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# Durability and Mechanical Performance of Differently Treated Glulam Beams during Two Years of Outdoor Exposure

## Trajnost i mehanička svojstva različito obrađenih lameliranih nosača tijekom dvije godina izlaganja u eksterijeru

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**ABSTRACT** • The performance of the composites is influenced by the service life of input raw wood material and used adhesives. The aim of the study was to assess the durability and mechanical performance of glulam beams treated in a different way (thermally modified and/or treated with copper-based wood preservative) and exposed in an outdoor application. Glulam beams (83 mm × 68 mm × 1100 mm), made of three layers of Norway spruce (*Picea abies*) with PUR adhesives used have been exposed in use class 3.2 in a horizontal position since 4<sup>th</sup> November 2016. Part of the specimens was equipped with MC sensors. Every year, the degradation was evaluated visually. The dynamic modulus of elasticity was determined by longitudinal vibration, and the static modulus of elasticity using a 4-point bending test. On the smaller specimens, cut from glulams, compressive strength, delamination, and shear strength of adhesive bonds were determined. After two years of exposure, the results indicate that the performance of glulams is determined by the wood modification and applied wood preservative.

**Keywords:** degradation; glulam; mechanical testing; performance; service life; wood

**SAŽETAK** • Na svojstva kompozita utječu trajnost sirovine i svojstva primijenjenih ljepila. Cilj ovog istraživanja bio je procijeniti trajnost i mehanička svojstva različito obrađenih lameliranih nosača (toplinski modificiranih i/ili impregniranih bakrom) izloženih u eksterijeru. Lamelirani nosači (83 mm × 68 mm × 1100 mm) izrađeni su od tri sloja smrekovine (*Picea abies*) koji su slijepljeni PUR ljepilom. Nosači su prema klasi uporabe 3.2 izloženi u vodoravnom položaju od 4. studenoga 2016. u trajanju od dvije godine. Na dio uzoraka postavljeni su senzori za mjerenje sadržaja vode u njima. Svake je godine vizualno ocjenjivano propadanje uzoraka. Dinamički modul elastičnosti određen je longitudinalnom vibracijom, a statički modul elastičnosti savijanjem u četiri točke. Na manjim uzorcima ispitivanjima od nosača određena je tlačna čvrstoća, delaminacija i čvrstoća lijepljenog spoja na smicanje. Nakon dvije godine rezultati izlaganja pokazali su da svojstva lameliranih nosača ovise o toplinskoj modifikaciji drva i sredstvu za impregniranje.

**Ključne riječi:** razgradnja; glulam; mehanička ispitivanja; svojstva; vijek trajanja; drvo

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## 1 INTRODUCTION

### 1. UVOD

Wood is one of the earliest construction materials, and the structural use of wood and wood-based composites continues to steadily increase. In fact, new wood-based materials continue to be developed and successfully introduced into the engineering and construction marketplace. The primary driving force behind the increased use of wood-based composites is the ever-increasing need to provide economical housing. Supporting this demand, however, has been an evolution of our understanding of wood as a structural material and our ability to analyse and design safe and functionally efficient wood and wood-based composites (Kržišnik *et al.*, 2018). Modern building and construction practice would not be possible without the use of wood composites. They have the potential to replace other construction materials, such as steel, in many building applications (Ansell, 2015). Wood composites include a range of derivative wood products, which are produced by binding the fibres, strands, particles, veneers or boards of wood with adhesives, or other methods of fixation. All of these components form composite materials. This approach enables the use of wood of lower quality for the production of materials with engineered properties for specific, target applications. At the beginning, composites were predominately used in indoor applications, however, nowadays they are more and more frequently used in outdoor applications, as well (Ansell, 2015). Some of the composites, like glulams, are used in rather exposed conditions, like bridges (Niklewski *et al.*, 2018). Wood, as well as wood composites in outdoor applications, are exposed to biological degradation and weathering (Humar *et al.*, 2019). The positive aspect of biological decomposability of waste wood can turn into the opposite when the wood is used in moist conditions and exposed to various discolouring and degrading organisms (Despot, 1998). Protective measures are therefore unavoidable for many outdoor applications where wood is exposed to a condensing environment, to the weather or is in contact with the ground (Preston, 2000). In order to increase the potential of wood composites, their performance in outdoor applications has to be determined.

The service life of wooden objects and building components is one of the most important data, which enables the safe and environmentally acceptable selection of the materials. Service life is defined as the time during which a particular wooden structure or component will perform its task (Isaksson and Thelandersson, 2013). The technical service life of the wood is predominately affected by wood-decaying fungi (brown and white rot fungi) in outdoor applications (van den Bulcke *et al.*, 2011). In addition to a material-inherent durability, the moisture conditions and temperature are the most important factors influencing the ability of fungi to degrade wood (Brischke *et al.*, 2008). These two factors are influenced by the design of the construction, exposure conditions and local climatic conditions that can be referred to as microclimate. If mois-

ture content (*MC*) and temperature (*T*) are monitored, the severity of a particular location can be evaluated (Welzbacher *et al.*, 2009). Based on the location conditions, additional protection can be applied with design or other measures if necessary (Kutnik *et al.*, 2014).

Usually, composites are manufactured from the wood used to manufacture lumber. Therefore, some properties of the composites reflect the properties of the source material. Hence, composites are, similarly as most of the European wood species, prone to degradation that can be caused by various abiotic and biotic factors (CEN, 2013). The service life of the composites is influenced by the service life of wood and adhesives, therefore both parameters need to be considered. Studies about the long term performance of wood composites in outdoor applications are rather rare. Therefore, we believe that this kind of study is necessary as they will enable safer constructions. The aim of the present study was to elucidate the overall performance of the composites exposed to outdoor conditions, namely to determine the development of decay, do determine the changes of the glue-line after weathering and to assess the moisture performance of glulam.

## 2 MATERIALS AND METHODS

### 2. MATERIJALI I METODE

The running experiment started on 4<sup>th</sup> November 2016 and is based on the model glulam beams (83 mm × 68 mm × 1100 mm), exposed in use class 3.2 conditions, 500 mm above ground in a horizontal position on the test field of the University of Ljubljana, Biotechnical faculty (Figure 1) (46°02'55.7" N 14°28'47.3" E, elevation above sea level 293 m). The average temperature in Ljubljana is 10.4 °C, the annual precipitation is 1290 mm and the Scheffer Climate Index is 55.3 (Scheffer, 1971). The hazard potential of different climates was estimated by empirically determined decay intensity. Scheffer focused on the parameters temperature and distribution on rainfall as follows in Eq. 1:

$$Climate\ index = \frac{\sum_{Jan}^{Dec} [(T - 35)(D - 3)]}{30} \quad (1)$$

Where *T* is the mean day temperature of the month (°F), and *D* is the mean number of days with more than 0.001 inch of rain per month (-).

Three-layer glulam beams (Table 1) were made of Norway spruce (*Picea abies*), and thermally modified spruce according to Silvapro® process (Silvaproduct, Slovenia). A Polyurethane (PUR) adhesive was used. Thickness of lamella was between 24 mm and 22 mm. Outer lamellas were thinner than inner ones, as the beams were planed to the final dimension before the exposure. Final dimensions of the beams were comparable. One set of specimens was shell treated with a copper-ethanolamine based (CuEA) wood preservative (Silvanolin®) (Silvaproduct, Slovenia). Beams were immersed into copper-based preservative solution for 24 h. We did not want to use vacuum-pressure regime, as this might affect the quality of the glue-line. As a control, untreated solid Norway spruce sam-



**Figure 1** Glulams at the beginning of the experiment on the test field of the University of Ljubljana, Biotechnical faculty  
**Slika 1.** Lamelirani nosači na početku izlaganja na izlagalištu Biotehničkog fakulteta Sveučilišta u Ljubljani

**Table 1** List of presented Norway spruce glulam materials (1-4) and control solid Norway spruce sample (5). Silvanolin® is copper-based wood preservative and Silvapro® is process of thermal modification.

**Tablica 1.** Popis materijala za nosače od smrekovine (1 – 4) i kontrolni uzorak smrekovine (5); Silvanolin® je drvo impregnirano bakrom, a Silvapro® je proces toplinske modifikacije

Number <i>Broj</i>	Treatment <i>Postupak</i>	Adhesive <i>Ljepilo</i>
1	-	1K-PUR Type I
2	Silvanolin®	1K-PUR Type I
3	Silvapro®	1K-PUR Type I
4	Silvapro® and Silvacera®	1K-PUR Type I
5	-	-

ple with the same cross-section was used with the purpose of determining the influence of the glue lines as a water barrier in glulam beams.

Part of the specimens is equipped with moisture content sensors as shown in Figure 2. For moisture content (MC) measurements, resistance sensors were applied at 32 positions and linked to a signal amplifier (Gigamodule, Scantronik) that enabled wood MC measurements between 6 % and 60 %. Sensors were positioned in every lamella of three-layered glulam beams. In the top lamella, sensors were positioned approximately 10 mm below surface to avoid surface water-related phenomena. Similarly, in the two lower ones, approximately 10 mm from the glue line, the



**Figure 2** Distribution of moisture content sensors in each layer of tested samples  
**Slika 2.** Raspored senzora za mjerenje sadržaja vode u svakom sloju ispitivanih uzoraka

electrical resistance of the wood was measured every twelve hours and these data were used for calculating the wood MC. Resistance characteristics for each material were determined as reported by (Brischke and Lampen, 2014) using the methodology described by (CEN, 2015).

Selected beams were sampled annually. Three beams per treatment were selected and analysed. The degradation was evaluated visually according to the methodology suggested by Rapp and Augusta (2004) using the grading system according to EN 252 (CEN, 2015) to assess the extent of the decay. For bigger sized specimens, the rating scheme was adapted to the respective dimensions.

In addition, the dynamic modulus of elasticity ( $E_f$ ) was determined by longitudinal and transversal non-destructive testing techniques, and the static modulus of elasticity ( $E_s$ ) with a 4-point bending using a Zwick Roell Z100 testing machine (CEN, 2010). According to the cutting scheme (Figure 4), glulams were cut to smaller pieces, and decay on the cross-sections was determined. On the smaller specimens' compressive strength (CEN, 2013), total delamination according to method B (CEN, 2013), and shear strength (CEN, 2013) of the glue lines were determined.

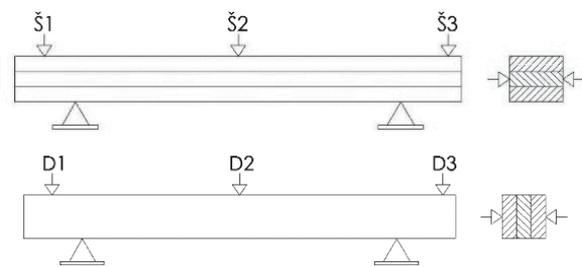
Non-destructive methods for testing wood are usually based on determining the speed of sound and damping sound oscillation. With the acoustic method, we can determine the mechanical properties and some anomalies of the wood (Bucur, 2006). The dynamic modulus of elasticity of the glulam specimens was determined from the frequency response of free-lying specimen vibration. The supports were placed at 0.224 lengths from each end of glulam specimens (Figure 3). With microphone (PCB-130D20) and the measuring

card (NI-9234), we determined the frequency response to transverse and longitudinal excitation of each glulam sample in the first vibration mode. In LabView 8.1 we determined, according to Bernoulli theory, the modulus of elasticity from the frequency response (Eq. 2) (Gorišek *et al.*, 2014).

$$E_f = \frac{4 \cdot \pi^2 \cdot L^4 \cdot \rho \cdot f_n^2 \cdot A}{I \cdot k_n^4} \quad (2)$$

Where,  $E_f$  – modulus of elasticity determined by the frequency response (GPa),  $L$  – length of specimen (m),  $\rho$  – density of specimen ( $\text{kg/m}^3$ ),  $f_n$  – natural frequency of specimen in the first vibration mode ( $\text{s}^{-1}$ ),  $A$  – area of cross section ( $\text{m}^2$ ),  $I$  – moment of inertia ( $\text{m}^4$ ) and  $k$  – Bernoulli constant ( $k = 4.73$ ).

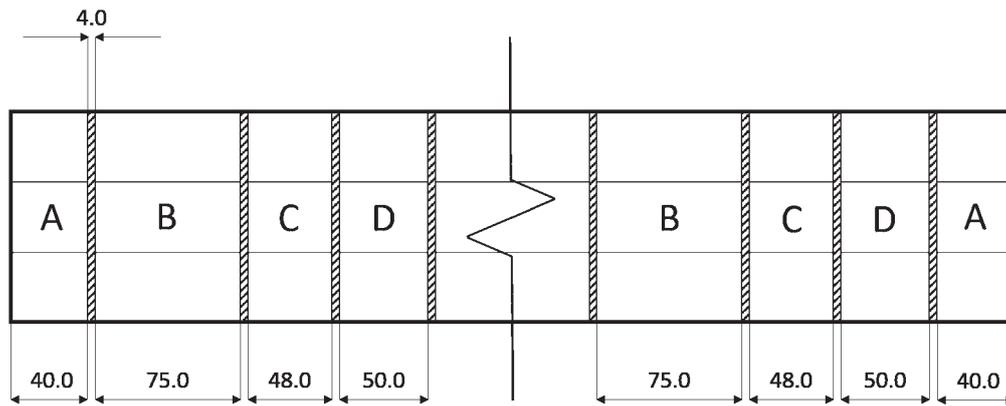
Acoustic determination of modulus of elasticity enabled the comparative evaluation of visual classification with results of acoustic measurements.



**Figure 3** Measuring the frequency response of glulams. Transverse vibration  $\parallel$  to the lamellas (top picture) and transverse vibration  $\perp$  to the lamellas (bottom picture). Š1-Š3 and D1-D2 mark the locations of measurements  
**Slika 3.** Mjerenje frekvencije odziva lameliranih nosača. Poprečna vibracija  $\parallel$  na lamele (gornja slika) i poprečna vibracija  $\perp$  na lamele (donja slika); Š1 – Š3 i D1 – D2 oznake su mjesta mjerenja

**Table 2** Grading system for decay according to EN 252 (CEN, 2015)  
**Tablica 2.** Ocjene propadanja prema EN 252 (CEN, 2015.)

Rating Ocjena	Description Opis	Definition / Definicija
0	Sound bez znakova propadanja	No evidence of decay. Any change of colour without softening has to be rated as 0. Nema dokaza propadanja. Svaka promjena boje bez omekšanja uzorka treba se ocijeniti kao 0.
1	Slight attack blago propadanje	Visible signs of decay, but of very limited intensity or distribution: - changes which only reveal themselves externally by very superficial degradation, softening of the wood being the most common symptom, to an apparent depth in the order of one millimetre. Vidljivi znakovi propadanja, ali vrlo ograničenog intenziteta ili distribucije: - promjene koje su vidljive samo na površini kao posljedica površinske razgradnje; najčešće je vidljivo omekšanje drva do dubine 1 mm.
2	Moderate attack umjerenom propadanje	Clear changes to a moderate extent according to apparent symptoms: changes reveal themselves by softening of the wood to a depth of approximately 1 to 3 millimetres over more than 1 cm <sup>2</sup> per stake. Jasne promjene umjerenog intenziteta: promjene koje su uzrokovane omekšanjem drva do dubine 1 – 3 mm na više od 1 cm <sup>2</sup> površine.
3	Severe attack izraženo propadanje	Severe attack: - marked decay in the wood to a depth of more than 3 millimetres over a wide surface (more than 20 cm <sup>2</sup> ) or by softening deeper than 10 mm over more than 1 cm <sup>2</sup> per stake. Izraženo propadanje: - značajno propadanje drva do dubine veće od 3 mm na znatnijoj površini (većoj od 20 cm <sup>2</sup> ) ili omekšanje površine dublje od 10 mm na više od 1 cm <sup>2</sup> površine.
4	Failure propali uzorak	Impact failure of the stake. Izraženo propadanje površine.



**Figure 4** Cutting scheme of three-layer glulams. A was cut off and saved, B sample was used for delamination test according to EN 14080, C samples were used for testing shear strength of glue lines, and D sample for compressive strength. The rest of glulams was stored. Prior to delamination test, mass and dimensions of B specimens in the oven-dried condition were determined and used in density ( $\rho_0$ ) calculation

**Slika 4.** Shema piljenja troslojnoga lameliranog nosača (uzorak A ispiljen je i sačuvan, uzorak B upotrijebljen je za ispitivanje delaminacije prema EN 14080, uzorak C rabljen je za ispitivanje čvrstoće lijepljenih spojeva na smicanje, uzorak D služio je za ispitivanje čvrstoće na tlak, a ostatak lameliranog nosača je spremljen; prije ispitivanja delaminacije određene su masa i dimenzije uzoraka B u apsolutno suhom stanju i te su vrijednosti iskorištene za izračun gustoće ( $\rho_0$ )).

The glulam samples were also tested on the 4-point bending test of the universal testing machine Zwick/Roel Z100. The distance between the lower supports of the specimen was 938 mm and between upper supports 335 mm. The test pieces were tested according to standard EN 408. The load was applied on the specimen at a displacement rate of 1 mm/min. The static modulus of elasticity ( $E_s$ ) was determined from the slope of the stress-strain curve in the range between 10 % and 40 % of maximum force (Eq. 3). Please replace Eq. 3 with the following one and with the text provided here.

$$E_{m,g} = \frac{3al^2 - 4a^3}{2bh^3 \left( 2 \frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh} \right)} \quad (3)$$

Where  $E_{m,g}$  is the global modulus of elasticity in bending ( $N/mm^2$ ),  $F_2 - F_1$  is an increment of load on the regression line with a correlation coefficient (N),  $w_2 - w_1$  is the increment of deformation corresponding to  $F_2 - F_1$  (mm),  $a$  is distance between a loading position and the nearest support (mm),  $l$  is span in bending (mm),  $b$  is the width of cross-section (mm),  $h$  is the depth of cross-section (mm), and  $G$  is shear modulus ( $N/mm^2$ ). Because unknown,  $G$  was taken as infinite.

### 3 RESULTS AND DISCUSSION

#### 3. REZULTATI I RASPRAVA

##### 3.1 Visual assessment of degradation

###### 3.1. Vizualna ocjena propadanja

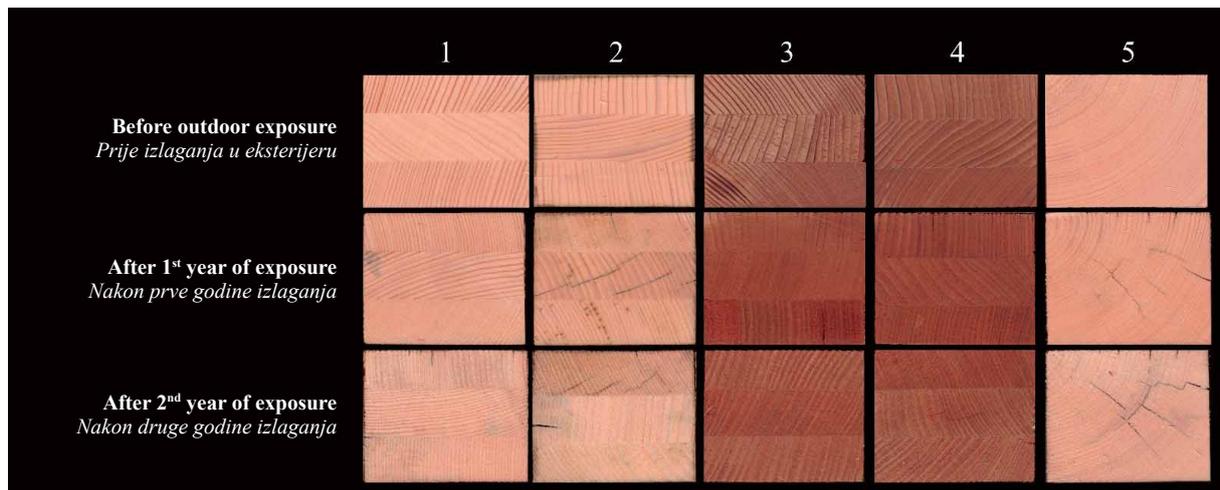
A visual assessment can provide many details, predominately information about cracking, blue staining and ongoing decay. It has to be considered that initial stages of decay are difficult to assess because there is no visible evidence of damage to the wood by incipient brown-rot decay shortly after brown-rot fungi initiate colonization and release enzymes (Clausen and Kartal, 2003). Besides, by definition, visual inspection is neither objective nor sure (Schmidt, 2006).

Figure 5 gives the crosscuts of samples. Scanned crosscuts before outdoor exposure are presented in the top row; the second and third row show images after one and two years of weathering in 3.2 use class. From the pictures in the second row, it can be observed that the samples in columns 1, 2, and 5 show some signs of discolouration due to the presence of blue-stain fungi on the surface and in the vicinity of cracks and crack formation in different layers of glulam beams. Thermally modified samples (columns 3 and 4) look intact. This observation indicates that the higher dimensional stability and durability of TMT is reflected in less cracked glulam. Higher dimensional stability of thermally modified wood can be ascribed to lower equilibrium moisture content (EMC) associated to the chemical modification of organic functional end-groups (Willems *et al.*, 2015), and additionally to the fungal durability (Altgen *et al.*, 2014). This is also in line with previous observations of the performance of thermally modified wood in outdoor applications (Esteves and Pereira, 2009; Humar *et al.*, 2015).

##### 3.2 Density

###### 3.2. Gustoća

The density and porosity of wood affect the moisture gain, which is proportional to the pore volume of wood: the pore volume, as well as the water capacity of decayed wood, is higher than that of undecayed, sound wood (Viitanen, 1997). Consequently, the same amount of water absorbed will cause larger gain in moisture content in a light specimen than in a heavy one. The density of the thermally modified ( $440.2 \text{ kg/m}^3$ ) wood was slightly lower than that of unmodified wood ( $469.4 \text{ kg/m}^3$ ). This is expectable, as wood mass is lost during the modification process. However, no mass loss was recorded in the material tested due to the outdoor exposure. Even if the exposed specimens did lose some of the mass, due to leaching of extractives, etc., this small reduction was hindered



**Figure 5** Crosscuts of glulam beams before outdoor exposure and after the first and the second year of outdoor exposure  
**Slika 5.** Presjeci lameliranih nosača prije izlaganja u eksterijeru i nakon prve i druge godine izlaganja na otvorenom prostoru

by the natural variability of the material investigated. However, it should be considered that incipient decay is hardly visible, and usually does not result in mass loss (Highley, 1999).

### 3.3 Bonding strength of glue lines

#### 3.3. Čvrstoća lijepljenog spoja

Performance requirements of glued laminated timber were evaluated according to EN 14080 (CEN, 2013). The bonding strength of glue lines can be either

evaluated by the delamination test or shear test. The shear strength of the glue lines depends on properties of the bulk adhesive, properties of the wood-adhesive interphase region, and properties of wood adherents. After one year of exposure, fungal degradation was not noted, yet. After the second year, first signs of decay appeared on some of the untreated spruce specimens. Samples were evaluated according to the modified EN 252 rating scheme. Untreated spruce wood samples were rated as 1, corresponding to a slight attack, which

**Table 3** Results of different performed tests and measurements before outdoor exposure and for each year of exposure in use class 3.2

**Tablica 3.** Rezultati testova i mjerenja provedenih prije izlaganja u eksterijeru i za svaku godinu izlaganja u klasi uporabe 3.2

No. Broj	Visual assessment of degradation <i>Vizualna ocjena propadanja</i>			Oven dry density, kg/m <sup>3</sup> <i>Gustoća u apsolutno suhom stanju, kg/m<sup>3</sup></i>			Delamination test Total delamination, % <i>Test delaminacije</i> Ukupna delaminacija, %			Shear test / <i>Smično ispitivanje</i> Shear strength, N/mm <sup>2</sup> / Wood failure, % <i>Čvrstoća na smicanje, N/mm<sup>2</sup> / Lom po drvu, %</i>					
	Year of outdoor exposure <i>Godina izlaganja u eksterijeru</i>			Year of outdoor exposure <i>Godina izlaganja u eksterijeru</i>			Year of outdoor exposure <i>Godina izlaganja u eksterijeru</i>			Year of outdoor exposure <i>Godina izlaganja u eksterijeru</i>					
	0	1	2	0	1	2	0	1	2	0		1		2	
1	/	0	1	450	457	465	0.0	1.6	9.5	7.9	100 %	8.7	84 %	6.1	100 %
2	/	0	0	461	448	475	0.4	1.0	1.0	8.8	94 %	7.1	97 %	9.3	98 %
3	/	0	0	464	433	429	0.0	5.8	7.3	9.1	97 %	7.5	93 %	8.0	99 %
4	/	0	0	454	424	437	0.0	0.0	2.3	7.3	99 %	7.7	86 %	9.6	96 %
5	/	0	1	506	493	477				8.5	100 %	8.0	100 %	9.2	100 %

No. Broj	Compressive strength, N/mm <sup>2</sup> <i>Čvrstoća na tlak, N/mm<sup>2</sup></i>			Static $E_s$ - 4-point bending test, GPa <i>Statički <math>E_s</math> - ispitivanje u 4 točke, GPa</i>			Dynamic $E_f$ - longitudinal vibration, GPa <i>Dinamički <math>E_f</math> - longitudinalna vibracija, GPa</i>			Dynamic $E_f$ - transverse vibration $\perp$ , GPa <i>Dinamički <math>E_f</math> - poprečna vibracija <math>\perp</math>, GPa</i>			Dynamic $E_f$ - transverse vibration $\parallel$ , GPa <i>Dinamički <math>E_f</math> - poprečna vibracija <math>\parallel</math>, GPa</i>		
	Year of outdoor exposure <i>Godina izlaganja u eksterijeru</i>			Year of outdoor exposure <i>Godina izlaganja u eksterijeru</i>			Year of outdoor exposure <i>Godina izlaganja u eksterijeru</i>			Year of outdoor exposure <i>Godina izlaganja u eksterijeru</i>			Year of outdoor exposure <i>Godina izlaganja u eksterijeru</i>		
	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
1	43.5	42.5	51.2	12.0	11.4	9.1	13.6	13.2	14.6	11.6	11.8	13.3	12.7	12.1	-
2	40.7	41.1	47.4	10.2	11.8	11.7	13.0	13.7	14.2	11.4	12.1	13.2	10.7	12.9	-
3	53.4	48.9	47.3	12.1	10.6	10.9	14.0	12.9	12.0	12.2	10.9	10.6	12.7	11.0	-
4	48.6	49.3	50.2	11.8	12.5	12.1	14.5	13.8	14.1	12.4	11.7	12.5	12.4	13.0	-
5	43.0	46.5	50.1	11.3	9.6	9.5	16.0	13.5	12.3	12.9	11.6	11.2	13.0	11.9	-

is of very limited intensity or distribution. Changes on the surface are indicated as superficial degradation, softening of the wood, to an apparent depth in the order of one millimetre. This is reflected in the loss of the analysed mechanical properties (Table 3).

The type of material, surface coating applied, and type of adhesive used affect the adsorption and desorption properties and moisture content of glulam beams. Predominately, crack development and potential delamination has a considerable effect on the moisture content of individual lamellas and the number of days when MC exceeds the fibre saturation point. According to the requirements of EN 14080 standard (CEN, 2013), the shear strength of the glue lines of all groups of beams is still adequate after two years of exposure. On the other hand, the total delamination of glue layers in glulams without the surface treatment is too high. A more pronounced strength loss of glue layers was only observed in glulams made of unmodified Norway spruce without surface coating (after two years of exposure, the shear strength was 6.1 N/mm<sup>2</sup>). For glulams without surface protection (both unmodified and thermally modified Norway spruce), an increased degree of delamination was noticed. For unmodified and modified glulams, the total delamination increased to 7.3 % and 9.5 %, respectively.

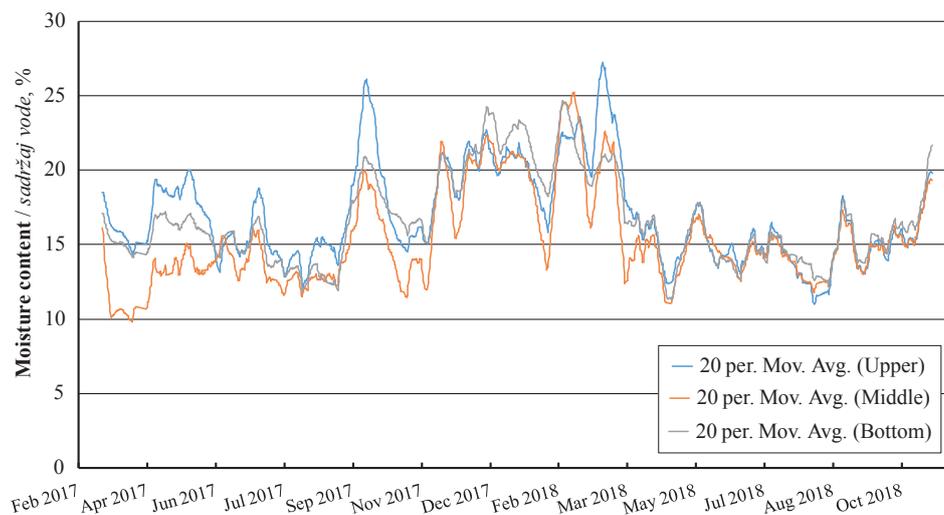
Table 3 gives indications of what happens with the overall performance of glulam. Past observations indicate that the bending test is in general a much better indicator than the compressive test (Humar and Thaler, 2017). From the respective data, it can be seen that the compressive strength remained rather constant through the exposure. Variation can be ascribed to natural variation of wood. On the other hand, much more prominent variation was noticed at 4-points static modulus of elasticity. A decrease in static modulus of elasticity was noticed in the untreated beam (material 5) and untreated spruce glulam (material 1). Static modulus of elasticity decreased from 12.0 GPa at the beginning to 11.4 GPa

after one year and 9.1 GPa after two years of exposure. This reduction of modulus of elasticity can be ascribed to incipient decay, and changes in the adhesive.

### 3.4 Monitoring of moisture content in glulams

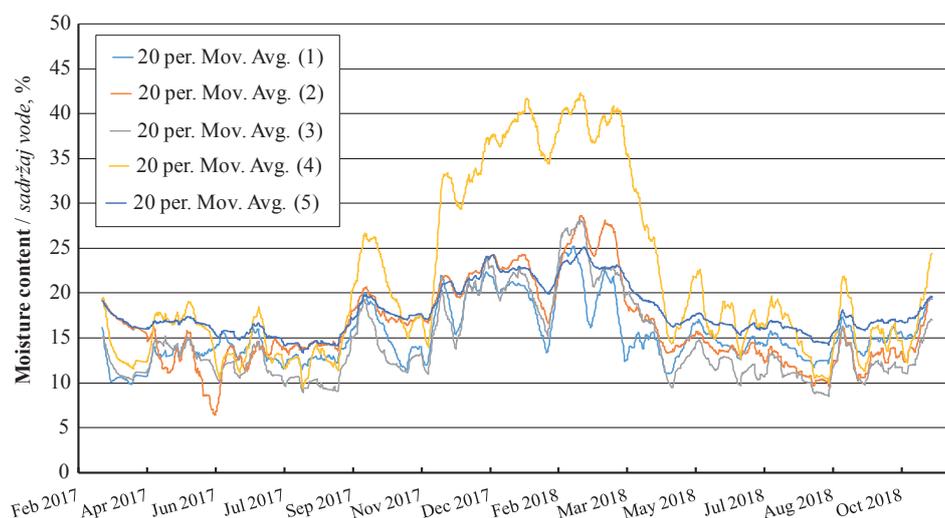
#### 3.4. Praćenje sadržaja vode u lameliranim nosačima

Products like glued laminated timber (glulam) and other structural composite lumber all have different moisture dynamics to solid timber (Jones and Brischke, 2017). The main reasons for this originate in the possible surface treatment and the presence of glue lines. Glue lines act like barriers that considerably slow down water flows through different layers. Additionally, high daily variations of moisture, at high levels of relative humidity, can cause large moisture gradient close to external surfaces with the development of so-called moisture-induced stress (MIS) and possible increase of crack risk, because the MIS perpendicular to grain may exceed the tensile and compressive strength also in the absence of external mechanical loads (Angst and Malo, 2012; Fragiacomio *et al.*, 2011). Figure 6 illustrates the moisture content variations for all three lamellas in the glulam made from Norway spruce. From the beginning of monitoring in February 2017 until approximately July 2018, the differences between the lamellas can be seen (e.g. the upper lamella had higher MC than the other two, middle and bottom one). After July 2018, MCs in all three lamellas become much more similar due to the occurrence of deep cracks throughout the cross-section of the glulam. As can be seen from the respective plot, differences are more prominent in the wet part of the year. During summer months, MCs of respective lamellas are more uniform. In general, the upper lamella has the highest MC, with the exception of the period when the snow covered the samples (Dec 2017 – Jan 2018). The slow melting of the snow resulted in a slow diffusion of water into the samples. Snow coverage prevented drying, so water accumulated in the interior of the glulam. A similar effect was ob-



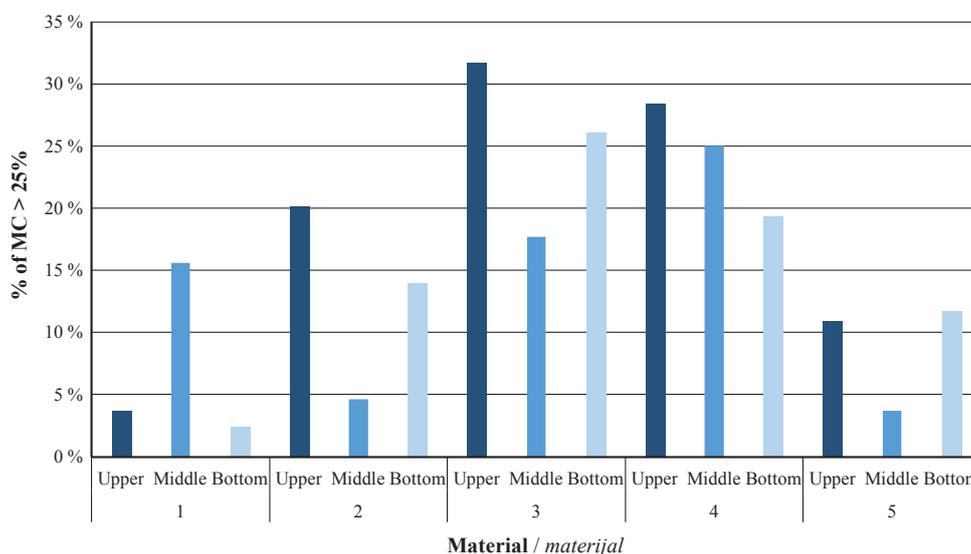
**Figure 6** Moisture content in three lamellas of Norway spruce glulam. The MCs of upper (blue line), middle (orange line), and bottom (grey line) lamella are displayed as twenty measurements moving average

**Slika 6.** Sadržaj vode u tri lamele lameliranog nosača od smrekovine; sadržaj vode gornje lamele (plava linija), srednje lamele (narančasta linija) i donje lamele (siva linija) prikazan je kao srednja vrijednost 20 mjerenja



**Figure 7** Moisture contents of middle lamellas of all five presented glulams. Measured MCs are presented using twenty measurements moving average values. In brackets are numbers of test materials

**Slika 7.** Sadržaj vode u srednjoj lameli svih pet lameliranih nosača (izmjereni sadržaj vode prezentiran je kao srednja vrijednost 20 mjerenja; u zagradama su brojevi ispitivanog materijala)



**Figure 8** Percentage of measurements ( $N = 1216$ ) when MC was equal or higher than 25 %. Results are presented for each lamella individually

**Slika 8.** Postotak mjerenja ( $N = 1216$ ) kada je sadržaj vode bio 25 % ili veći (prikazani su rezultati za svaku lamelu pojedinačno)

served in other glulams. Similarly, MCs of the five samples are plotted in Figure 7. The poor moisture performance of thermally modified spruce is well known and it has been already reported. Reduced moisture performance is associated with degraded pit membranes during thermal modification and micro-cracks formed on the surface acting as capillaries that take up water (van Acker *et al.*, 2015; Žlahtič and Humar, 2016). Variations in MC dynamics are higher in all the glulams compared to the massive timber presented with dark blue line. On average, the highest MC was measured in thermally modified and wax treated glulam, while the lowest MCs were measured in thermally modified glulam. Despite the variety in the nature of different modification techniques, efficacy in improving decay resistance has often been linked with reduced amounts of moisture in the wood (Hill, 2002; Ibach and Rowell, 2000; Thybring *et al.*, 2018). Fungal attack can occur

on wood, if the substrate can be metabolised by the fungi and if the substrate moisture content is above a certain threshold level. Figure 8 presents the percentage of measurements exceeding the threshold level of 25 % for all glulams in all three lamellas (Meyer and Brischke, 2015). Commonly, this threshold can be reached for 15 % of measurements in at least one lamella with the exception of solid Norway spruce timber. The respective graph indicates that there were two general patterns. At glulam made of untreated spruce, the highest MC content was determined at the middle lamella. The prime reason for this is the development of cracks on the upper lamella, which opens voids for water through the glue line. As thermally modified wood is considerably more resistant to cracking, there were no cracks formed through the glue line, hence water stayed in the upper lamella. A similar effect was also determined in copper treated lamellas (material 2).

## 4 CONCLUSIONS

### 4. ZAKLJUČAK

The preliminary test of the model glulam beams indicates that the performance of the respective material is determined by wood modification, adhesive used and surface coatings applied. In the first period of exposure, the adhesive line served as a barrier that limits the penetration of moisture to lower lamellas. Later on, deep cracks developed, opening voids for water penetration. No prominent degradation developed in the glulams after the first two years of exposure. Incipient decay developed on untreated spruce wood, only. Surface treatment reduced decay development, however it can be expected that decay will proceed after the first damages of the surface coating. Exposure of the glulams is reflected in the slight loss of the mechanical properties of adhesives. The test is about to continue to obtain more reliable results.

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