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An Assessment of Environmental Impact on Glued Wood Building Elements

Procjena utjecaja okolišnih uvjeta na lijepljene drvne elemente u graditeljstvu

ABSTRACT • *The research investigated the impact of environmental factors (temperature and humidity) on pine glulam, oak glulam, and laminated veneer lumber (LVL) elements, all of which can be used in building structures. Elements underwent freezing, heating, drying, and wetting processes in different modes, thereby simulating different environmental conditions that could be encountered during the service period of the materials. Their mechanical properties (modulus of elasticity - MOE and coefficient of damping) were recorded at each stage. It was determined that, in the case of dry construction elements (where a moisture content was between 7.0 and 14.0 %), the MOE increases by a few percentage points with decreasing temperature and humidity levels, and decreases with increasing temperature and humidity levels. The coefficient of damping varied by 20 % - in most cases, when the modulus of elasticity increased, this decreased, and vice versa. Under extreme environmental changes (with the elements being soaked, frozen at -25 °C, and dried at 40 °C), the MOE of the glued timber decreased by 16 % when this parameter of LVL decreased by about 10 %. Alterations in viscous properties produced similar results (the coefficient of damping increased by 50 % for the glued timber and by 66 % for the LVL). This is explained by the partial destruction of the element structure, the occurrence of cracks, and the decreased anisotropy of the LVL structure.*

Keywords: glued wood (glulam); laminated veneer lumber; modulus of elasticity; coefficient of damping; wood defects

SAŽETAK • *U radu je istraživan utjecaj okolišnih čimbenika (temperature i vlage) na elemente lameliranih nosača izrađenih od borovine i hrastovine te na elemente lamelirane furnirske građe (LVL), koji se često rabe u graditeljstvu. Elementi su bili na različite načine podvrgnuti smrzavanju, zagrijavanju, sušenju i vlaženju kako bi se simulirali različiti okolišni uvjeti koji bi se mogli pojaviti tijekom uporabe tih materijala. U svakoj su fazi ispitivanja bilježena mehanička svojstva promatranih drvnih elemenata (modul elastičnosti – MOE i koeficijent prigušenja). Utvrđeno je da se u suhih građevinskih elemenata (sadržaj vode između 7,0 i 14,0 %) s padom temperature i vlage MOE povećava za nekoliko postotnih bodova, a smanjuje se s porastom temperature i vlage. Koeficijent prigušenja u većini je ispitivanja varirao za 20 %: kako se modul elastičnosti povećavao, koeficijent prigušenja se smanjivao, i obrnuto. Pri ekstremnim promjenama okolišnih uvjeta (potapanjem elemenata, smrzavanjem na –25 °C i sušenjem na 40 °C) MOE lameliranih nosača se smanjio za 16 %, a LVL-a za oko 10 %. Glede promjena viskoelastičnih svojstava, zabilježeni su slični rezultati (koeficijent prigušenja lameliranih nosača povećao se za 50 %, a LVL-a za 66 %). To se objašnjava djelomičnom razgradnjom strukture drvnih elemenata, pojavom pukotina i smanjenom anizotropijom strukture LVL-a.*

Ključne riječi: lamelirani drvni nosači; lamelirana furnirska građa; modul elastičnosti; koeficijent prigušenja; greške drva

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1 INTRODUCTION
1. UVOD

Timber and timber elements are widely used in building structures (Rindler *et al*., 2018; Sanscartier Pilon *et al*., 2019; Žlahtič-Zupanc *et al*., 2018; Risse *et al*., 2019; Subhani *et al*., 2017; Gilbert *et al*., 2017; Markström *et al*., 2018; Hildebrandt *et al*., 2017; Musselman *et al*., 2018). The production of various timber articles (laminated timber) has a purpose both in economic and ecological terms. In order to reduce emissions it is appropriate to use timber materials instead of concrete and steel structures. The demand for these materials is projected to continuously increase (Risse *et al*., 2019, Hildebrandt *et al*., 2017). The construction of buildings with more than two floors is one of the latest trends in which more timber products could be used (Markström *et al*., 2018).

Constructions that are made using glued timber materials, such as laminated veneer lumber (LVL) and cross laminated timber (CLT), can be used to reinforce concrete and steel structures and ensure better protection levels against earthquakes (Sanscartier Pilon *et al*., 2019).

More lately, identifying, improving, and forecasting the properties of timber structures has become a topical subject. It is already known that, in most cases, timber becomes wet or dry when in service under the changing ambient temperature and humidity levels. Alterations in timber moisture content may result in alterations in terms of dimensions and shape of timber materials, or the occurrence of various defects and changes in mechanical properties (Wood Handbook, 2010). It has already been established that an increase in temperature from -30 °C to +30 °C will decrease the *MOE* in timber materials (Ayrilmis *et al*., 2010).

The impact of different factors on alterations in the moisture content of timber materials under ambient conditions was also something that has previously been investigated. The absorption properties of timber materials can be altered by applying thermal modifications, along with wax, oil, and biocide treatments (Žlahtič-Zupanc *et al*., 2018). It has been determined that the moisture content of glued timber materials - which changes under the influence of the ambient temperature - also alters its mechanical properties. In addition, the change in these properties also depends on the glue that has been used (Rindler *et al*., 2018). The mechanical properties of one of the most commonly used construction materials - LVL - can be improved by using other materials, such as polymeric options (Subhani *et al*., 2017). Thanks to the digital model developed, it is possible to predict the LVL mechanical properties in various directions and to produce beams of the desired mechanical properties (Gilbert *et al*., 2017). Building structures often require holes to be made in the materials. It has been determined that both the diameter of those holes and, especially, their location affect the strength properties and durability of LVL beams (Musselman *et al*., 2018).

The aim of the study is to evaluate the impact of environment factors on the mechanical properties of glulam beams in both oak and pine, as well as LVL beams.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The research study used glued oak and pine glulam beams (each glued segment consisting of five planks) and LVL beams (the thickness of the layer was about 3 mm) with the dimensions of 1200 mm × 75 mm ×100 mm, a humidity level was between 10.5-14.0 %, and the density was accordingly within the limits of 740-780 kg/m³, 520-550 kg/m³, and 590-670 kg/m³, respectively. The glulam beams were glued by using water-resistant polyurethane glues, and the LVL specimens were glued by using formaldehyde-based glues. There were 10 beams of each type. A schematic for specimen cross-sections is provided in Figure 1.

In order to simulate changes in environmental parameters, the climatic conditions were modelled in the climatic chamber (the appropriate air temperature and relative humidity are determined in the chamber, all samples are stacked in chamber and the change in their mechanical properties is recorded every 7 days). In the chamber, the temperature was maintained within an accuracy level of 1 °C, and the relative humidity level was maintained within an accuracy level of 2 %. The length of the specimens was measured using a tape measure within an accuracy of 1 mm, while the width and thickness were measured using sliding callipers within an accuracy of 0.05 mm, and the mass was measured using a balance within an accuracy of 0.1 g. The moisture content for the specimens was measured with an electric resistance moisture meter.

4 cycles were simulated: "cold" - samples frozen in air at -25 °C, "dry" - samples kept at 40 °C at 40 % relative humidity, "wet" - samples irrigated at 20 °C at 85 % humidity and "extreme" - the samples were soaked in water at 20 °C, frozen in air at -25 °C and dried at 40 °C and 40 % relative humidity.

Before carrying out the research study, all specimens were conditioned in a climatic chamber for a total of fourteen days at 20 °C and with a relative air
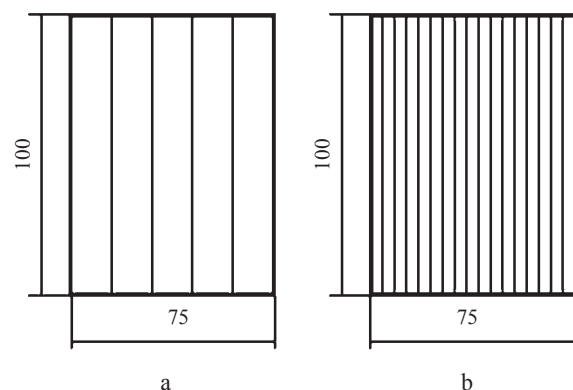
Figure 1 A schematic of specimen cross-sections: a) oak and pine glulam beams; b) LVL beams
Slika 1. Shema poprečnog presjeka uzoraka: a) lamelirani nosači od hrastovine i borovine; b) nosači od lamelirane furnirske građe
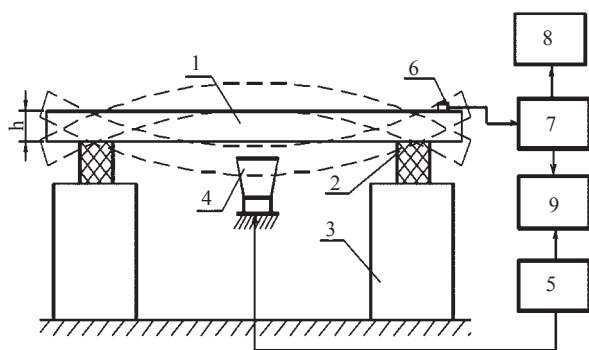
Figure 2 Scheme of the test stand:1 - specimen; 2 - vibration damping material (foam rubber); 3 - massive supports; 4 - loudspeaker; 5 - vibration generator; 6 - sensor; 7 - measuring instrument; 8 - oscilloscope; 9 - phase meter
Slika 2. Shema ispitnog postolja: 1 – uzorak; 2 – materijal za prigušivanje vibracija (spužvasta guma); 3 – masivni nosači; 4 – zvučnik; 5 – generator vibracija; 6 – senzor; 7 – mjerni uređaj; 8 – osciloskop; 9 – mjerač faze

humidity of 60 %. After completing the conditioning process, the moisture content of the specimens was measured at between 11.0-12.5 %.

The special test stand (Figure 2) was used to determine the *MOE* and the coefficient of damping on the basis of the non-destructive testing (transverse resonant vibrations) method, which also allowed assessing the mechanical properties of the specimens (Albrektas and Vobolis, 2003; Albrektas and Vobolis, 2004; Timoshenko *et al.*, 1985). The studies were performed at a frequency of 20-2000 Hz.

The *MOE* was calculated based on the following Eq. 1 (Timoshenko *et al.*, 1985):

$$E = \frac{f_{\text{rez}}^2 \cdot 4 \cdot \pi^2 \cdot \rho \cdot s \cdot l^4}{I \cdot A^2} \qquad (1)$$

Where: *E*–modulus of elasticity, f_{rez} – frequency of transverse vibrations, ρ –density of wood, s – cross-sectional area, l – beam length, I – cross-sectional moment of inertia, A – method of fastening represented by a coefficient

The viscous properties of studied specimens were evaluated based on the following Eq. 2

$$tg\delta \approx \frac{\Delta f}{f_{\text{rez}}} \qquad (2)$$

Where: f_{rez}– frequency of transverse vibrations, Δf – frequency bandwidth when amplitude of vibrations decreases by 0.7 times.

The *MOE* and the coefficient of damping for each specimen were determined in two directions: with the glue joints on the specimens orientated as shown in Figure 1 and the specimen turned at an angle of 90°.

For example, the oak glulam beam that falls within code 'O1', should be coded 'O1.1' when placed on a test stand as shown in Figure 1, and 'O1.2' when turned at an angle of 90°. The average values for all ten oak timber beams are marked as 'OX.1' and 'OX.2', respectively. Meanwhile, the groups into which the pine glulam beams have been organised are marked as 'PX.1' and 'PX.2', respectively, and the LVL specimens are marked as 'LX.1' and 'LX.2', respectively.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The measurements for the *MOE* and the coefficient of damping for the specimens was carried out after completing the conditioning process. These values are displayed in Table 1.

It was estimated that the *MOE* of oak glulam beams altered within the limits of 11500-14200 MPa, and for pine glulam beams it was within the limits of 11000-13400 MPa, while the LVL altered within the limits of 12900-14900 MPa. The coefficient of damping for all specimens remained within the limits of 0.0085-0.0145 r.u. These values correspond to the values that are given in the available literature (Albrektas and Vobolis, 2003; Wagenführ, 2000; Wood Handbook, 2010; Albrektas *et al.*, 2019).

It should be noted that the *MOE* of the LVL specimens is slightly higher, although it corresponds to the *MOE* of natural wood. In addition, having carried out a statistical analysis of the *MOE* and coefficient of damping values for each group, it was found that the coefficient of variation for the *MOE* values in the LVL specimens was approximately 2 %, and the coefficient of variation of the coefficient of damping was approximately 5 %. These coefficients of variation for oak and pine specimens altered within the limits of 6-8 %.

In order to simulate the various operating conditions of their structures, the specimens underwent a freezing phase at -25 °C and were observed for changes in their mechanical properties. Variations in the *MOE* are displayed in Figure 3.

The results show that, during a freezing phase, the *MOE* increased for all specimens. The most significant increase was recorded after the first seven days. For the oak specimens the increase amounted to 1.5 %, for the pine specimens it was 4.9 %, and for the LVL specimens it was 5.5 %. After a period of 21 days, the *MOE* for the oak specimens increased by 3.1 %, for the pine specimens by 5.5 %, and for the LVL by 6.6 % in comparison to the original value. In all cases the increase in the *MOE* for group '1' is higher than that of

Table 1 Average values for *MOE* and coefficient of damping for specimens
Tablica 1. Srednje vrijednosti *MOE*-a i koeficijenta prigušenja za ispitivane uzorke

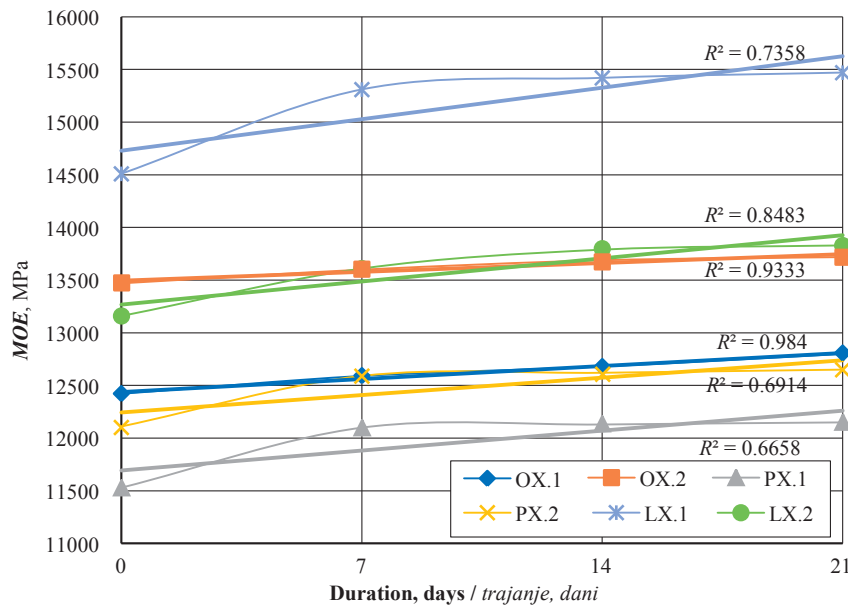| Group of specimens	Oak / Hrastovina		Pine / Borovina		LVL	
Grupa uzoraka	*MOE*, MPa	Coef. of damping, r.u. *Koeficijent prigušenja, r.u.*	*MOE*, MPa	Coef. of damping, r.u. *Koeficijent prigušenja, r.u.*	*MOE*, MPa	Coef. of damping, r.u. *Koeficijent prigušenja, r.u.*
X1	12420	0.0100	11530	0.0115	14510	0.0113
X2	13470	0.0121	12110	0.0110	13160	0.0118

Figure 3 Variations of *MOE* in specimens during a freezing phase
Slika 3. Varijacije *MOE*-a na uzorcima tijekom faze smrzavanja

group '2'. This can be explained by the fact that, just as with the timber, the glue becomes stiffer at lower temperatures and, with its existing orientation, the influence of glue on the entire composite is greater, although its *MOE* is significantly lower (Konnerth *et al*., 2006; Stoeckel *et al*., 2013). Similar results were obtained for other glued timber materials (Ayrilmis *et al*., 2010).

The viscous properties of the specimens also altered during the freezing phase. The variations in the coefficient of damping are shown in Figure 4.

It is clear that the coefficient of damping for all specimens tended to decrease during the freezing phase, i.e. the specimens lost plasticity. The most significant decrease was recorded after the first seven days. The most significant decrease in the coefficient of damping was observed in pine specimens (with an average decrease of 17.4 %), while the least significant decrease was observed in the LVL specimens (at an average of 7.1 %). During further freezing, the coefficient of damping decreased less. For pine specimens, it decreased by an average of 20.0 %, for oak specimens by an average of 16.5 %, and for the LVL specimens by an average of 10.6 %. Unlike the *MOE*, the coefficient of damping in oak and pine specimens was particularly unaffected by the orientation of the glue joint. For the LVL specimens alone, the average coefficient of damping of group '1' specimens decreased by 10.6 %, and by 5.1 % for the specimens in group '2'.

Afterwards, the specimens underwent a drying phase at 40 °C, at 40 % relative air humidity, and with about 1 m/s forced circulation. During the drying process, the mass of the specimens decreased by between
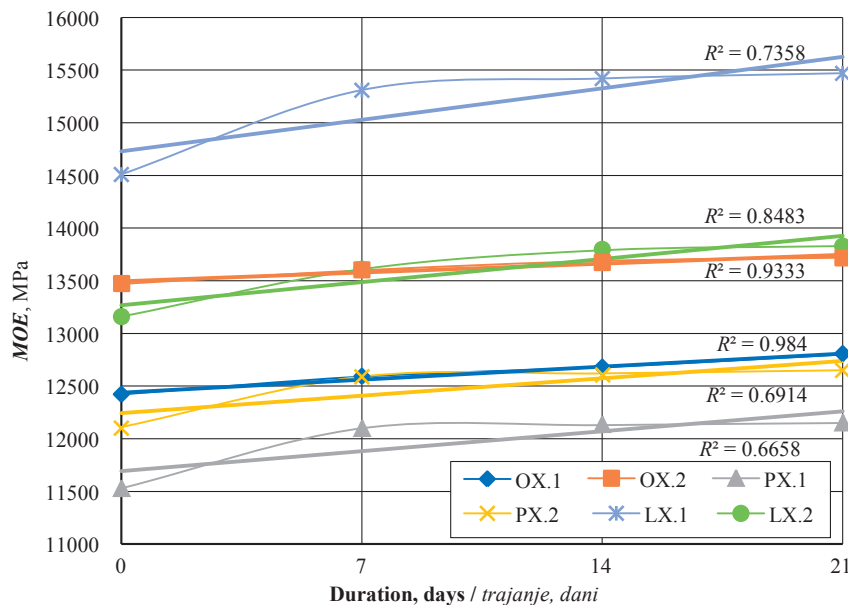

Figure 4 Variations in coefficient of damping for specimens during the freezing phase
Slika 4. Varijacije koeficijenta prigušenja na uzorcima tijekom faze smrzavanja
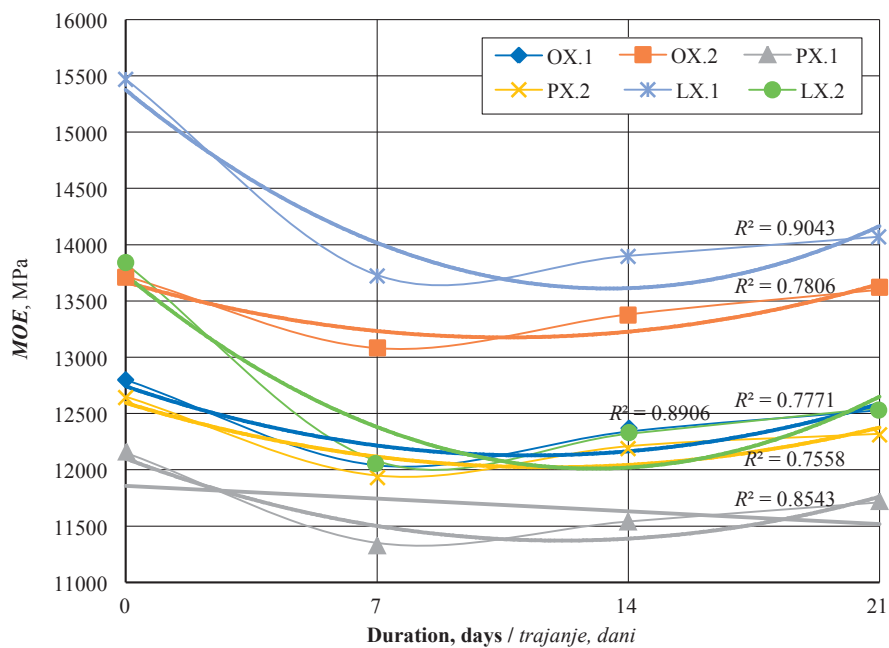
Figure 5 Variations in *MOE* for specimens during the drying phase
Slika 5. Varijacije *MOE*-a na uzorcima tijekom faze sušenja

54-98 g per week. The variations in the *MOE* for the specimens are shown in Figure 5.

It was established that, at the beginning of the drying phase (after the first seven days), the *MOE* for the specimens decreased (by 5.9 % for oak specimens, 6.6 % for pine specimens, and 12.7 % for LVL specimens). This could be explained by the fact that the moisture content decreased by an insignificant level during the first seven days (the specimen mass decreased on average by about 52 g and the average moisture content decreased by about 1.0-1.2 %); however, the timber warmed up and became more flexible. Later, during the drying process, the mass of the specimen decreased, and

the *MOE* increased at a similar rate. When compared to the *MOE* of the frozen specimens before drying, after a period of 21 days the average *MOE* for the oak specimens decreased by 2.1 %, for the pine specimens by 3.6 %, while the LVL specimens decreased by 9.3 %. In this case the orientation of the glue joint did not have any significant impact (the difference did not exceed 1 %).

The variation in the coefficient of damping during the drying process is shown in Figure 6.

The results show that, after the first seven days of drying, the coefficient of damping for all specimens increased (by 13 % for the pine and the LVL specimens, and by 9 % for the oak specimens); this was due to the
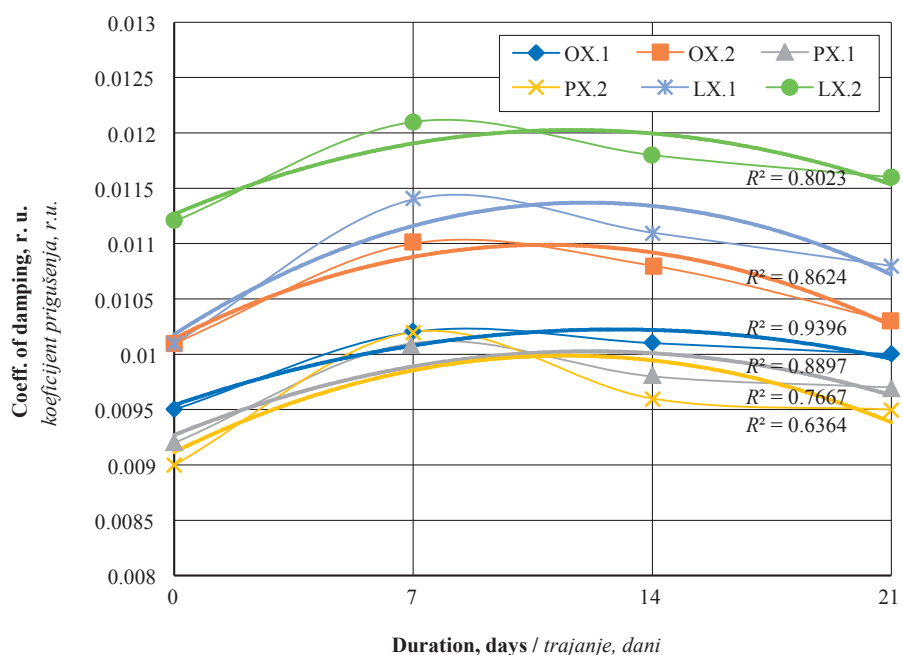

Figure 6 Variation in coefficient of damping for specimens during the drying process
Slika 6. Varijacije koeficijenta prigušenja na uzorcima tijekom faze sušenja
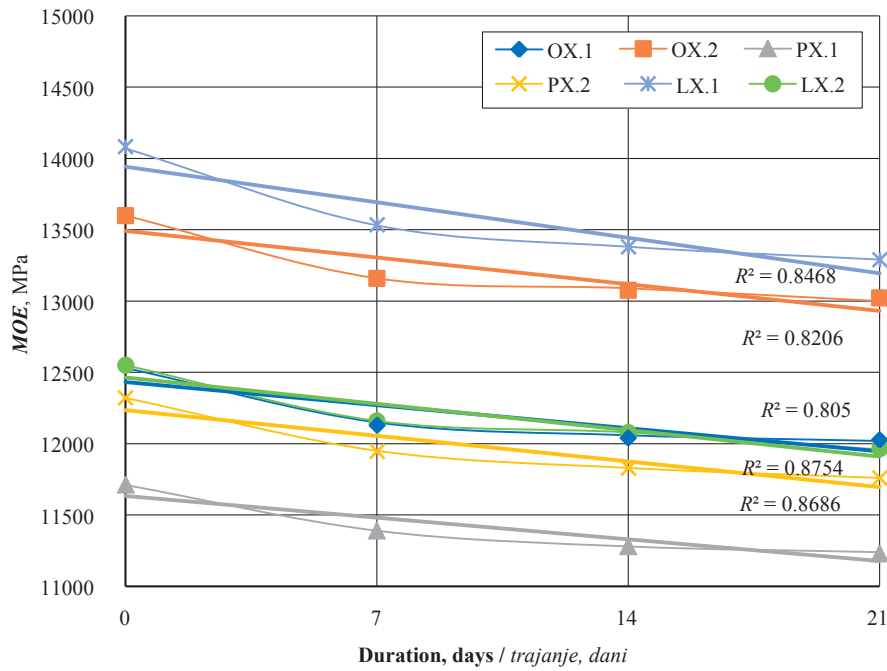
Figure 7 Variation in *MOE* of specimens during the wetting process
Slika 7. Varijacije *MOE*-a na uzorcima tijekom faze vlaženja

fact that the timber warmed up and became more flexible. During further drying, the coefficient of damping decreased by an insignificant amount. When compared to the primary coefficient of damping (after freezing), the coefficient of damping for all specimens, which were dried for 21 days, managed to increase by between 2.0-6.9 %.

The specimens were dampened in a climate chamber at 20 °C and at a relative air humidity of 85 %. The variation in the *MOE* during the wetting process is shown in Figure 7.

It was found that the *MOE* for all specimens decreased by an insignificant amount during the wetting process. The greatest decrease in the *MOE* was observed in the LX.1 specimen group (by an average of 3.8 % during the first seven days and by an average of 5.5 % during a period of 21 days). Variations for other groups of specimens were found to be 3.0 % and between 4.0-4.7 %, respectively. The differences are very small (the mass of the specimens pretty much increased in an identical manner); therefore it can be stated that the humid air had an equal effect on the elastic properties of all of the specimens. The variations in viscous properties (the coefficient of damping) are shown in Figure 8.

It was established that the coefficient of damping for the specimens increased during the wetting process.
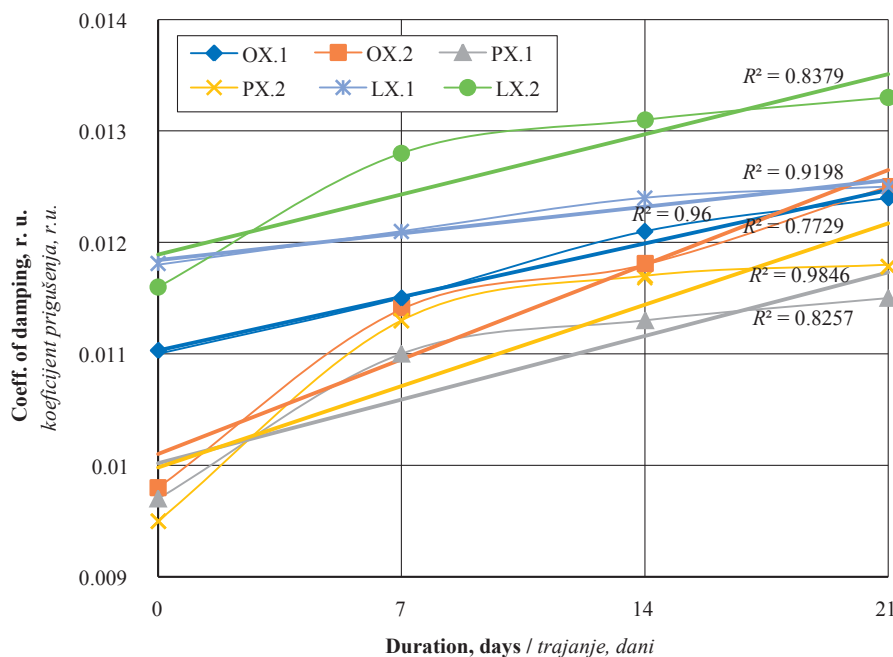

Figure 8 Variations in coefficient of damping for specimens during the wetting process
Slika 8. Varijacije koeficijenta prigušenja na uzorcima tijekom faze vlaženja

The highest growth levels were observed during the first seven days (for all groups of specimens the coefficient of damping increased by between 10-19 %). The lowest growth in coefficient of damping after 21 days was observed for the LVL specimens (14.7 % and 15.7 %, respectively, for individual groups). The average growth of the coefficient of damping in the oak specimens was at 21.4 % and 24.0 %, respectively, whereas the coefficient of damping for the pine specimens was at 18.6 % and 24.2 %. It is likely that the slightly different behaviour of the LVL specimens was prompted by the relatively large number of glue joints, which ensured a more uniform structure in the entire specimen.

The specimens were then immersed in water at a temperature of 20 °C and were then stored for a period of fourteen days; then they were removed from the water and stored at -25 °C for fourteen days; subsequently they were dried at 40 °C for fourteen days with a relative air humidity of 40 % and forced air circulation. This was done in order to intentionally cause defects in the specimens.

Pictures of several specimens after the immersion/freezing/drying process are shown in Figure 9.

It is evident that the drastic environmental impact in most cases caused a serious level of damage to the glulam specimens tested. Clearly-visible cracks emerged when exposed to sources of tension. Visually significant defects were not observed in the LVL specimens. In most cases there were shallow cracks (single-layer thickness) that became visible on the face. Small peelings on the cross section were also observed.

Table 2 shows the values for the mechanical properties of the specimens following the conditioning process (initial) and after the immersion/freezing/drying process (final).

It was established that the extreme humidity and temperature fluctuations had a significant impact on the specimens. The results show that the cracks that appeared resulted in a decrease in the *MOE* of glulam beams by between 13-16 %, while for the LVL specimens this value was a little lower at around 10 %. However, the coefficient of damping for the specimens changed much more significantly. The uniform struc-
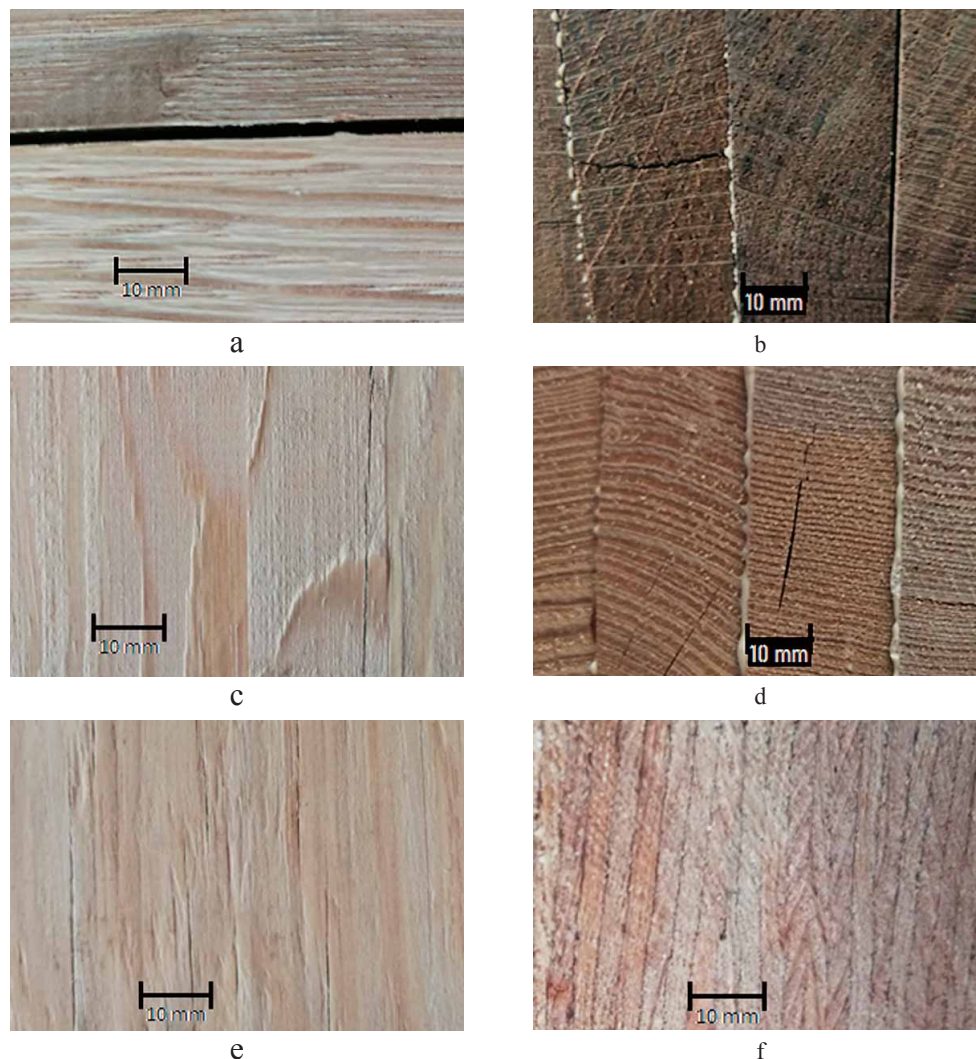
Figure 9 Examples of typical defects in specimens: a) face of oak specimen; b) cross section of oak specimen; c) face of pine specimen; d) cross section of pine specimen; e) face of LVL specimen; and f) cross section of LVL specimen
Slika 9. Primjeri tipičnih grešaka na uzorcima: a) lice uzorka hrastovine; b) poprečni presjek uzorka hrastovine; c) lice uzorka borovine; d) poprečni presjek uzorka borovine; e) lice LVL uzorka; f) poprečni presjek LVL uzorka

Table 2 Changes in mechanical properties after immersion/freezing/drying process
Tablica 2. Promjene mehaničkih svojstava nakon procesa potapanja, smrzavanja i sušenja

Group *Grupe*	*MOE*, MPa		Difference, MPa/% *Razlika, MPa/%*		Coefficient of damping, r.u. *Koeficijent prigušenja, r.u.*		Difference, r.u./% *Razlika, r.u./%*	
	Initial / *Početno*	Final / *Završno*			Initial /*Početno*	Final / *Završno*		
OX.1	12420	10510	1910	15.4	0.0110	0.0168	0.0058	52.7
OX.2	13470	11680	1790	13.3	0.0121	0.0179	0.0058	47.9
PX.1	11530	9980	1550	13.4	0.0115	0.0173	0.0058	50.4
PX.2	12110	10350	1760	14.5	0.0110	0.0167	0.0057	51.8
LX.1	14510	13030	1480	10.2	0.0113	0.0185	0.0072	63.7
LX.2	13160	11790	1370	10.4	0.0118	0.0196	0.0078	66.1

ture of the specimens was destroyed, causing the specimen that underwent vibration treatment to behave like a system involving several bodies rather than as a single body. The coefficient of damping for the natural timber specimens increased by about 50 % and the one for the LVL specimens increased even more.

All of the results were statistically processed. The coefficient of variation for the *MOE* and the coefficient of damping for different groups after each test cycle did not exceed 9.6 % (Pekarskas, 2007).

4 CONCLUSIONS
4. ZAKLJUČAK

It was established that, due to different mechanical properties of timber in different directions (perpendicular and parallel to the positioning directions of the joints), the same glulam beam had different mechanical properties. This difference for individual glulam beams was up to 4.8 %.

During freezing process, the dry glulam beams (at between 11.0-12.5 %) become more elastic. This is shown by the *MOE* which increased by 6.6 % and by the coefficient of damping which decreased by 20.0 %.

After starting the drying process in frozen specimens, during the first seven days their moisture content decreased by an insignificant amount (by 1.2 %). However, the timber warmed up and became more flexible. Therefore, during the period of seven days of drying, the *MOE* decreased by 12.7 %, whereas the coefficient of damping increased by 13.0 %.

As the moisture content of glulam beams decreases, its *MOE* increases and the coefficient of damping decreases (with a moisture content reduction of about 3 % the *MOE* increased by an average of between 2.8-3.2 %, whereas the coefficient of damping decreased by between 2.3-8.5 %).

During the process of wetting, glulam specimens in the air had a moisture content that increased by an average of between 3.0-4.0 %, while their *MOE* decreased by 5.5 %, and the coefficient of damping increased by 24.2 %. This is mainly due to the increase in surface humidity and plasticity.

Coefficient of damping for the LVL specimens increased the least only during the wetting process (on average by 15.7 %). It is likely that the slightly different behaviour of the LVL specimens was prompted by the relatively large number of glue joints, which ensured a more uniform structure in the entire specimen.

Freezing wet glulam specimens and their subsequent drying (which served to cause the defects) showed the lowest levels of deterioration in LVL elastic properties (by an average of 10.4 %); however, the viscous properties increased significantly (the coefficient of damping increased by 66.1 %).

In general it can be stated that the glulam beams and the LVL beams reacted similarly to changing environmental conditions.

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