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Impact of Wood Moisture Content on Structural Integrity of Wood Under Dynamic Loads

Utjecaj sadržaja vode u drvu na strukturnu cjelovitost drva pri dinamičkim opterećenjima

ORIGINAL SCIENTIFIC PAPER
Izvorni znanstveni rad
Received – prispjelo: 10. 10. 2022.
Accepted – prihvaćeno: 15. 3. 2023.
UDK: 630*82
https://doi.org/10.5552/drvind.2023.0067

ABSTRACT • *The majority of mechanical wood properties are negatively affected by wood moisture within the hygroscopic range, disregarding the stress relaxation of wood at very low moisture contents (MC). In contrast, the structural integrity and thus the brittleness of wood appears to be positively affected by moisture. This study aimed at examining the effect of wood MC on the structural integrity of wood between the oven-dry state and MC well above cell wall saturation (CWS), i.e., at approx. 100 %. For both softwood (Picea abies) and hardwoods (Fagus sylvatica and Quercus robur), the structural integrity was assessed on the basis of the Resistance to Impact Milling (RIM) originating from High-Energy Multiple Impact (HEMI) tests. RIM increased with increasing MC in the hygroscopic range, which might be explained by stress relaxation and 'gluing effects' inside the cell wall polymer structure, resulting from a growing network of hydrogen bonds on cell wall level. Increasing MC above CWS caused a slight decrease of RIM in the selected hardwood species, whereas no significant change in RIM was observed when MC varied in the range from CWS to approx. 100 % for the softwood species Norway spruce.*

KEYWORDS: *brittleness, High-Energy Multiple Impact (HEMI) test, moisture content, moisture states, resistance to impact milling (RIM)*

SAŽETAK • *Sadržaj vode u drvu unutar higroskopskog područja negativno utječe na većinu mehaničkih svojstava drva, bez obzira na popuštanje naprezanja pri vrlo niskom sadržaju vode. Nasuprot tome, čini se da voda u drvu pozitivno utječe na strukturnu cjelovitost, a time i na krtost drva. Cilj ovog istraživanja bio je ispitati utjecaj sadržaja vode u drvu na njegovu strukturnu cjelovitost u području između apsolutno suhog stanja i sadržaja vode znatno većeg od točke zasićenosti vlakanaca, oko 100 %. Strukturna cjelovitost za četinjače (Picea abies) i listače (Fagus sylvatica i Quercus robur) procijenjena je na temelju otpornosti na mljevenje udarcima (RIM), određene primjenom testova višestrukih udaraca visoke energije (HEMI test). S povećanjem sadržaja vode u drvu u higroskopskom se području povećao i RIM, što se može objasniti popuštanjem naprezanja i „efektom lijepljenja" unutar polimerne strukture stanične stijenke zbog povećanja broja vodikovih veza. Povećanje sadržaja vode iznad točke zasićenosti vlakanaca uzrokovalo je blago smanjenje RIM-a odabranih listača, dok je primijećena značajna promjena RIM-a u smrekovine kada je sadržaj vode varirao u rasponu od točke zasićenosti vlakanaca do približno 100 %.*

KLJUČNE RIJEČI: *krtost, test višestrukih udaraca visoke energije (HEMI test), sadržaj vode, stanja vlažnosti drva, otpornost na mljevenje udarcima (RIM)*

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1 INTRODUCTION
1. UVOD

Wood density and moisture content (*MC*) are the main variables affecting the mechanical properties of wood (Ghelmeziu, 1938; Kollmann, 1951; Wang and Wang 1999; Lachenbruch *et al*., 2010). The stiffness and strength properties of wood are usually positively correlated with wood density (Niemz and Sonderegger, 2003; Niklas and Spatz, 2010; Brischke, 2017), and negatively correlated with wood *MC* in the hygroscopic range, i.e., below cell wall saturation. The latter is often referred to as fibre saturation, which is a somewhat misleading term and does not necessarily represent the moisture state of the wood, from which the mechanical properties and dimensional changes stay unaffected (Brischke and Alfredsen, 2020). However, the latter relationship is more complex. Several mechanical properties show an optimum at 6–12 % wood *MC* and decrease from there with increasing wood *MC* until cell wall saturation (Kretschmann and Green, 1996; Müller, 2015). Below this optimum, stress relaxation of the cellulose fibrils may occur, and provoke an increase in strength and stiffness (Ishimaru *et al*., 2001).

Above cell wall saturation, i.e., when the cell lumens start to get filled with free water, no further changes in mechanical properties are expected, since water bodies inside the cell lumens are not supposed to contribute to the overall stiffness and strength of moist wood (e.g., Hering *et al*., 2012). Solely, at very high moisture loads of the xylem tissue, the incompressibility of the liquid water may enhance its compression strength and derivative properties of the wood. Similar observations were made by Megnis *et al*. (2002) and Ulvcrona *et al*. (2006), who suggested hydraulic effects in Norway spruce (*Picea abies*) wood impregnated with vegetable oils.

Remarkably enhanced structural integrity was observed in wood samples after water pressure impregnation and soaking in a study by Brischke *et al*. (2014), who conducted High-Energy Multiple Impact (HEMI) tests on different timbers for marine applications. The Resistance to Impact Milling (*RIM*) was significantly higher for the majority of wood species under test compared to those obtained with oven-dry specimens. In contrast, the dynamic and static hardness of the matched samples were reduced through wetting. However, intermediate *MC*s between the absolute dry state and water saturation were not the focus of their study. In HEMI tests, small defect-free wood specimens were crushed using steel balls in the bowl of a heavy vibratory disc mill. The fragments obtained were analysed and the degree of integrity (I) as well as a percentage of fine fragments (F, fragments smaller than 1 mm in width) were determined. The *RIM* data can be used to detect traces of wood degradation, e.g., through thermal and chemical modification, fungal decay, gamma irradiation, and salt-induced damage (Brischke *et al*., 2006, 2012; Rapp *et al*., 2006; Despot *et al*., 2007; Welzbacher *et al*., 2011; Kirker *et al*., 2020; Emmerich *et al*., 2021). The *RIM* values obtained in HEMI tests are rather insensitive to wood density variation and macroscopic defects such as checks after weathering (Brischke, 2017). In contrast, the structural integrity of wood, expressed as *RIM*, seems to be affected by wood moisture content, opposite to the well-known relationship between different strength properties of wood and *MC*.

The aim of this study was therefore to examine the impact of changes in the wood *MC* below and above cell wall saturation on the structural integrity of wood. Therefore, three wood species were investigated as examples, representing coniferous, ring-porous, and diffuse-porous hardwoods.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Preparation and conditioning of wood specimens
2.1. Priprema i kondicioniranje uzoraka drva

Axially matched specimens of 5 mm × 20 mm × 10 mm (ax.) were prepared from European beech (*Fagus sylvatica*), English oak (*Quercus robur*), and Norway spruce (*Picea abies*). The specimens were cut from 20 lattices per wood species with a cross-section of 5 mm × 20 mm. Thus, each set of 20 specimens contained one specimen per lattice. In total, 1,300 specimens were prepared from each wood species representing 65 sets, i.e., sets for n=5 replicate tests for each target moisture content (*MC*), which was calculated according to Eq. 1. The target *MC* and the respective conditioning regimes are summarised in Table 1.

$$MC = \frac{m_0 - m_{\text{cond}}}{m_0} \cdot 100\ [\%] \tag{1}$$

where the moisture content *MC* is calculated on the basis of the initial oven-dry mass before conditioning (m_0 after drying at (103±2) °C for 48 h) and the conditioned mass in equilibrium state (m_{cond}).

2.2 High-Energy Multiple Impact (HEMI) tests
2.2. Test višestrukih udaraca visoke energije (HEMI test)

The development and optimisation of the HEMI test was described by Rapp *et al.* (2005) and Brischke *et al.* (2006a, b). In the present study, the following procedure was applied: 20 oven-dried specimens of 10 mm (ax.) × 5 mm × 20 mm were placed in the bowl (140 mm in diameter) of a heavy-vibratory-impact ball mill (Herzog HSM 100-H; Herzog Maschinenfabrik, Osnabrück, Germany) together with one steel ball of 35 mm diame-

Table 1 Target moisture contents and corresponding conditioning regimes
Tablica 1. Ciljani sadržaj vode i odgovarajući režimi kondicioniranja

Target moisture content, % *Ciljani sadržaj vode, %*	**Conditioning regime** / *Režim kondicioniranja*
0	Oven-drying at 103°C
5	23 % RH (CH_3CO_2K)*, 20 °C
8	43 % RH (K_2CO_3)*, 20 °C
12	65 % RH, Climate cabinet
15	75 % RH (NaCl)*, 20 °C
18	85 % RH (KCl)*, 20 °C
25	98 % RH (K_2SO_4)*, 20 °C
30	Exposed above a deionised water body, 20°C
30	Vacuum-pressure impregnation during submersion in water and subsequent re-drying *Vakuumsko-tlačna impregnacija vodom i ponovno naknadno sušenje*
40	
60	
80	
100	

*Exposure above respective saturated salt solution or deionised water until constant mass / *izlaganje iznad odgovarajuće zasićene otopine soli ili deionizirane vode do konstantne mase*

ter for crushing the specimens. Three balls of 12 mm diameter and three of 6 mm diameter were added to ensure the impact with smaller wood fragments. The bowl was shaken for 60 s at a rotary frequency of 23.3 s^{-1} and a stroke of 12 mm. The fragments of the 20 specimens were fractionated on a slotted sieve according to ISO 5223 (1996) with a slit width of 1 mm using an orbital shaker at an amplitude of 25 mm and a rotary frequency of 200 min^{-1} for 2 min. Sieving served to identify the fine fragments being smaller than 1 mm, whereas the 20 biggest fragments from the entire fraction were selected visually. Subsequently, the degree of integrity (*I*), fine fraction (*F*) and Resistance to Impact Milling (*RIM*) were calculated according to Eq. 2-4:

$$I = \frac{m_{20}}{m_{\mathrm{all}}} \cdot 100\ [\%] \tag{2}$$

where the degree of integrity *I* is the ratio of the mass of the 20 biggest fragments m_{20} to the mass of all fractions m_{all} after crushing.

$$F = \frac{m_{\mathrm{fragments<1mm}}}{m_{\mathrm{all}}} \cdot 100\ [\%] \tag{3}$$

where the fine fraction *F* is the ratio of the mass of fragments < 1 mm to the mass of all fractions m_{all} multiplied by 100.

$$RIM = \frac{(I - 3 \cdot F) + 300}{400}\ [\%] \tag{4}$$

where *RIM* is the resistance to impact milling as a measure for the structural integrity of the material.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The structural integrity of the tested wood species was significantly affected by wood moisture in the hygroscopic range, as shown in Table 2 and Figure 3. The Resistance to Impact Milling (*RIM*) of all three wood species was linearly positively correlated with the wood moisture content (*MC*), but this effect was wood-species-specific, with beech being less affected than Norway spruce and English oak. In contrast to the hygroscopic range, only the *RIM* of the hardwoods was negatively affected by the wood *MC* above cell wall saturation (CWS), showing a slight logarithmic decrease with increasing *MC*. In contrast, the *RIM* of Norway spruce occurred to be unaffected by the wood *MC* above CWS (Figure 3). The absolute values of the degree of integrity (*I*), the fine fraction percentage (*F*) and the *RIM* as well as their standard deviations are summarised in Table 2. The latter is remarkably low regardless of the *MC*. Even at the highest *MC*, i.e., approximately at 100 %, the coefficients of variation (COV) were less than 2 %.

The effect of wood *MC* on structural integrity was opposite to those on different mechanical properties, as reported by Gerhards (1982), who found negative effects of moisture content in a range between 6 and 20 % on the following in descending order: compressive strength $_{\text{parallel to the grain}}$ > compressive strength $_{\text{perpendicular to the grain}}$ > bending strength > MOE $_{\text{perpendicular to the grain}}$ > shear modulus > tensile strength $_{\text{parallel to the grain}}$ > tensile strength $_{\text{perpendicular to the grain}}$ > MOE $_{\text{parallel to the grain}}$. Similar negative effects of wood *MC* on different mechanical properties have been observed by Wang and Wang (1999), Nocetti *et al*. (2015), and Mvondo *et al*. (2017). At *MC* below 10 %, some mechanical properties such as tensile strength increase with increasing *MC*. The latter is commonly accepted to be the result of stress relaxation (e.g., Kretschmann and Green, 1996; Ishimaru *et al*., 2001). The progressive moistening of wood leads to a decline of different static and dynamic mechanical properties since more

Table 2 Moisture content (*MC* in %), degree of integrity (*I* in %), fine fraction (*F* in %) and Resistance to Impact Milling (*RIM* in %) depending on wood species (mean values with standard deviation in parentheses)
Tablica 2. Sadržaj vode (*MC*, u %), stupanj cjelovitosti (*I*, u %), fina frakcija (*F*, u %) i otpornost na mljevenje udarcima (*RIM*, u %) ovisno o vrsti drva (srednje vrijednosti sa standardnom devijacijom navedene su u zagradama)

Wood species / *Vrsta drva*	***MC*, %**	***I*, %**	***F*, %**	***RIM*, %**
Quercus robur L.	0 (± 0)	43.9 (± 1.5)	6.4 (± 0.9)	81.2 (± 1.0)
	4.1 (± 0.1)	47.7 (± 2.8)	6.4 (± 0.9)	83.9 (± 1.3)
	7.1 (± 0.1)	51.1 (± 3.9)	2.7 (± 0.9)	85.7 (± 1.4)
	11.3 (± 0.2)	58.3 (± 1.8)	1.0 (± 0.1)	88.8 (± 0.4)
	11.9 (± 0.1)	59.1 (± 2.1)	1.1 (± 0.6)	88.9 (± 0.5)
	14.7 (± 0.1)	63.1 (± 3.8)	0.6 (± 0.1)	90.3 (± 1.0)
	18.9 (± 0.2)	66.8 (± 2.6)	0.2 (± 0.1)	91.5 (± 0.6)
	21.9 (± 0.3)	69.0 (± 4.9)	0.2 (± 0.0)	92.1 (± 1.3)
	32.0 (± 0.1)	78.7 (± 6.8)	0.1 (± 0.0)	94.6 (± 1.7)
	41.7 (± 0.4)	76.1 (± 7.8)	0.1 (± 0.0)	93.9 (± 2.0)
	61.7 (± 0.4)	70.4 (± 4.6)	0.1 (± 0.0)	92.5 (± 1.2)
	80.2 (± 1.6)	67.0 (± 6.1)	0.1 (± 0.0)	91.6 (± 1.6)
	98.9 (± 2.9)	69.9 (± 2.7)	0.1 (± 0.0)	92.4 (± 0.7)
Fagus sylvatica L.	0 (± 0)	53.5 (± 2.0)	1.1 (± 0.1)	87.5 (± 0.5)
	4.1 (± 0.1)	55.6 (± 2.0)	0.6 (± 0.1)	88.4 (± 0.5)
	7.0 (± 0.1)	58.3 (± 3.6)	0.3 (± 0.0)	89.4 (± 0.9)
	11.4 (± 0.1)	63.0 (± 4.7)	0.2 (± 0.1)	90.6 (± 1.2)
	12.1 (± 0.1)	62.3 (± 3.9)	0.1 (± 0.0)	90.5 (± 1.0)
	15.7 (± 0.1)	67.0 (± 3.9)	0.1 (± 0.0)	91.7 (± 1.0)
	20.7 (± 0.0)	71.3 (± 2.9)	0.0 (± 0.0)	92.8 (± 0.8)
	24.6 (± 0.7)	77.0 (± 4.1)	0.1 (± 0.1)	94.2 (± 1.1)
	32.0 (± 0.2)	80.9 (± 4.0)	0.0 (± 0.0)	95.2 (± 1.0)
	41.1 (± 0.9)	77.0 (± 6.7)	0.0 (± 0.0)	94.2 (± 1.7)
	61.6 (± 0.2)	71.8 (± 5.2)	0.0 (± 0.0)	92.9 (± 1.3)
	81.1 (± 0.7)	69.8 (± 4.0)	0.0 (± 0.0)	92.4 (± 1.0)
	98.8 (± 1.5)	71.2 (± 6.2)	0.0 (± 0.0)	92.8 (± 1.6)
Picea abies (L.) H. Karst.	0 (± 0)	28.1 (± 3.4)	1.7 (± 0.3)	80.8 (± 0.8)
	4.8 (± 0.1)	35.7 (± 3.7)	1.1 (± 0.2)	83.1 (± 0.8)
	8.1 (± 0.1)	37.4 (± 5.1)	0.9 (± 0.1)	83.7 (± 1.3)
	12.2 (± 0.1)	49.5 (± 3.1)	0.4 (± 0.1)	87.1 (± 0.8)
	13.2 (± 0.1)	49.4 (± 1.7)	0.3 (± 0.1)	87.1 (± 0.4)
	16.6 (± 0.2)	56.1 (± 4.2)	0.4 (± 0.1)	88.7 (± 1.1)
	21.2 (± 0.3)	63.7 (± 2.2)	0.2 (± 0.1)	90.8 (± 0.6)
	22.8 (± 0.5)	67.5 (± 3.3)	0.3 (± 0.2)	91.7 (± 0.7)
	33.3 (± 0.3)	72.9 (± 4.3)	0.2 (± 0.2)	93.0 (± 1.1)
	41.6 (± 1.6)	73.0 (± 4.1)	0.2 (± 0.1)	93.1 (± 1.0)
	62.5 (± 0.3)	72.4 (± 3.3)	0.1 (± 0.0)	93.0 (± 0.8)
	82.5 (± 0.5)	74.8 (± 0.8)	0.1 (± 0.1)	93.6 (± 0.2)
	100.4 (± 2.7)	70.9 (± 4.1)	0.1 (± 0.1)	92.6 (± 1.0)

and more water molecules lose the bonds within the hierarchical cell wall structure. The situation is different with the structural integrity of wood. Both, the degree of integrity *I* and the *RIM* increased with increasing *MC* in the hygroscopic range (Figure 1 and Figure 3), which again might be explained to some extent by stress relaxation. In consideration of the fine fraction percentage *F*, which clearly dropped from the oven-dry state to the CWS (Figure 2), 'gluing effects' (Brischke *et al*., 2012) might have a further positive effect on the structural integrity and occur with increasing amount of hydrogen bonds.

In contrast, the values of *I* and *RIM* in English oak and beech decreased slightly with increasing *MC* in a range between CWS and approx. 100 %. The structural integrity of Norway spruce was not significantly affected by *MC* changes above CWS.

Ghelmeziu (1938) conducted comprehensive experiments on numerous factors influencing the Impact Bending Strength (*IBS*) of wood, including the wood *MC*. Since impact bending is among the dominating loads in HEMI tests (Welzbacher *et al*., 2011), one may expect similar interrelationships between wood *MC* and *IBS* and *RIM,* respectively. As shown in Figure 4,

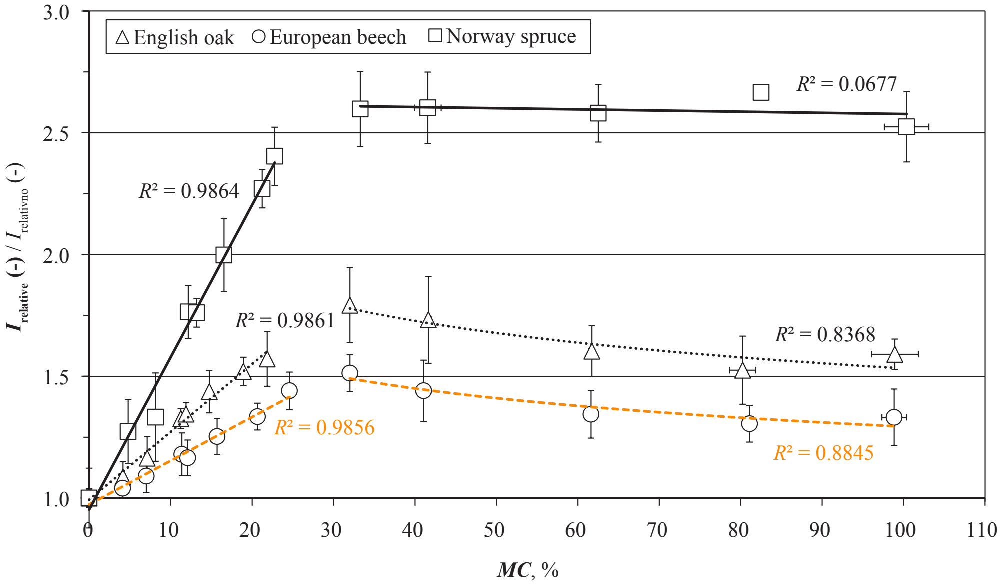

Figure 1 Relative degree of integrity ($I_{relative}$) depending on *MC* in hygroscopic and over-hygroscopic *MC* range shown for English oak (*Quercus robur* L.), European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) H. Karst.)
Slika 1. Relativni stupanj cjelovitosti ($I_{relativno}$) ovisno o sadržaju vode u higroskopskom području i iznad njega za hrastovinu (*Quercus robur* L.), bukovinu (*Fagus sylvatica* L.) i smrekovinu (*Picea abies* (L.) H. Karst.)

Ghelmeziu's data do not demonstrate a clear relationship between *IBS* and wood *MC*, neither below nor above the CWS. While IBS and *RIM* are quite well correlated for a given *MC* in both untreated (Brischke, 2017) and modified wood specimens (Emmerich *et al*., 2021), they are apparently affected differently by wood *MC*. A general issue with the results of dynamic mechanical testing of wood is their high variability. As Ghelmeziu (1938) and many others have noted, this is particularly valid for the wood's impact bending strength and may have masked a possible relationship between the *IBS* and *MC* data presented in Figure 4. Thus, on opposite to standardised dynamic mechanical testing methods, *RIM* as a measure of the structural integrity turned once more out as an appropriate and sensitive method to detect physical or chemical changes on cell wall level, which in this study originated from deposits of water molecules.

4 CONCLUSIONS
4. ZAKLJUČAK

The structural integrity of wood, as a measure of the resistance of wood against dynamic impacts, seemed

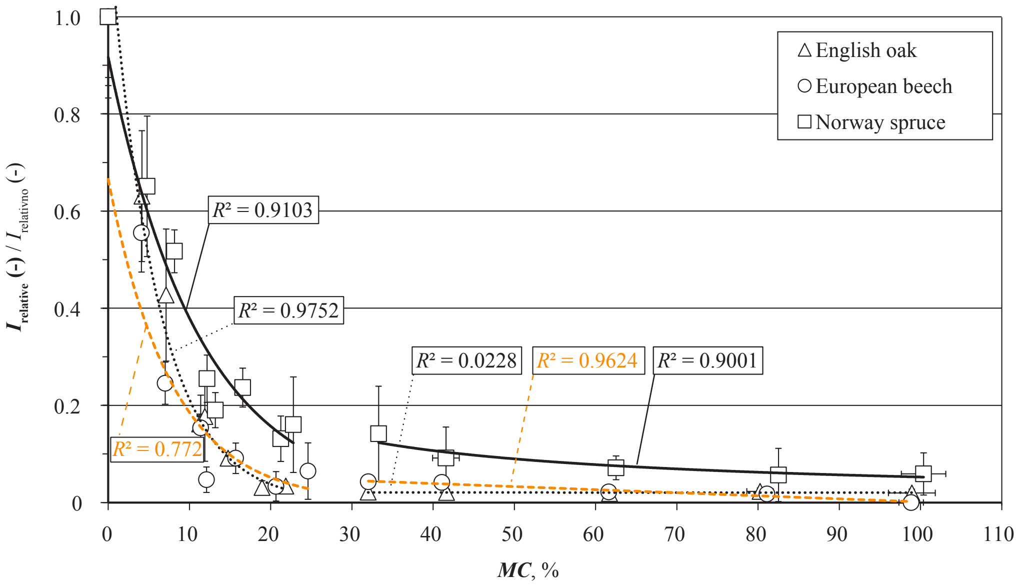

Figure 2 Relative fine fraction ($F_{relative}$) depending on *MC* in hygroscopic and over-hygroscopic *MC* range shown for English oak (*Quercus robur* L.), European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) H. Karst.)
Slika 2. Relativna fina frakcija ($F_{relativno}$) ovisno o sadržaju vode u higroskopskom području i iznad njega za hrastovinu (*Quercus robur* L.), bukovinu (*Fagus sylvatica* L.) i smrekovinu (*Picea abies* (L.) H. Karst.)

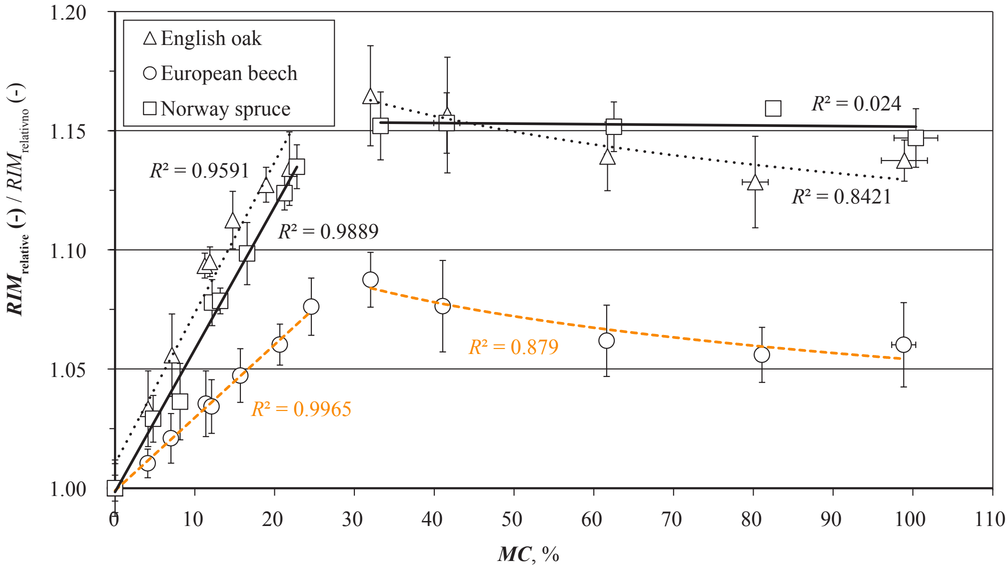

Figure 3 Relative resistance to impact milling ($RIM_{relative}$) depending on *MC* in hygroscopic and over-hygroscopic *MC* range shown for English oak (*Quercus robur* L.), European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) H. Karst.)
Slika 3. Relativna otpornost na mljevenje udarcima ($RIM_{relativno}$) ovisno o sadržaju vode u higroskopskom području i iznad njega za hrastovinu (*Quercus robur* L.), bukovinu (*Fagus sylvatica* L.) i smrekovinu (*Picea abies* (L.) H. Karst.)

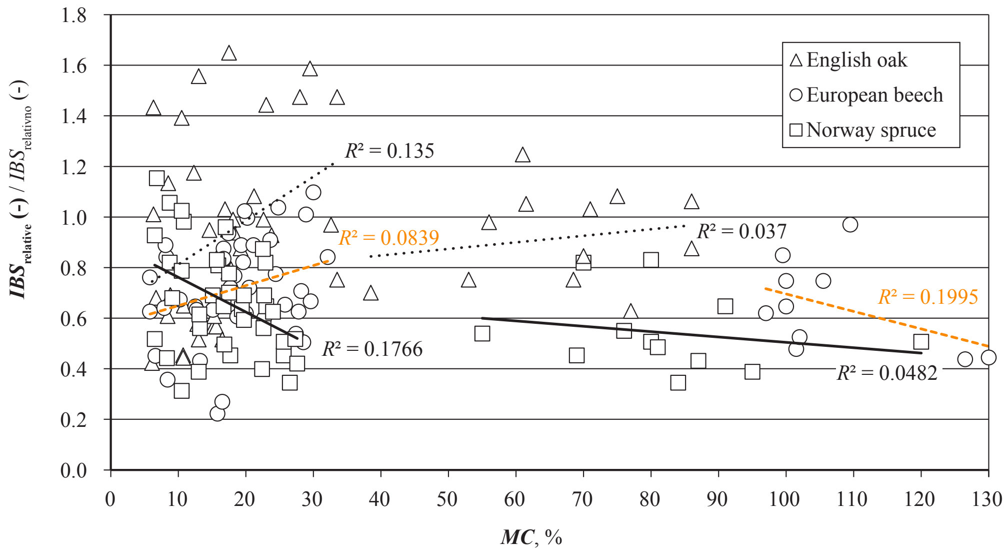

Figure 4 Relative impact bending strength ($IBS_{relative}$) depending on *MC* in hygroscopic and over-hygroscopic *MC* range shown for English oak (*Quercus robur* L.), European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) H. Karst.)
Slika 4. Relativna udarna čvrstoća ($IBS_{relativno}$) ovisno o sadržaju vode u higroskopskom području i iznad njega za hrastovinu (*Quercus robur* L.), bukovinu (*Fagus sylvatica* L.) i smrekovinu (*Picea abies* (L.) H. Karst.)

to be significantly affected by the wood *MC* in the range from 0 % *MC* to CWS. Such interrelationship between wood *MC* and its behaviour under dynamic loads was derived from a multiple dynamic impact test (HEMI test) and this could hardly be verified in standardised single dynamic impact tests (e.g. impact bending strength). In particular, the structural integrity (*RIM*) increased linearly with increasing wood *MC* up to CWS for both softwoods and hardwoods. Conversely, increasing the wood *MC* from CWS to ca. 100 % caused a slight decrease in *RIM* for the hardwood species, without a significant impact on the *RIM* of Norway spruce. *MC* induced changes in structural integrity (*RIM*) along the hygroscopic range could be explained by stress relaxation and 'gluing effects' resulting from a growing network of hydrogen bonds at the cell wall level.

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