on longitudinal side-grain faces, with water absorption coefficients ( $A_w$ ) for softwoods ranging from 10 to 16  $\frac{g}{m^2\sqrt{s}}$  in the longitudinal direction and from 1 to 7  $\frac{g}{m^2\sqrt{s}}$  in the transverse directions [2]. Similar values were reported in [36], which also showed that sapwood absorbs significantly more water than heartwood. The same study reports that the absorption ratios along the three principal wood directions, radial (R), tangential (T), and longitudinal (L), have been reported as 1:1:7 (R:T:L) for sapwood and 1:1:4 for heartwood. End-grain surfaces should therefore be carefully designed to avoid water stagnation and highly aggressive decay conditions. The risk associated with an exposed surface is not limited to liquid water absorption but also includes moisture uptake. Methods for calculating liquid water

absorption are described in [2], while vapor absorption has been studied by [13] using a multi-Fickian moisture transport model. It is worth noting that an exposed surface is not inherently detrimental, as demonstrated by several of the inspected structures where exposed timber elements remain in good condition despite years of service. In the Fluelen\_1991 (No. 1, Table 1) and Bouchs\_1990 No. 9, Table 1) bridges, as well as in the Seedorf\_2012 (No. 16, Table 1) or Goldau\_2016 (No. 17, Table 1) towers, for example, timber is intentionally left visible to exploit natural ventilation. Defining shapes and construction details that promote water drainage and prevent stagnation, through adequate slopes, rounded edges and correct fibre orientation, is a good starting point, as exposed timber can dry more rapidly thanks to ventilation. As reported in [35], the drying time is approximately 2.5 times the wetting duration. Surfaces that do not have sufficient time to dry between wetting events are particularly susceptible to decay due to prolonged wetness.

### 7.2.2. Natural durability

Intrinsic capacity of wood to resist biological degradation (fungi, insects, termites), mainly determined by wood species and, to a lesser extent, by the portion of the trunk utilized. Sapwood is generally less durable than heartwood due to the absence of extractives and the presence of reserve nutrients that feed fungi. Wood is classified into five natural durability classes, from 1 (most durable) to 5 (least durable), according to EN 350 [26]. Several studies report the expected lifespan of timber exposed above ground or in contact with soil, depending on species and durability class. In particular, [37] and [38] provide data on the above-ground longevity of conifers and broadleaves without treatments. Recent research emphasizes the need for reliable testing: [39] proposes the “bundle test” as a standard method for evaluating wood durability in above-ground conditions (Use Class 3). This method uses a bundle of wood specimens to create water-trapping interfaces, which accelerate fungal infestation by maintaining high moisture levels. The study demonstrates that non-durable species may degrade within about five years in Central Europe. In [40], natural durability is analysed based on actual service life data from 163 records across 31 sites worldwide, using 10 test methods. Resistance factors were introduced to standardize comparisons, indicating how much more or less durable a species is relative to a reference and how quickly it degrades.

### 7.2.3. Microclimate

The biological decay of wood is strongly influenced by local climatic conditions. Factors such as humidity, temperature, wind and sun exposure directly affect the drying rate or moisture retention of timber elements, thus determining the likelihood of fungal or insect attacks. The impact of climate on above-ground wood structures has been widely studied in the literature. The Scheffer Climate Index (SCI) [41] is one of the earliest indices, developed in 1970 to assess the potential of a climate to promote decay of above-ground wood, based on temperature and the number of rainy days, as defined by the formula below.

$$SCI = \frac{\sum_{Jan}^{Dec} (T - 2)(D - 3)}{16.7} \quad (3)$$

Where:

- $T$  is the mean monthly temperature (°C.)
- $D$  is the mean number of days in the month with 0.25 mm or more of precipitation

Using this index, risk maps were produced for the United States in the 1970 s [41] and in 2000 [42]. Additionally, [43] reports a significant increase in SCI values for various locations in the UK from 1990 to 2017, with projections of further increases until at least 2055. In this study, the microclimatic impact on decay is illustrated by Boudry\_2003 and Fluelen\_1991, structurally similar but located in different contexts. As reported in Table 8, the Scheffer Climate Index is slightly higher for Fluelen than for Boudry, yet Fluelen, despite being over 20 years older, is in much better condition. This shows that local factors such as ventilation, sun exposure, element position, and proximity to water courses, strongly affect decay, beyond what the SCI alone predicts.

An alternative approach is described in the Australian manual by Forest & Wood Products [27], where a climate parameter  $K_{climate}$  is defined. This parameter is then used to produce an above-ground decay hazard map for Australia, dividing the continent into four zones according to the relative vulnerability of locations to fungal decay due to climatic variation. For Europe, [44] calculated the

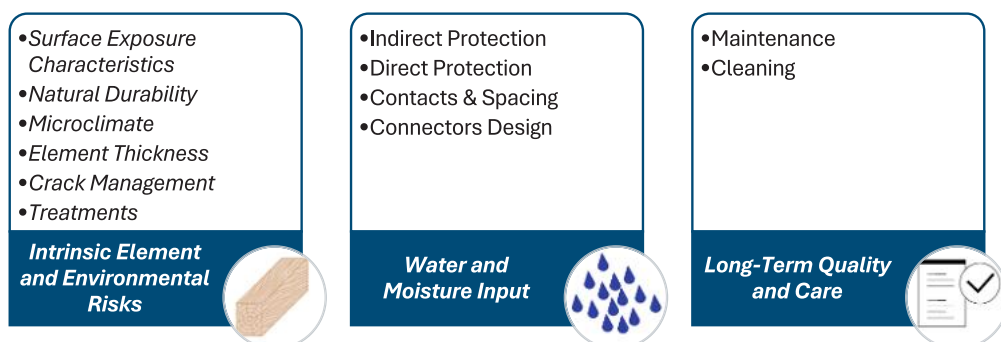


Fig. 9. Durability criteria and operational sub-criteria.

relative risk of timber decay under different climatic conditions and produced decay risk maps based on field tests conducted at 28 sites, using two models:

- Dose–response model: links wood moisture content (MC) and temperature (T) to the observed fungal decay. Long-term field tests allowed defining a mathematical relationship between the “dose” of moisture and temperature and the fungal decay response [45].
- Climate model: converts general climatic data (daily average temperature, rainfall, and air humidity) into actual wood conditions (MC, wood temperature, and drying), allowing the application of the dose–response model.

#### 7.2.4. Thickness

Element thickness significantly affects the drying behaviour of wood sections: the outer layers reach hygrometric equilibrium more quickly, while the inner layers take longer, particularly below the fibre saturation point (FSP). Several studies analyse drying times in industrial kilns as a function of lamella thickness [46]. In [47], drying is modelled as water diffusion according to Fick’s second law, also under natural conditions, considering the influence of thickness, wood species, temperature, relative humidity and air velocity. The results show that drying times and moisture uniformity depend on the interaction of these variables. In general, the literature mainly focuses on small thicknesses, typical of lamella, while there is limited bibliographic information on natural drying of thicker elements, such as structural components found in bridges and towers.

#### 7.2.5. Crack management

Wood cracks are inevitable, yet they can be designed to avoid becoming preferential paths for water ingress and retention, by orienting them to facilitate water runoff and/or reducing their width and frequency. On horizontal surfaces or where water runoff is slow, the combined action of rain and solar radiation produces cycles of swelling and shrinkage that gradually create deeper cracks, allowing water to penetrate and accumulate in the inner layers of the timber, as shown in the Fig. 10. In solid timber, proper drying is important to limit large cracks and elements should be oriented so that cracks face the less exposed sides. In glued laminated elements, the upper boards can be placed with the pith upwards so that cracks develop on the underside. Beam ends are particularly sensitive and should be tapered or inclined to reduce cracking. Round timber also tends to develop wide cracks, for which anti-cracking relief cuts can help reduce their size and frequency. Table 9 summarises such scenarios. In general, the relationship between cracking and durability is rarely addressed in the literature, making it an interesting topic for further experimental studies to better understand how crack management can affect water and vapor diffusion in timber and ultimately its durability.

#### 7.2.6. Treatments

Treatments are interventions aimed at increasing the natural durability of timber. Surface treatments provide mainly aesthetic protection and some resistance against insects, but they are less effective against biological decay, since cracks in the wood reduce their performance. Impregnation treatments, on the other hand, can generally offer higher durability, although their effectiveness depends on the timber species, as described in UNI 350 [26]. Some softwoods, such as spruce and pine, are easy to impregnate, while oak and chestnut are much less permeable. The impregnation process is usually carried out by submersion or using autoclave, but penetration remains limited to a few millimetres. An alternative approach is thermal treatment, which modifies the chemical structure of wood at high temperatures (>120 °C). This process reduces hygroscopicity and improves dimensional stability, while avoiding the risks associated with toxic substances. However, it also leads to a reduction in mechanical properties, especially strength and stiffness. For this reason, thermal treatments are more suitable for non-structural or cladding elements. It is important to emphasise that treatment alone does not automatically guarantee long-term durability. Careful assessment based on the species and intended use is always necessary, as its combination with other construction measures and/or protective measures.

### 7.3. Water and moisture input

#### 7.3.1. Indirect protection

The roof and other parts of the structure can create areas where timber elements are sheltered and well-ventilated (rain shadow angle). Weather protection is a key factor in ensuring the durability of timber structures. The German standard DIN 68800 (2019) [48] recommends that, in the design phase, rainfall should be assumed to fall at an angle of about 30° from the vertical. Similarly, in the prEN 1995:2025 [15] part 2, dedicated to timber bridges, specifies that surfaces located within 30° from the vertical under an overhang may be considered protected from moisture and designed according to service class 2, except in particularly severe climatic conditions. In exposed environments, such as windy coasts or valleys, rainfall angles of up to 70° from the vertical have been observed. Overhanging elements, such as roofs or other structural components, are therefore an effective strategy to enhance durability, as they

**Table 8**  
Monthly mean T and D values used to calculate SCI for Boudry and Fluelen (MeteoSwiss data 2014–2024).

Location		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	SCI
Boudry(Neuchâtel Station)	T (°C)	2.6	4.2	7.2	10.7	14.1	19.2	21.2	20.4	16.4	11.8	6.5	3.6	57.56
	D	14	11	12	11	14	12	12	10	9	12	12	13	
Fluelen(Altdorf Station)	T (°C)	2.2	4	6.8	10.3	13.8	18.4	19.8	19.1	15.4	11.7	6.4	3	69.74
	D	12	10	12	11	15	16	16	15	12	11	12	13	

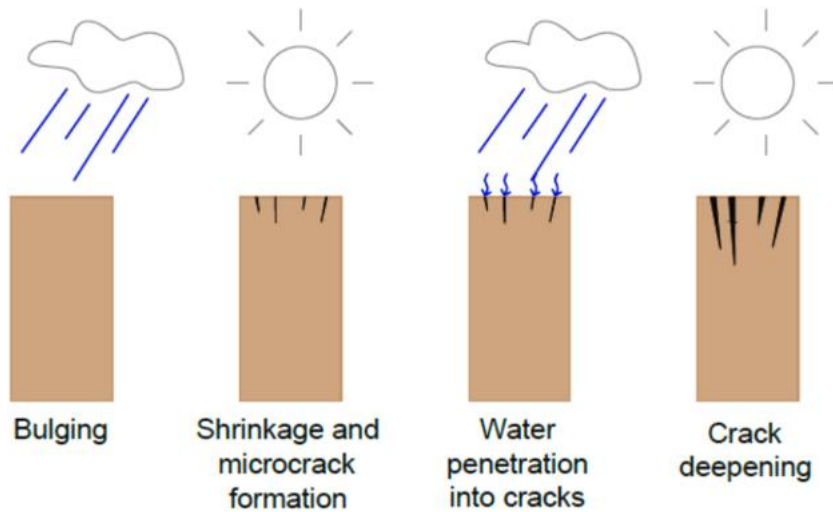


Fig. 10. Formation and propagation of cracks.

Table 9  
Cracking Management on different timber elements.

		Solid wood	GLT	Round timber	Wood headers
Cracking Management	No				
	Yes				

significantly reduce the frequency of wetting events on the elements below, limiting moisture exposure mainly to exceptional circumstances. Moreover, the protection offered by the overhang allows underlying timber surfaces to remain uncovered and ventilated, thus promoting natural drying.

7.3.2. Direct protection

Design solutions should effectively prevent timber decay through deflection and drainage measures, while promoting adequate ventilation to eliminate the conditions that favour biological attack. They may consist of simple details, such as drip grooves that reduce water accumulation on the underside or more complex protective systems. Direct protection can be partial, when only the most vulnerable surfaces or joints are covered following risk assessment, while the areas that allow water drainage remain exposed and rely on the natural durability of wood. It can also be total, when the entire element is covered. Examples include metal flashings, protective timber boards on the upper surface, ventilated facades, metal caps at joints and other solutions. The effectiveness of protection is crucial. Water diverted by the system must not flow onto unprotected areas and connections between protective elements must be carefully designed and executed to avoid infiltration. Inadequate details can cause premature decay, as described in paragraph 4.2 with reference to the bridges of Montreux\_2005, Corcelles\_2008 and Boudry\_1998.

7.3.3. Contacts and spacing

Adequate spacing between timber elements ensures effective ventilation, prevents water accumulation and allows for dimensional changes and maintenance. Joints should be designed with spacers or “open” configurations to minimize moisture retention. Direct contact between timber elements, or between wood and other materials, should be avoided as much as possible to reduce the risk of moisture accumulation. Attention should also be given to situations where water can reach timber surfaces not only through direct rainfall. For example, an element placed too close to a horizontal surface may be affected by capillary rise or splash water. Similarly, insufficient distance from highly humid areas, such as grassy soil or a watercourse, may increase the risk of decay. The new version of

Eurocode 5 provides recommendations for minimum spacing in different conditions, as summarized in Table 10.

In the standard, no distinction is made between whether the surface considered is a timber side-grain surface or end-grain surface. Moreover, no reference is provided regarding the spacing between the top metal sheet and the outer surface of the timber element. It is only specified that the protection must extend beyond both sides and that a separation layer must be ensured beneath the metal sheet to prevent the accumulation of condensation water [15]. Inspections have shown that gaps smaller than 1 cm are critical. Future research will evaluate whether these distances are adequate, excessive, or insufficient.

#### 7.3.4. Connectors design

Connectors can cause cracks and localized water accumulation if not properly designed. Proper placement in areas not directly exposed, adequate notching and protective measures help prevent water ingress and ensure effective drainage. Joints and metal plates should be designed with downward-facing openings and protected notches to allow continuous water runoff. Cylindrical elements can also be used to facilitate drainage. Screws, washers and nuts pose a particular risk, as they can obstruct water flow and induce localized stresses, especially when directly exposed. Moreover, the corrosion of connectors can accelerate the decay of the surrounding timber, as reported in [49].

### 7.4. Long-Term quality and care

#### 7.4.1. Maintenance

Monitoring the decay of timber elements, the performance of protection systems and the integrity of welds and connectors is essential to ensure their effectiveness throughout the structure service life. Even if well-designed, if these protection systems and joints are not properly maintained, they can become a weak point and compromise the durability of the timber structures they are meant to protect. Regular inspections of welds and timber protection elements, such as top boards or face battens, should be planned from the very beginning, as shown, for example, in [8,9] and [10].


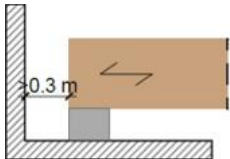
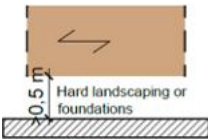
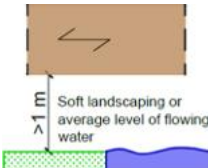
#### 7.4.2. Cleaning

Regular cleaning is essential to maintain the durability of timber structures. Removing vegetation, leaves, dust and other debris is crucial as water and moisture can accumulate in these areas. If such dirt comes into contact with the timber, it becomes a preferred pathway for moisture to enter, creating conditions conducive to the development of fungi and rot. Keeping designated ventilation spaces and paths clear ensures proper air circulation and reduces the risk of condensation. It is therefore essential to schedule periodic cleaning of all “at-risk” areas in order to preserve both the protection systems and the timber components themselves.

### 7.5. Discussion on possible interdependencies among the durability criteria

The lack of correlation between structural age and health conditions of the inspected structures, with recent structures showing premature decay while others remain in optimal condition after more than 30 years of service, further underscores that durability cannot be attributed to single parameters but is instead governed by complex interdependencies. Specifically, a lack of long-term maintenance (long-term quality and care) significantly amplifies the risks of moisture ingress; for instance, in Corcelles\_2008 and Boudry\_1998, insufficient care compromised the effectiveness of direct protection and spacing. In Fluelen\_1991, the wide clearance between the beam and the upper protective board facilitated drainage, thereby reducing water accumulation and preserving the system's effectiveness even in the presence of decay and damage to the protective element, thus partially compensating the lack of maintenance. Regarding the environmental risk criterion, a favourable microclimate as anticipated has a positive influence on durability. This is particularly evident when adequate ventilation and proper spacing between elements allow for moisture evaporation, as seen in the case of Bouchs\_1990. Additional strategies aimed at reducing water and moisture input, such as indirect protection systems (e.g. roofs or overhangs), while not fully protective, contribute to lowering wetting frequency and facilitate the leveraging of the material's natural durability. Natural durability, alongside element-specific characteristics (e.g. exposed surface type), can be significantly bolstered by proper moisture management design. However, a hierarchy of influence exists among these factors. In particular, effective total direct protection represents a primary determinant for service life extension (Muotathal\_2009), whereas conceptual design errors leading to water infiltration and localized moisture accumulation can trigger severe and premature decay.

**Table 10**  
Recommended spacing in new EC5 [15].

Deck planks spacing	Support Horizontal spacing (for inspection)	Timber – hard ground spacing	Timber – soft ground spacing
			

## 8. Conclusion

This study defines general durability criteria for exposed timber structures based on the inspection of 14 bridges and 5 observation towers in Switzerland. A Condition Index was developed and applied to key components and construction details, providing a consistent and transferable basis for condition assessment across different structures. The condition index proved effective in identifying high-risk components and enabling comparative evaluations. The findings consolidate previously fragmented knowledge into a structured framework composed of three main durability criteria: (a) Intrinsic Element and Environmental Risks, (b) Water and Moisture Input, and (c) Long-Term Quality and Care, each articulated through operational sub-criteria. The results demonstrate once more that timber durability is governed by the interaction of multiple factors rather than by isolated variables. The analysis indicates that inadequate direct protection, improper spacing, and insufficient maintenance are dominant drivers of early and severe decay. In contrast, effective protection strategies and favourable microclimatic conditions significantly enhance structural longevity. Within the investigated dataset, wood treatments appear to play a secondary role in overall performance. Future research will focus on quantifying the interdependencies among the identified criteria, assigning relative weights to support a more rigorous durability assessment, and establishing a formal hierarchy of influencing factors. Further investigations should also address protected and layered timber structures to evaluate how durability criteria evolve under different exposure conditions. The ultimate objective is to develop a robust methodological framework to support risk-informed evaluation, design, and management of timber structures.

### CRedit authorship contribution statement

**Salzani Daniele:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Andrea Gaspari:** Writing – review & editing, Conceptualization. **Bernasconi Andrea:** Writing – review & editing, Supervision, Conceptualization. **Maurizio Piazza:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Ivan Giongo:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgements

The authors gratefully thank the 2024-2026 ReLUIIS-DPC project (Italian University Network of Seismic Engineering Laboratories and Italian Civil Protection Agency) for the financial support given to this study. This work was also supported by the Italian Ministry of Education, Universities and Research (MUR) in the framework of the project DICAM-EXC (Departments of Excellence 2023-2027, grant L232/2016).

### Data availability

Data will be made available on request.

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