Deterioration and Protection of Timber Bridges

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Absract

The timber structures exposed to weather, such as bridges, lose in time the original properties of material, and therefore their bearing capacity decreases, they lose functionality and their service life is shortened. The paper considered examination of deterioration causes, assessed bearing capacity and functionality of glued laminated timber bridges.The remediation methods and protection of bridge supports were proposed on the basis of the data showing the causes of damage to the bridge.The results of examination of the causes of damage of a timber bridge made of laminated wood located in the vicinity of the University of Nis, in Serbia, have been presented. The bridge was designed and constructed according to the all the standing standards. The service life of the structure was 30 years. Since the construction, the bridge was regularly monitored by the designers. In the first 10 years, there was a progressive deterioration of timber, endangering the bearing capacity and serviceability of the bridge. A laboratory analysis of the damage was done and remediation design of the bridge was produced, and then the bridge was rehabilitated. The design provided structural preventive measures for the bridge, on the basis of the parameters which had caused the damage. Regular inspections of the bridge, 16 years after it was rehabilitated, yielded no observable damages of the bridge, so the bridge is safe for daily service.

Keywords: Deterioration, Protektion, Timber, Bridges, Service life

Introduction

The considered footbridge constructed of glued laminated timber crossing a trench of a medieval fort near the University of Nis has a span of 26 meters and width of 4 meters. After the bridge had rapidly dilapidated, the University initiated examinations of the bridge. The efficient measures of remediation successfully put the bridge back in order. The examinations of the bridge by the University included visual inspection of the bridge, laboratory tests of the properties and moisture content of material, and then, on the basis of characteristic damage, the main theoretical methods were developed for the purpose of proving the safety of the structure. The bridge has two main support beams and a system of longitudinal and transversal beams. The main beams exhibited exterior deterioration from the top of the beam downwards. After the damaged laminas were removed (three to five laminas) it was found that the lower part of the beam was in perfectly good condition. Such damage was considered in the theoretical section of the paper. Also, the top surface of longitudinal joists was damaged, at the contact of the joist and the deck

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planks. The ultimate longitudinal joist was joined laterally with the main beam, so it developed a lateral exterior deterioration.
The theoretical solutions proving the structural safety were produced according to the standing European standards. The design bearing capacity model is defined on the basis of geometrical measured damage and mechanical characteristics determined in laboratories. Based on the analysis of parameters, a diagram for determination of bearing capacity of damaged support beams was produced. The analysis contains general solutions, for various constellations of loads and shapes of cross-sections so it can be used for solution of similar problems in practice.

Deterioration Agents and Implemented Bridge Inspection Methods

The bridge was designed for pedestrian traffic, and directly exposed to all atmospheric impacts. In the first ten years of service, the bridge sustained heavy damage due to timber deterioration. The inspection officials closed the bridge down, and the University took up the task to identify the causes of bridge dilapidation and to propose the bridge remediation and protection procedure. Samples for laboratory tests were collected. In a relatively dry season, at the temperature of 25°C and the air humidity of 63%, the recorded moisture content of the timber in the damaged zone was increased, ranging from 33 to 39%.
As at the time the laboratory did not possess the equipment for detection of the location of damage, the following methods for detecting exterior deterioration were used: visual, picking/probing, moisture content, boring/drilling, physical properties methods, The visual inspections of timber members revealed areas that needed further investigation such as checks, splits, shakes, fungus decay, deflection, or loose fasteners.
In majority of the cases, the tests with the hammer and needle penetration were conducted.
The tests yielded good results and the damage inside the bearing elements of the structure were properly recorded.
The causes of rapid dilapidation of the structure were poorly designed structural details, so there were points, especially at the interface of elements, which accumulated moisture. The moisture retained in the timber elements interface lingered there for protracted periods of time as there was no ventilation, thus constituting the main cause for timber decay. The bridge has no cover, thus being directly exposed to the rain, snow and ice water. It is also exposed to sunlight, that is, UV rays action, frequent temperature oscillations, as well as to freezing in the winter season and to over 40°C of temperature in the summer season. Penetration of decay in the structure was found at the points where water penetrated the structure, top down, so the upper laminas of the bridge sustained damage. Minor damage was detected on the lateral sides of the joists, on the exterior side of the bridge. The lower lamina was not damaged.

Theoretical Identification of the Problem

For the design of timber structures in the paper the EN 1995 standard is used.
The values for partial safety factors for actions are taken from EN 1990. Where:
γ_F is partial factors for actions, also accounting for model uncertainties and dimensional variations
γ_G (Partial factors for permanent actions, also accounting for model uncertainties and dimensional variations),
γ_Q (Partial factors for variable actions, also accounting for model uncertainties and dimensional variations),
γ_M (Partial factors for a material property, also accounting for model uncertainties and dimensional variations).
Characteristic Actions Fk according to EN 1991, can be, for instance
for permanent actions $F_k = G_k$ (such as self-weight)
variable actions $F_k = Q_k$ (such as wind, snow, traffic)
Design value of an action is $F_d = \gamma_F F_k$
The symbol F can denote:
G - permanent actions or Q - variable actions.
In design of the beams loaded with uniaxial bending, in a general case, there are 3 criteria for Design resistance for cross-sections area dimensions:

- Usage of true normal bending stresses - $\sigma_{m,d}$

$$\frac{\sigma_{m,d}}{f_{m,d}} = 1 \qquad (1)$$

$$\sigma_{m,d} = f_{m,d} \Rightarrow \frac{M_d}{W_n} = f_{m,d} \qquad (1.1)$$

that is, section modulus: $W_n = \frac{M_d}{f_{m,d}}$ [cm^3] (1. 2.)

$\sigma_{m,d}$ is design value of bending stress
M_d = design value of bending moment
W_n = netto moment of resistance considering the cross section weaks
$f_{m,d}$ = design value of bending strength

-usage of true shear stress - τ_d

$$\frac{\tau_d}{f_{v,d}} = 1 \qquad (2)$$

$$\tau_d = f_{v,d} \Rightarrow \frac{V_d S}{I\, b} = f_{v,d}, \qquad (2.1)$$

or $A_v = \frac{Ib}{S}$, that is surface area: $A_v = \frac{V_d}{f_{v,d}}$ [cm^2] (2. 2.)

V_d = design value of the shear force

S = static moment (section modulus)
I = second moment of area (moment of inertia)
b = width
$f_{v,d}$ =design shear strength for the actual condition

deflection of beams

- usage of true maximal deflection - w_{inst}

where $w_{inst} = w_{net,fin}$

$$w_{inst} = \frac{l}{m} \Rightarrow \int_l \frac{M_d \bar{M}}{E_d I} dx = \psi \frac{l^2 M_d}{E_d I} = \frac{l}{m}, \tag{3}$$

I is moment of inertia:

$$I = \psi \frac{l^2 M_d m}{E_d l} \ [\text{cm}^4] \tag{3.1}$$

w_{inst} is the instantaneous deflection

$w_{net,fin}$ is the net final deflection

$E_d = E_{0,mean}$ =*Modulus of elasticity*

$\frac{l}{m}$ =limiting values for deflection of beams (see Table 7.2: Examples of limiting values for deflections of beams in Eurocode 5, Part 1-1)

The parameter equations for the simple beam static system with rectangular cross section are as follows:

The values for V_d and M_d are calculated for the load $\bar{q}$ from Table 1, depending on the kind of load and beam static system. The paper does not consider combination of various loads, but analyzes only one kind of load, for example, only permanent actions.

The values Δq and ΔP represent reduction of beam bearing capacity in time, due to deterioration.

If the height is h and width is b of cross section in the observed moment of the deterioration process, then

$b = b_0 - \Delta b$ and $h = h_0 - \Delta h$

Where

b_0 and h_0 - width and height of the cross section prior to onset of deterioration

Δb and Δh reduction of width and height of cross section due to deterioration

For rectangular cross-section, geometrical characteristics are

$$S = \frac{bh^2}{8}, I = \frac{bh^3}{12} \text{ and } W = \frac{bh^2}{6}$$

If the deterioration process is manifested as a reduction of the cross section height for the value Δh, and the width and length of the beam are constant, the final height of the cross section will be

$h - \Delta h$, and thus

$$S = \frac{b(h_0 - \Delta h)^2}{8}, I = \frac{b(h_0 - \Delta h)^3}{12} \text{ i } W = \frac{b(h_0 - \Delta h)^2}{6}$$

Figure 1.Deterioration of the main beam of the timber bridge

By transforming the expressions (1),(2) and (3) by entering the previously defined values, the following result is obtained

-from the expression (1) follows $\frac{\bar{q}}{b} = \alpha f_{m,d} \left(\frac{h}{l}\right)^2$ i.e. $\frac{\bar{q}}{bf_{m,d}} = \alpha \left(\frac{h}{l}\right)^2$ (4)

- from the expression (2) follows $\frac{\bar{q}}{b} = \beta f_{m,d} \left(\frac{h}{l}\right)$ i.e. $\frac{\bar{q}}{bf_{m,d}} = \beta \frac{f_{v,d}}{f_{m,d}} \left(\frac{h}{l}\right)$ (5)

- from the expression (3) follows $\psi \frac{l^2 M_d}{E_d I} = \frac{l}{m}$ follows $\frac{\bar{q}}{b} = \delta \frac{\gamma_F E_d}{m} \left(\frac{h}{l}\right)^3$

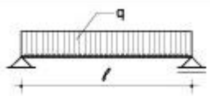
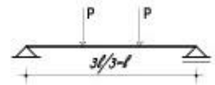
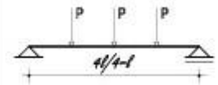
i.e. $\frac{\bar{q}}{bf_{m,d}} = \delta \frac{\gamma_F}{m} \frac{E_d}{f_{m,d}} \left(\frac{h}{l}\right)^3$ (6)

The (4), (5) and (6) are given in the Diagram, Figure 2

The parameters in the expressions (4), (5) and (6) are *b*,*h* and *l* defining the geometry of the beam and E_d , $f_{m,d}$ and $f_{v,d}$ defining the properties of material.

The value $\bar{q} = \gamma_F q$ is the desired bearing capacity of the beam, and coefficients ψ , α , β , δ are given in the Table 1 for rectangular cross section for various kinds of load.

Table 1. Coefficient values ψ , α , β , δ and load $\bar{q}$

System and load					
load		$\bar{q}=\gamma_F\, q$	$\bar{q}=\gamma_F \frac{P}{l}$	$\bar{q}=\gamma_F \frac{2P}{l}$	$\bar{q}=\gamma_F \frac{3P}{l}$
koeficient	ψ	5/48	1/12	23/216	19/192
	α	4/3	2/3	1	1
	β	4/3	4/3	4/3	4/3
	δ	384/60	4	108/23	96/19

If the beam is a square cross section beam, it should be entered in the expression that the square side is $a=b=h$,

In the further text, a beam of rectangular cross section ***b/h*** will be considered, loaded with uniformly distributed load ***q***. The beam span is ***l***.

If it is assumed that deterioration only occurred along the height of the element, and the cross section remained rectangular, so that

$h=h_0-\Delta h$, $b=b_0$ and, then from the expression (4) it follows:

$$\frac{\bar{q}}{bf_{m,d}}=\frac{\gamma_F(q-\Delta q)}{bf_{m,d}} \text{ i.e. } \frac{\gamma_F(q-\Delta q)}{bf_{m,d}}=\alpha\left(\frac{h_0-\Delta h}{l}\right)^2$$

$$\Delta q=q-\alpha\frac{bf_{m,d}}{\gamma_F}\left(\frac{h_0-\Delta h}{l}\right)^2 \qquad (7)$$

from the expression (5) it follows:

$$\frac{\bar{q}}{bf_{m,d}}=\beta\frac{f_{v,d}}{f_{m,d}}\left(\frac{h_0-\Delta h}{l}\right)$$

$$\gamma_F\frac{(q-\Delta q)}{bf_{m,d}}=\beta\frac{f_{v,d}}{f_{m,d}}\left(\frac{h_0-\Delta h}{l}\right)$$

$$\Delta q=q-\beta\frac{bf_{v,d}}{\gamma_F}\left(\frac{h_0-\Delta h}{l}\right) \qquad (8)$$

from the expression (6) it follows:

$$\frac{\bar{q}}{bf_{m,d}}=\delta\frac{\gamma_F}{m}\frac{E_d}{f_{m,d}}\left(\frac{h_0-\Delta h}{l}\right)^3$$

$$\gamma_F \frac{q-\Delta q}{bf_{m,d}} = \delta \frac{\gamma_F}{m} \frac{E_d}{f_{m,d}} \left(\frac{h_0 - \Delta h}{l} \right)^3$$

$$\Delta q = q - \delta \frac{bE_d}{m} \left(\frac{h_0 - \Delta h}{l} \right)^3 \qquad (9)$$

If it is assumed that the deterioration occurred along the width of the support element then $b = b_0 - \Delta b$

or if it simultaneously occurred along the height and width of the element then $b = b_0 - \Delta b$ and $h = h_0 - \Delta h$, and these values are given in the Table 2

Table 2. Expressions for determining of bearing capacity of the beam

	$\frac{\sigma_{m,d}}{f_{m,d}} = 1$	$\frac{\tau_d}{f_{v,d}} = 1$	$w_{inst} = \frac{l}{m}$
$b = b_0$ $h = h_0 - \Delta h$	$\frac{\bar{q}}{bf_{m,d}} = \alpha \left(\frac{h_0 - \Delta h}{l} \right)^2$	$\frac{\bar{q}}{bf_{m,d}} = \beta \frac{f_{v,d}}{f_{m,d}} \left(\frac{h_0 - \Delta h}{l} \right)$	$\frac{\bar{q}}{bf_{m,d}} = \delta \frac{\gamma_F}{m} \frac{E_d}{f_{m,d}} \left(\frac{h_0 - \Delta h}{l} \right)^3$
$b = b_0 - \Delta b$	$\frac{\bar{q}}{(b_0 - \Delta b) f_{m,d}} = \alpha \left(\frac{h}{l} \right)^2$	$\frac{\bar{q}}{(b_0 - \Delta b) f_{m,d}} = \beta \frac{f_{v,d}}{f_{m,d}} \left(\frac{h}{l} \right)$	$\frac{\bar{q}}{(b_0 - \Delta b) f_{m,d}} = \delta \frac{\gamma_F}{m} \frac{E_d}{f_{m,d}} \left(\frac{h}{l} \right)^3$
$b = b_0 - \Delta b$ $h = h_0 - \Delta h$	$\frac{\bar{q}}{(b_0 - \Delta b) f_{m,d}} = \alpha \left(\frac{h_0 - \Delta h}{l} \right)^2$	$\frac{\bar{q}}{(b_0 - \Delta b) f_{m,d}} = \beta \frac{f_{v,d}}{f_{m,d}} \left(\frac{h_0 - \Delta h}{l} \right)$	$\frac{\bar{q}}{(b_0 - \Delta b) f_{m,d}} = \delta \frac{\gamma_F}{m} \frac{E_d}{f_{m,d}} \left(\frac{h_0 - \Delta h}{l} \right)^3$

On the basis of the performed inspection and laboratory tests of the bridge, it was found that in this case, the deterioration occurred along the height of the beam. After the damaged parts were removed (figure 1), the sound part of the beam had satisfactory, unaltered mechanical characteristics. Also, there was no damage along the element width. The calculation of beam bearing capacity is performed according to the expression (7). The results of the parametric analysis are displayed in the diagram, figure 2. Based on expressions 1, 2 and 3, that is, expressions 4,5 and 6, three curved lines are presented. To each of the values of the beam L/h correspond three different values of load $\bar{q}/(bf_{m,d})$. The least value of the load represents the bearing capacity of the beam. On the other hand, to each of the values of load $\bar{q}/(bf_{m,d})$ correspond three different values of l/h , but the solution is the least ratio l/h.

The value *l/h* in the point „A" in Figure 1 is determined from the equality conditions of the right hand sides of the expressions (1) and (2), That is, : $\frac{l}{h} = \frac{\alpha}{\beta}\frac{f_{md}}{f_{vd}}$ (10)

The value of l/h in the point „B" is determined from the equality conditions of the right hand sides of the expressions (2) and (3),

$$\frac{l}{h} = \frac{\delta E_d}{\alpha f_{md} m} \quad (11)$$

From the ratio diagrams $\frac{\bar{q}}{b}$ and $\frac{l}{h}$ the following may be concluded:

1. If the ratio is $\frac{l}{h} \le \frac{\alpha}{\beta}\frac{f_{md}}{f_{vd}}$ - *short beams* – then the tangential stress is the required design value;
2. If the ratio is $\frac{\alpha}{\beta}\frac{f_{md}}{f_{vd}} < \frac{l}{h} < \frac{\delta E_d}{\alpha f_{md} m}$ –*medium beams* – the normal stress is the required design value;
3. If the ratio is $\frac{l}{h} \ge \frac{\gamma}{\alpha}\frac{E}{\sigma_{md}}\frac{1}{m}$ – *long beams* – the beam deflection is the required design value.

The equality sign in these expressions indicates the intersection points of curved lines.

By testing the beam material, it was found that the beam corresponds to the GL 28 class whose characteristics are displayed in the Table 1 in EN 1194, as well as the characteristic strength and stiffness in N/mm^2 and densities in kg/m^3 for homogenous glulam.

$$f_{m,g,k=28\frac{N}{mm^2}}$$

$$f_{v,g,k=3,2\frac{N}{mm^2}}$$

$$E_{0,g,mean} = 12600\frac{N}{mm^2}$$

For these values, the position of the point "A" can be determined

$$f_{m,d} = k_{\text{mod}}\frac{f_{m,k}}{\gamma_M}$$

Partial factors for a material property for glued laminated timber (Table 2.3 in EN 1995) is

$$\gamma_M = 1,25$$

k_{mod} is a modification factor taking into account the effect of the duration of load and moisture content

$$f_{m,d} = 0,9\frac{28}{1,25} = 20,16 N/mm^2$$

$$f_{v,d} = k_{\text{mod}} \frac{f_{v,k}}{\gamma_M}$$

$$f_{v,d} = 0,9 \frac{3,2}{1,25} = 2,304 N / mm^2$$

$$E_d = \frac{12600}{1,25} = 10080 \frac{N}{mm^2}$$

$$\frac{l}{h} = \frac{\alpha}{\beta} \frac{f_{m,d}}{f_{v,d}} = \frac{f_{m,d}}{f_{v,d}} = \frac{20,16}{2,304} = 8,75$$

and similarly, the position of the point „B".

$$\frac{l}{h} = \frac{\delta \gamma_F E_d}{\alpha f_{m,d} m} = \frac{3 \cdot 1,35 \cdot 384 \cdot 10080}{4 \cdot 60 \cdot 20,16 \cdot 200} = 16,20$$

In the zones, close to the points A, i.e. B in the diagram, Figure1, due to the reduction of the height $h = h_0 - \Delta h$, the changes of the required design value may occur. For example, $h = h_0 = 34cm$, $l / h = 7,75$ and $\overline{q} = \overline{q}_0 = ?$

$$\frac{\overline{q}}{bf_{m,d}} = \beta \frac{f_{v,d}}{f_{m,d}} \left(\frac{h}{l} \right) = \frac{4}{3} \frac{2,3}{20,16} \frac{1}{7,75} = 0,0196$$

$$\overline{q} = 0,0196 bf_{m,d} = 0,0196 \cdot 0,08 \cdot 20,16 \cdot 10^3 = 31,61 kN / m$$

$$q = \frac{\overline{q}}{\gamma_F} = \frac{31,61}{1,35} = 24,41 kN / m$$

For $\Delta h = 6,2cm$, $h = h_0 - \Delta h = 34 - 6,2 = 27,8cm$, $l / h = 9,5$ and $\overline{q} = \overline{q}_0 - \Delta q = ?$

$$\frac{\overline{q}}{bf_{m,d}} = \alpha \left(\frac{h_0 - \Delta h}{l} \right)^2 = \frac{4}{3} \left(\frac{1}{9,5} \right)^2 = 0,0148$$

$$\overline{q} = 0,0148 bf_{m,d} = 0,0148 \cdot 0,08 \cdot 20,16 \cdot 10^3 = 23,87 kN / m$$

$$q = \frac{\overline{q}}{\gamma_F} = \frac{23,87}{1,35} = 17,68 kN / m$$

$$\Delta q = 31,61 - 17,68 = 13,93 kN / m$$

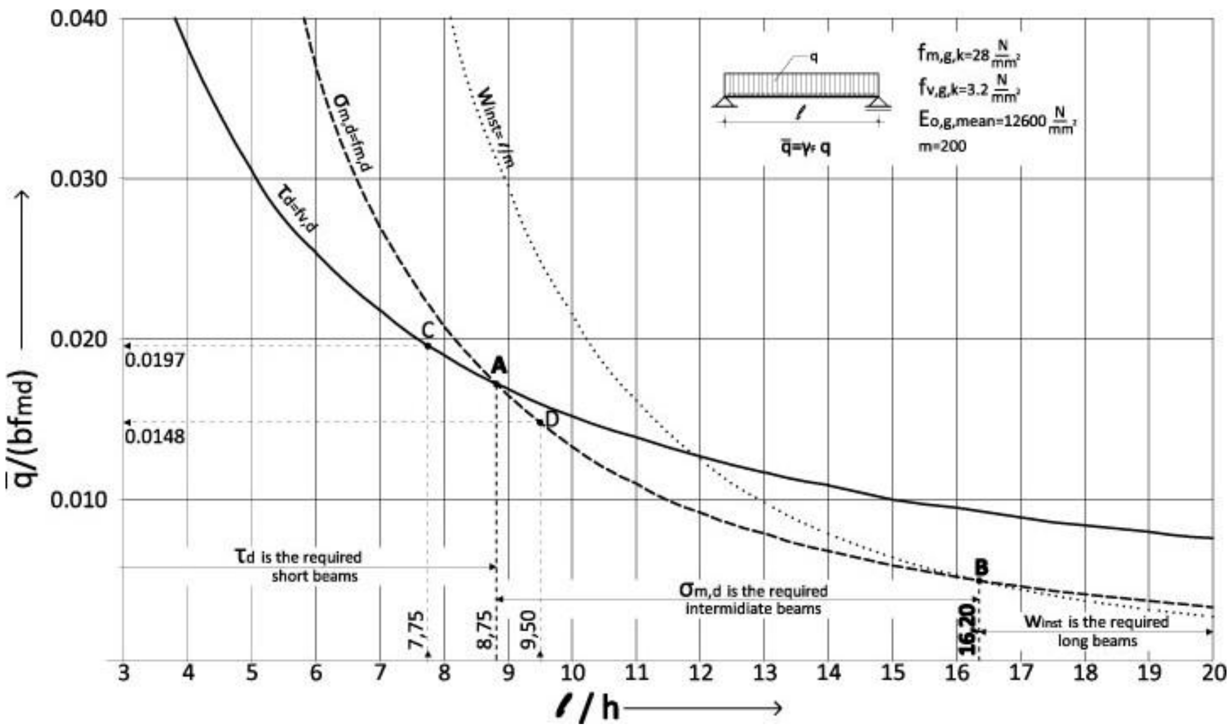


Figure 2. Bearing capacity of the beam

the tangential stress is the required design value, and after reduction of the height to h_0 – the normal stress is the required design value; In the area of the point B, the values of bearing capacity for l/h are displayed in the diagram

Structural Remediation Measures

The structural remediation measures were undertaken with the purpose of facilitating a better ventilation between the timber joists and beams thus prolonging the timber durability, and they include:

a) Separation of lateral sides of the main beam and longitudinal joists, so the spacing permits ventilation and fast drying up of the beams.

b) Separation of the upper surface of longitudinal joists and insertion of rubber spacers at the interface plane and mounting of waterproof membrane for the purpose of preventing bridge deck water penetration into support structure.

c) Construction and mounting of the upper lining lamina of oak wood .This lamina is wider than the main beam at it is planned to be replaced after a certain time. (Figure3)

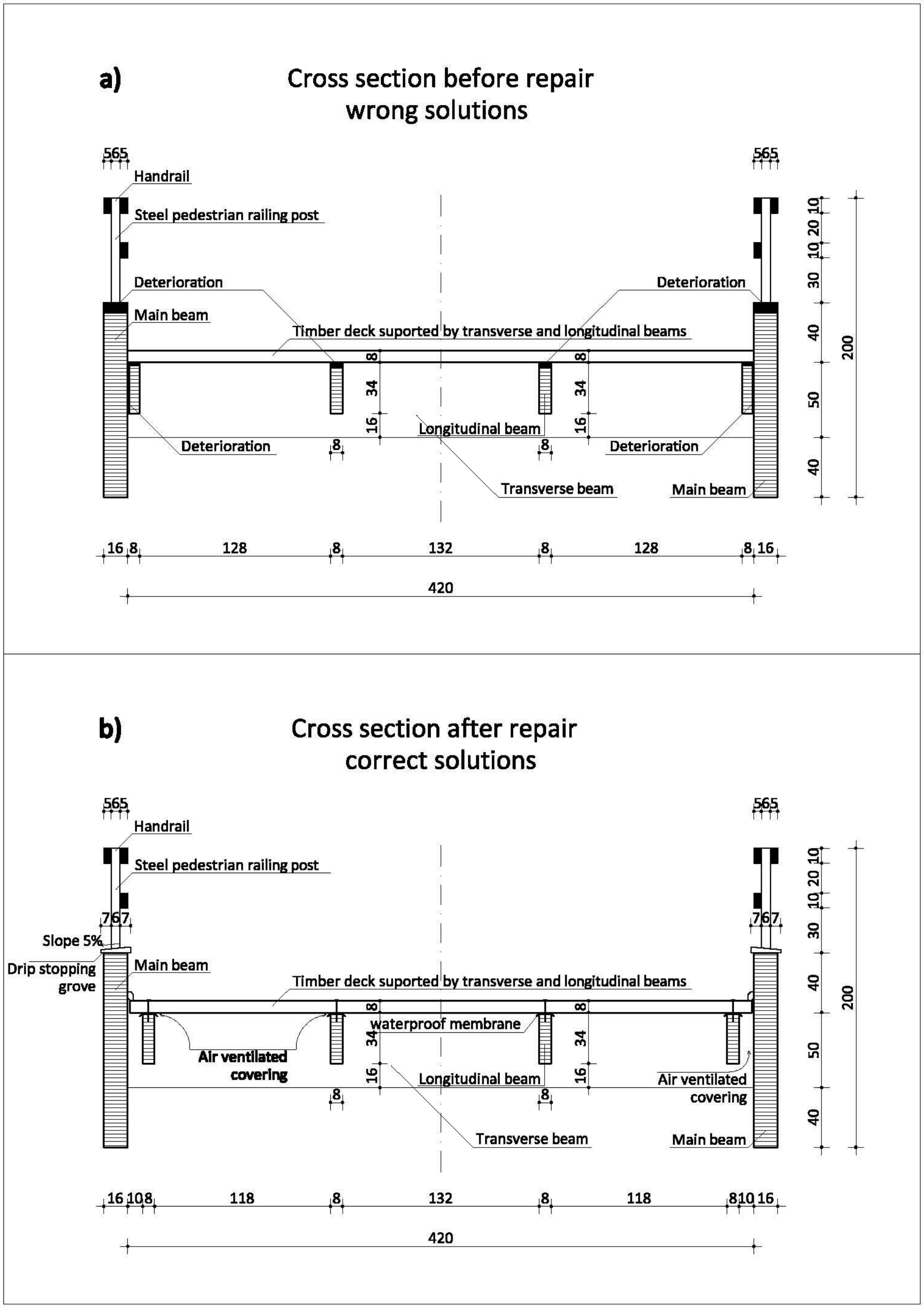


Figure 3. Cross section before and after repair of the beam

Conclusions

The contribution of the paper to the issue of deterioration processes in the observed timber beams which are exposed to (wetting) moisture is in

a) u identification of the damage and implementation of parameters determined in laboratory ,
b) in determination of theoretical calculation models, depending on the deterioration direction ,
c) in determination of practical algorithms for calculation and construction of the beam bearing capacity diagram,
d) in removal of deterioration causes by structural measures and
e) in universalizing of deterioration issue and potential of implementation of presented methods in practice, on any timber bridge.
f) The applied structural remediation measures have proven to be proper, so after 16 years of service, the timber does not exhibit any major damage indications.

The presented calculation procedures are very suitable for practical implementation, and the enclosed bearing capacity diagram is very suitable for quick identification of desired unknown parameters. If the mechanical characteristics of timber for some other bridge are different from those presented in this paper, it is necessary to construct a different bearing capacity diagram, with different mechanical characteristics of timber.

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