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Interrelationship between Static and Dynamic Strength Properties of Wood and its Structural Integrity

Međusobna ovisnost statičkih i dinamičkih svojstava čvrstoće drva i njegova strukturnog integriteta

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ABSTRACT • *Various biotic and abiotic agents affect the performance of wood products. Chemicals, thermal energy, radiation, as well as different organisms have the potential to alter the optical, haptic and functional performance of wood. These effects come along with a change of structural integrity of wood, which in turn affects its strength properties. Therefore, a test was developed to quantify the structural integrity of wood in terms of its Resistance to Impact Milling (RIM). In a High-Energy Multiple Impact (HEMI) – test, steel balls were used in a heavy vibratory mill for crushing wood samples. Thousands of single events were captured by analyzing the fragments. Based on the degree of integrity and the percentage of fine fragments (< 1mm), an indicator has been defined to detect structural changes on cell wall level with high sensitivity.*
The aim of this study was to investigate the variation of structural integrity within and between ten different wood species in comparison with some strength properties according to standardized test protocols and in dependence of wood density. HEMI-tests, bending tests, and impact bending tests were performed with matched specimens. Wood density turned out to have only a subsidiary effect on structural integrity, but is dominanting standard strength properties. Thus, RIM was found to be only slightly correlated with the impact bending strength (IBS) and bending strength (MOR). On the other hand, the method shows clear insensitivity to natural variation in anatomy of wood.

Key words: *bending strength, High-Energy Multiple Impact (HEMI) tests, impact bending strength, modulus of elasticity, Resistance to Impact Milling (RIM)*

SAŽETAK • *Na svojstva proizvoda od drva utječu brojni biotički i abiotički činitelji. Kemikalije, toplinska energija, zračenja i različiti organizmi mogu promijeniti optička, haptička i funkcionalna svojstva drva. Te učinke prate i promjene strukturnog integriteta drva, što pak utječe na njegovu čvrstoću. Stoga je razvijen test za kvantificiranje strukturnog integriteta drva s obzirom na njegovu otpornost na udarce (RIM). Za provedbu testa višestrukih udar-*

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aca visoke energije (HEMI test) upotrijebljene su čelične kuglice u teškome vibracijskome mlinu za drobljenje uzoraka drva. Analizom fragmentiranog drva obuhvaćeno je više tisuća pojedinačnih događaja. Na temelju stupnja integriteta i postotka sitnih čestica (< 1 mm) definiran je pokazatelj vrlo visoke osjetljivosti koji otkriva strukturne promjene na razini stanične stijenke.

Ova je studija usmjerena na istraživanje varijacija strukturnog integriteta unutar i između deset različitih vrsta drva u usporedbi s odabranim svojstvima čvrstoće prema standardiziranim ispitnim testovima te u ovisnosti o gustoći drva. HEMI testovi, testovi savijanja i testovi ispitivanja žilavosti provedeni su na odgovarajućim uzorcima. Pokazalo se da gustoća drva ima samo sekundarni utjecaj na strukturni integritet, a da dominantnu ulogu imaju standardna svojstva čvrstoće. Rezultati su pokazali da je RIM slabo povezan sa žilavošću materijala (IBS) i čvrstoćom na savijanje (MOR). No predstavljeni je pokazatelj nedvojbeno neosjetljiv na prirodne varijacije u građi drva.

Ključne riječi: *čvrstoća na savijanje, test višestrukih udaraca visoke energije (HEMI), žilavost materijala, modul elastičnosti, otpornost na udarce (RIM)*

1 INTRODUCTION
1. UVOD

Various biotic and abiotic agents are affecting the performance of wood and wood based products. Chemicals, thermal energy, radiation, as well as different organisms have the potential to alter the optical, haptic and finally functional performance of wood (e.g. Berger *et al.*, 2006; Sandak *et al.*, 2015; Willems *et al.*, 2015). Many of these effects come along with a change of the structural integrity of wood, which in turn affects its strength properties. Therefore, a test was developed to determine the structural integrity of wood in terms of its resistance to impact milling. A High-Energy Multiple Impact (HEMI) – test has been designed using steel balls in a heavy vibratory mill for crushing wood samples. The development work started after realizing that bending and impact bending strength tests were not suitable for quality control of – in this case – thermally modified wood (Brischke *et al.*, 2006a). They suffered from insufficient reliability and reproducibility and required a high number of carefully selected and precisely manufactured replicate samples. Consequently, time and costs became unacceptably high for industrial quality control (Rapp *et al.*, 2006).

The aim was to overcome the drawbacks of standard strength testing, but keeping the advantage of examining a highly sensitive wood property such as its dynamic strength, which is strongly affected by structural changes of the material. Instead of using multiple replicates, the number of events affecting the wood should be multiplied. After a first attempt to use a shotgun to apply several hundred pellets at a time on wooden boards – which might cause significant security problems in the lab – a heavy vibratory ball mill was used for crushing wood samples (Brischke *et al.*, 2006a). The Resistance to Impact Milling (*RIM*), which can vary between 0 and 100 %, is used here as a measure of wood structural integrity.

Heat treatment of wood goes along with a drastic strength loss (e.g. Esteves and Pereira, 2008). In particular, the dynamic strength properties are affected, and so is *RIM*. Excellent correlation was obtained between *RIM* and the severity of thermal modification expressed as decrease in mass (*dm*) or in terms of color changes (Brischke *et al.*, 2006a, 2012; Rapp *et al.*, 2006). As shown for 14 different wood species by Welzbacher *et al.* (2012), the treatment intensity can be estimated from *RIM* with fairly high precision.

Different kinds of chemical modification were also examined. Their very different effects on the structural integrity of wood were found to be detectable. While furfurylation and treatments with DMDHEU (dimethylol dihydroxyethyleneurea) and melamine resin led to a significant decrease in *RIM*, hydrophobation with oils and waxes increased the structural integrity (Brischke *et al.*, 2012). Impregnation with oil and wax obviously did not weaken the wood structure, but increased the *RIM*, which might be explained by hydraulic effects (e.g. Ulvcrona *et al.*, 2006). Furthermore, a remarkably reduced amount of fine fragments indicated 'adhesion effects', which might also have a positive effect on the structural integrity.

Hydraulic effects have also been observed on water saturated samples by Brischke *et al.* (2014), when testing different wood species used in the marine environment. While the structural integrity decreased with increasing moisture content in the hygroscopic range, it increased again up to full water saturation due to hampered short term compression of the wooden cells when the lumens were filled with water.

The HEMI test was furthermore used to detect incipient decay (Brischke *et al.*, 2006b). Brown and white rot had clearly different effects on the structural integrity. Partly, differences were found even on fungal species level (Brischke *et al.*, 2008). Fungal decay was found to be detectable before significant mass loss was determined. Furthermore, Huckfeldt *et al.* (2010) showed that drilling cores taken from full size structures can also be used for HEMI tests for early detection of fungal degradation. Samples from archaeological objects, such as the Vasa shipwreck in Stockholm, Sweden, were investigated with the HEMI method (Rapp *et al.*, 2008).

Gamma radiation, which is a common method for sterilization of wood samples, e.g. for laboratory resistance tests, did negatively affect the structural integrity of wood (Despot *et al.*, 2007). Degradation of cellulose through radiation led to significantly reduced *RIM*. On the other hand, the HEMI method was found to be almost unaffected by wood density, weathering effects (e.g. cracking) and blue stain (Brischke *et al.* 2009), which requires further testing.

Previous tests with different wood-based materials indicated that *RIM* and mechanical properties, such as impact bending strength and bending strength, are only poorly correlated, although both are negatively affected e.g. by heat, fungal decay or radiation, but are obviously affected by different structural features (Welzbacher *et al.*, 2011; Brischke *et al.*, 2014).

Therefore, in this study, the structural integrity of different wood species was determined on samples, which had previously been submitted to standard impact bending tests. Furthermore, matched specimens were subjected to three-point-bending tests to determine the modulus of elasticity (*MOE*) and the modulus of rupture (*MOR*).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Wood
2.1. Drvo

Specimens were prepared from European-grown wood species, i.e. four softwoods and six hardwoods as shown in Table 1. Specimens for impact bending and bending tests were cut from the same planks; HEMI test specimens were cut from impact bending test specimens after the tests to match them exactly in axial direction.

2.2 Determination of oven-dry density
2.2. Određivanje gustoće apsolutno suhog drva

The oven-dry density was determined on HEMI test specimens since they were axially matched with the impact bending test specimens. The specimens were oven dried at 103 °C till constant mass, weighed to the nearest 0.01 g and the dimensions were measured to the nearest 0.01 mm. The oven dry density was calculated according to the following equation:

$$\rho_0 = \frac{m_0}{v_0}, \quad \frac{\text{g}}{\text{cm}^3} \qquad (1)$$

Where ρ_0 is the oven-dry density, m_0 is the oven-dry mass, and V_0 is the oven-dry volume of specimens.

2.3 Strength tests
2.3. Ispitivanje čvrstoće

Impact bending tests were performed on 300 x 20 x 20 mm³ specimens using a Otto-Wolpert pendulum impact machine according to DIN 52 189-1 (DIN 1981). The static bending tests were run to determine the bending strength (modulus of rupture *MOR*) and the modulus of elasticity (*MOE*) of wood according to DIN 52 186 (1978). Three-point bending tests were performed on 360 x 20 x 20 mm³ specimens with concentric force parallel to the grain on a universal testing machine Zwick/Roell Z100. Before the mechanical strength tests, all samples were conditioned in a standard climate at 20 °C and 65 % relative humidity until constant mass was achieved.

2.4 High-energy multiple impact (HEMI) – tests
2.4. Testovi višestrukih udaraca visoke energije (HEMI testovi)

The development and optimization of the High-Energy Multiple Impact (HEMI) - test have been 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 (ax.) x 5 x 20 mm³ were placed in the bowl (140 mm in diameter) of a heavy-impact ball mill (Herzog HSM 100-H; Herzog Maschinenfabrik, Osnabrück, Germany), together with one steel ball of 35 mm diameter for crushing the specimens. Three balls of 12 mm diameter and three of 6 mm diameter were added to ensure 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 slit 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 350 min^{-1} for 2 min. The following values were calculated:

$$I = \frac{m_{20}}{m_{\text{all}}} \cdot 100, \quad \% \qquad (2)$$

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

Table 1 Wood species under test
Tablica 1. Ispitivane vrste drva

Wood species / *Vrsta drva*	Botanical name / *Botanički naziv*	Number replicates[1] / *Broj ponavljanja*		
		HEMI tests / *HEMI test*	**Bending tests** / *Test savijanja*	**Impact bending tests** / *Test ispitivanja* žilavosti
Norway spruce / *norveška smreka*	*Picea abies* Karst.	30	38	60
Siberian larch / *siberijski ariš*	*Larix sibirica* Ledeb.	50	59	60
Douglas fir / *duglazija*	*Pseudotsuga menziesii* Franco.	25	29	25
Scots pine / *obični bor*	*Pinus sylvestris* L.	10	10	10
Beech / *bukva*	*Fagus sylvatica* L.	10	10	10
Poplar / *topola*	*Populus nigra* L.	10	10	10
Hornbeam / *grab*	*Carpinus betulus* L.	10	10	10
English oak / *hrast lužnjak*	*Quercus robur* L.	10	10	10
Ash / *jasen*	*Fraxinus excelsior* L.	10	10	10
Robinia / *bagrem*	*Robinia pseudoacacia* L.	10	10	10

[1] One replicate sample in HEMI tests consisted of 20 single specimens. / *Jedno ponavljanje mjerenja HEMI testovima obuhvaća 20 pojedinačnih uzoraka*.

Table 2 Oven-dry density, mechanical properties, and structural integrity measures for different wood species (*ODD* – oven-dry density, *MOR* – modulus of rupture, *MOE* – modulus of elasticity, *IBS* – impact bending strength, *RIM* – resistance to impact milling, *I* – degree of integrity, *F* – fine percentage)
Tablica 2. Gustoća apsolutno suhog drva te mehanička svojstva i mjere strukturnog integriteta različitih vrsta drva (*ODD* – gustoća apsolutno suhog drva, *MOR* – modul loma, *MOE* – modul elastičnosti, *IBS* – žilavost, *RIM* – otpornost na udarce, *I* – stupanj cjelovitosti, *F* – postotak sitnih čestica)

Wood species *Vrsta drva*	***ODD*** g/cm³	***MOR*** N/mm²	***MOE*** N/mm²	***IBS*** KJ/m²	***RIM*** %	***I*** %	***F*** %
Norway spruce *norveška smreka*	0.43 (0.05)	91.5 (9.9)	10379 (1303)	29.2 (9.3)	76.0 (2.9)	23.4 (5.0)	6.5 (2.6)
Siberian larch / *siberijski ariš*	0.57 (0.04)	123.1 (17.1)	12247 (1532)	40.8 (17.3)	78.0 (1.7)	32.4 (5.0)	6.8 (1.7)
Douglas fir / *duglazija*	0.55 (0.05)	113.2 (23.9)	12380 (2490)	45.4 (16.4)	83.0 (4.1)	41.3 (12.2)	3.2 (2.1)
Scots pine / *obični bor*	0.55 (0.02)	103.5 (11.3)	12637 (953)	34.1 (10.2)	78.5 (1.4)	28.8 (2.7)	5.0 (2.1)
Beech / *bukva*	0.71 (0.03)	140.8 (15.4)	12924 (1174)	62.8 (12.7)	86.9 (0.9)	52.4 (2.4)	1.6 (0.5)
Poplar / *topola*	0.37 (0.02)	72.9 (7.6)	8368 (566)	18.2 (8.6)	80.2 (2.1)	40.3 (3.1)	6.6 (1.9)
Hornbeam / *grab*	0.70 (0.07)	128.3 (9.0)	9062 (1569)	55.5 (7.3)	87.8 (1.0)	55.8 (4.0)	1.6 (0.5)
English oak / *hrast lužnjak*	0.66 (0.03)	97.3 (9.7)	9655 (729)	32.6 (8.4)	76.8 (2.7)	37.0 (6.5)	9.9 (1.6)
Ash / *jasen*	0.63 (0.02)	133.5 (12.5)	13477 (1448)	74.1 (12.1)	85.9 (1.2)	49.4 (4.7)	1.9 (0.6)
Robinia / *bagrem*	0.77 (0.02)	161.3 (23.5)	13457 (1089)	80.8 (40.0)	86.5 (1.0)	51.2 (3.4)	1.7 (0.5)

$$F = \frac{m_{\text{fragments<1mm}}}{m_{\text{all}}} \cdot 100, \quad \% \qquad (3)$$

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.

$$RIM = \frac{(I - 3 \times F) + 300}{400}, \quad \% \qquad (4)$$

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 results of various mechanical tests are summarized in Table 2. A wide range of density and different strength related properties was covered with Poplar showing lowest density and mechanical strength and Robinia with the best property values. However, Beech and Hornbeam showed similar or even higher *RIM* compared to Robinia. Compared to other mechanical properties, *RIM* differed significantly less between wood species. In contrast, *I* and *F* showed much higher variations than the resulting *RIM*, which points to the anatomical peculiarities of different wood species. For instance, high *F* values were found for softwoods, which also showed generally lower *IBS*, and English oak showed the highest *F* value of all. The softwoods are characterized by weak earlywood portions that alternate with latewood areas, whereby the transition from one tissue to the other can be more or less abrupt (e.g. Schweingruber, 2012). English oak, however, suffers from very thick parenchyma rays and large early wood vessels, which in combination might explain both, low *RIM* and *IBS*.

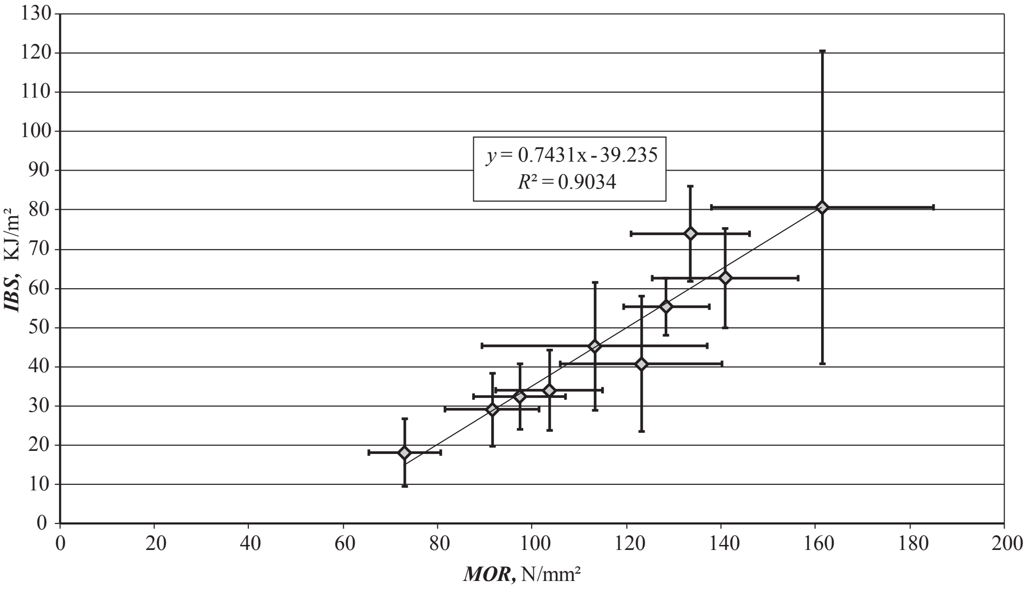

Figure 1 Relationship between modulus of rupture (*MOR*) and impact bending strength (*IBS*). (Dots represent mean values of wood species; Standard deviations are indicated by error bars.)
Slika 1. Odnos između modula loma (*MOR*) i žilavosti drva (*IBS*) (točke označuju prosječne vrijednosti za pojedine vrste drva, a standardne su devijacije prikazane linijama pogrešaka)

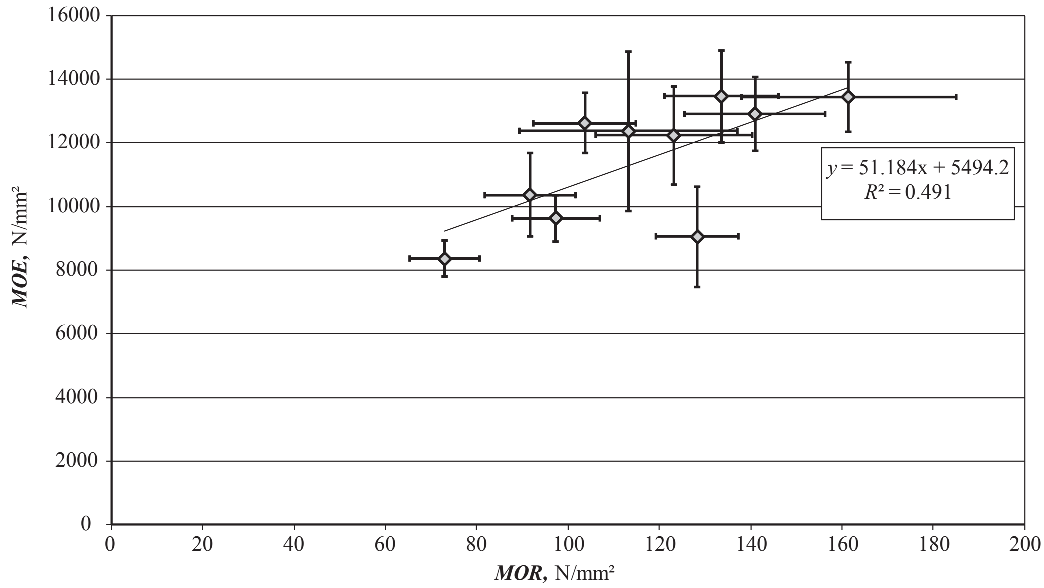

Figure 2 Relationship between modulus of rupture (*MOR*) and modulus of elasticity (*MOE*) (Dots represent mean values of wood species. Standard deviations are indicated by error bars.)
Slika 2. Odnos između modula loma (*MOR*) i modula elastičnosti drva (*MOE*) (točke predočuju prosječne vrijednosti za pojedine vrste drva, a standardne devijacije prikazane su linijama pogrešaka)

RIM showed very little variation for all tested wood species. The percentage standard deviation (coefficient of variation, *COV*) was between 1 and 5 %, which coincides with previous studies e.g. by Brischke *et al.* (2014). In contrary, *IBS* showed *COV* between 20 and 50 %. The two basic measures, *F* and *I,* used for calculating *RIM,* suffered from significantly higher variation. *I* showed *COV* up to 30 %, *F* scattered even more with a *COV* up to 66 %. However, in combination and expressed a RIM according to equation 4, the high variations are eliminated.

As expected, an excellent correlation was established between *IBS* and *MOR* (R^2 = 0.9034, Figure 1. Rather unexpected, the correlation between *MOE* and *MOR* was poor (R^2 = 0.491, Figure 2 and stands in contrast to earlier studies, e.g. by Young and Evans (2003), Niemz and Sonderegger (2003), and Lachenbruch *et al.* (2010), who found *MOE* and density clearly correlated, as well as the micro fibril angle and *MOE.*

The reason for *MOR* and *IBS* being so well correlated indicates a density dependency, which is illustrated in Figure 3. If only the mean values for different wood species are considered, *IBS* and *MOR* are well correlated with density, while *RIM* and *MOE* are not (Figure 3). However, if single values within one species are considered, as exemplarily shown for Norway spruce and Siberian larch in Figure 4, no correlation is achieved, neither between *RIM* nor *IBS* and density. This coincides with previous studies, where *RIM* appeared to be unaffected by density within one wood

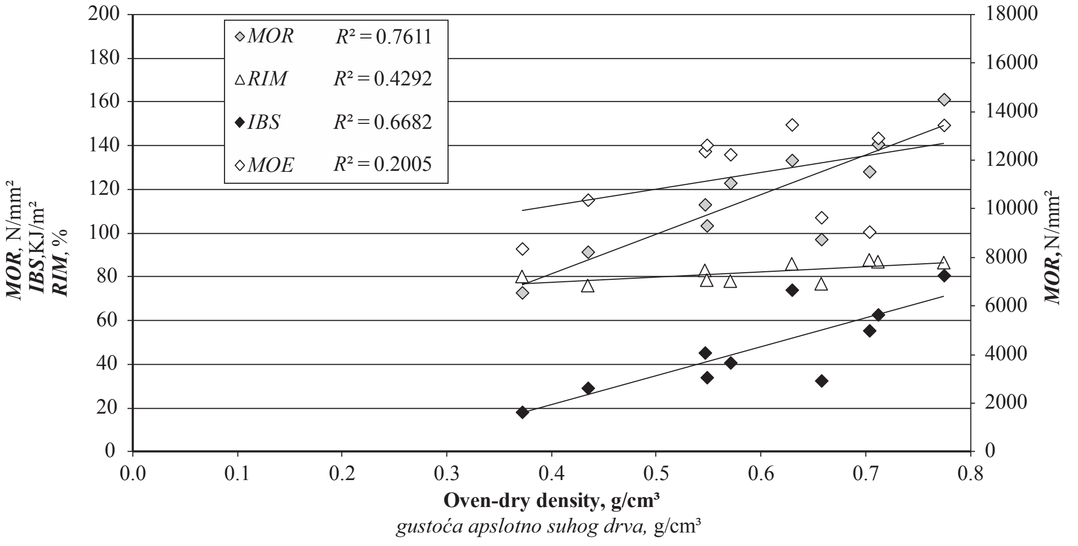

Figure 3 Relationship between oven-dry density and modulus of rupture (*MOR*), modulus of elasticity (*MOE*), impact bending strength (*IBS*), and resistance to impact milling (*RIM*) (Dots represent mean values of wood species)
Slika 3. Odnos između gustoće apsolutno suhog drva i modula loma (*MOR*), modula elastičnosti (*MOE*), žilavosti drva (*IBS*) i otpornosti na udarce (*RIM*) (točke označuju prosječne vrijednosti za pojedine vrste drva)

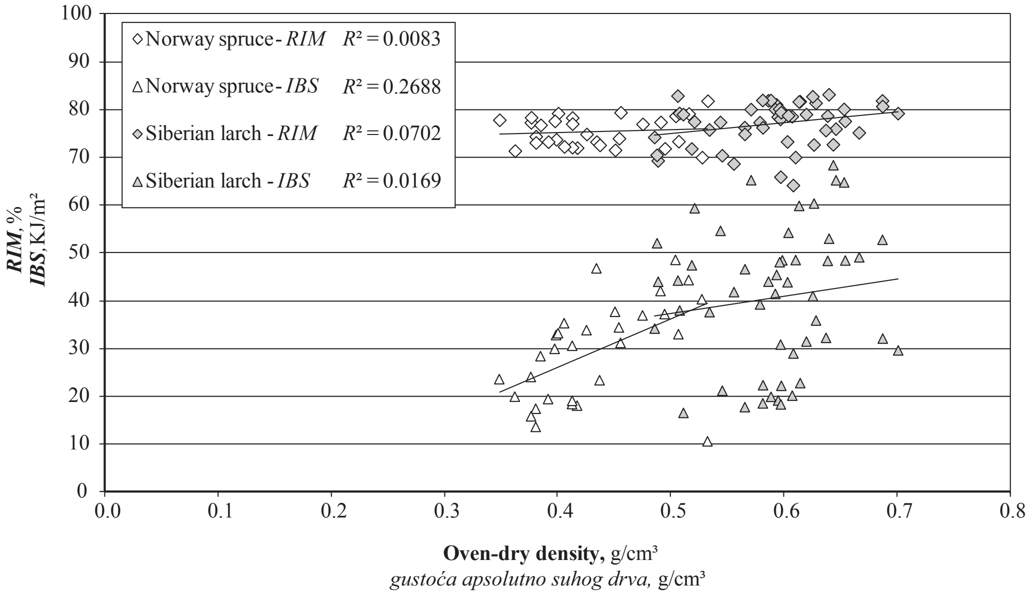

Figure 4 Relationship between oven-dry density and impact bending strength (*IBS*) and resistance to impact milling (*RIM*) for two different softwood species (Dots represent single values of replicate samples.)
Slika 4. Odnos između gustoće apsolutno suhog drva i žilavosti drva (*IBS*) te otpornosti na udarce (*RIM*) za dvije vrste mekog drva (točke predočuju vrijednosti pojedinačnih mjerenja)

Table 3 Coefficient of determination R^2 for different combinations of wood properties tested
Tablica 3. Koeficijent determinacije R^2 za različite kombinacije istraživanih svojstava drva

	RIM	*IBS*	*MOR*	*MOE*	Density
RIM	-	0.670	0.556	0.105	0.429
IBS		-	0.903	0.046	0.668
MOR			-	0.491	0.761
MOE				-	0.201
Density					-

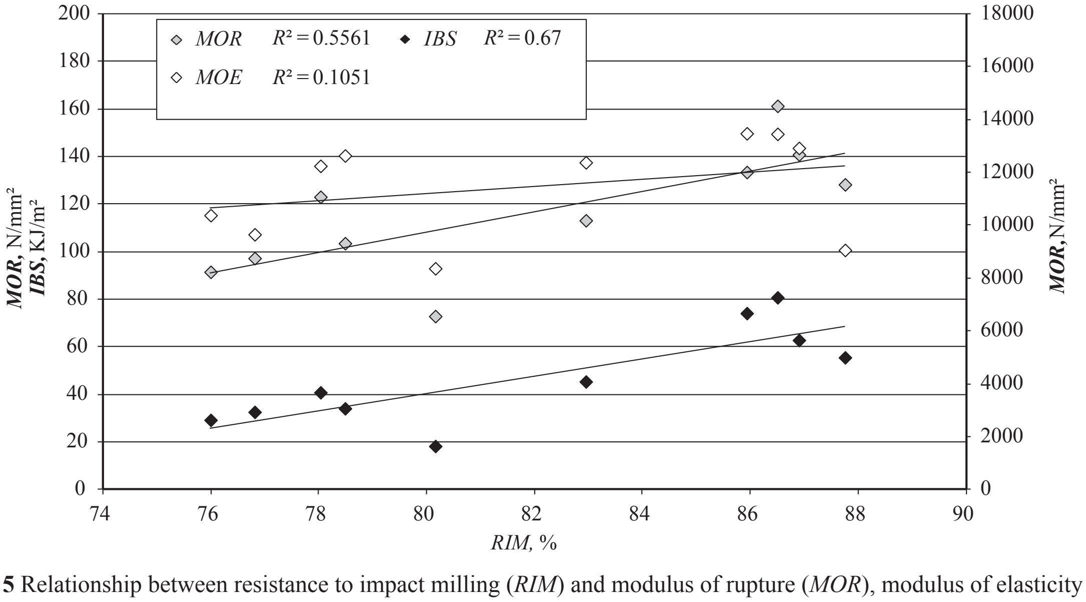

Figure 5 Relationship between resistance to impact milling (*RIM*) and modulus of rupture (*MOR*), modulus of elasticity (*MOE*), and impact bending strength (*IBS*) (Dots represent mean values of wood species.)
Slika 5. Odnos između otpornosti na udarce (*RIM*) i modula loma (*MOR*), modula elastičnosti (*MOE*) i žilavosti drva (*IBS*) (točke označuju prosječne vrijednosti za pojedine vrste drva)

species (Brischke *et al.*, 2009), but also across different wood species (Brischke *et al.*, 2014). Consequently, other anatomical characteristics need to be responsible for the significant differences in structural integrity between wood species. Nevertheless, as shown in Figure 5, *MOR* (R^2 = 0.5561) and *IBS* (R^2 = 0.67) seem to be correlated with *RIM*, but *MOE* (R^2 = 0.1051) is obviously not. An overview of cross-correlation of the investigated wood properties is given in Table 3.

Density is the dominating parameter for the majority of strength properties of wood, but numerous further factors have the potential to affect different strength and elasto-mechanical properties of wood. Fiber length, composition, size and amount of rays, lignin content, the micro fibril angle, and others lead to intra- and inter-species specific variation of wood properties (Niemz and Sonderegger, 2003) and are not necessarily the same for different wood properties such as the investigated parameters in this study. Dynamic strength properties, such as *IBS* and *RIM,* are affected by anatomical abnormalities, which can easily overrule the influence of wood density (Ghelmeziu, 1937; von Pechmann, 1953; Niemz and Sonderegger, 2003).

4 CONCLUSIONS
4. ZAKLJUČAK

Wood density seems to have only a subsidiary effect on the structural integrity of wood as determined in high-energy multiple impact (HEMI) tests. Furthermore, the *RIM* seems only slightly correlated with standard strength properties of wood such as *IBS* and *MOR*. More likely, anatomical features within one wood species, and in particular between wood species, have stronger effects on the structural integrity of wood and thus on its brittleness. Consequently, future studies need to include microscopic studies to further elaborate the effect of anatomical characteristics such as micro fibril angles and cell and tissue volume ratios.

The limited transferability of *RIM* to established strength properties of wood comes along with its insensitivity to natural variation in anatomy of wood. This retrieves the advantage of a high discriminatory power for detecting structural changes, e.g. caused by fungal decay or cell wall modification.

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5 REFERENCE
5. LITERATURA

1. Berger, G.; Katz, H.; Petutschnigg, A. J., 2006: What consumers feel and prefer: Haptic perception of various wood flooring surfaces. Forest Products Journal, 56: 42-47.
2. Brischke, C.; Iseler, N.; Meyer, L.; Sawyer, G., 2014: Testing the mechanical resistance of timber used for construction in the marine environment. International Wood Products Journal 5: 39-49. https://dx.doi.org/10.1179/2042645313Y.0000000050.
3. Brischke, C.; Rapp, A. O.; Welzbacher, C. R., 2006a: High-energy multiple impact (HEMI)-test – Part 1: A new tool for quality control of thermally modified timber. Document IRG/WP 06-20346. International Research Group on Wood Protection, Stockholm.
4. Brischke, C.; Welzbacher, C. R.; Huckfeldt, T., 2008: Influence of fungal decay by different basidiomycetes on the structural integrity of Norway spruce wood. Holz als Roh- und Werkstoff, 66: 433-438. https://dx.doi.org/10.1007/s00107-008-0257-1.
5. Brischke, C.; Welzbacher, C. R.; Huckfeldt, T.; Schuh, F., 2009: Impact of decay and blue stain causing fungi on the structural integrity of wood. Document IRG/WP 09-10699. International Research Group on Wood Protection, Stockholm.
6. Brischke, C.; Welzbacher, C. R.; Rapp, A. O., 2006b: Detection of fungal decay by high-energy multiple impact (HEMI) testing. Holzforschung, 60: 217-222. https://dx.doi.org /10.1515/HF.2006.036.
7. Brischke, C.; Zimmer, K.; Ulvcrona, T.; Bollmus, S.; Welzbacher, C. R.; Thomsen, O., 2012: The impact of various modification processes on the structural integrity of wood. In: Hill, C. A. S.; Militz, H.; Pohleven, F. (eds.): Proceedings of the 6th European Conference on Wood Modification, Ljubljana, Slovenia, 17-18 September 2012.
8. Despot, R.; Hasan, M.; Brischke, C.; Welzbacher, C. R.; Rapp, A. O., 2007: Changes in physical, mechanical and chemical properties of wood during sterilization by gamma irradiation. Holzforschung, 61: 267-271. https://dx.doi.org /10.1515/HF.2007.064.
9. Esteves, B.; Pereira, H., 2008: Wood modification by heat treatment: A review. BioResources, 4: 370-404.
10. Ghelmeziu, N., 1937: Untersuchungen über die Schlagfestigkeit von Bauhölzern. Holz als Roh- und Werkstoff, 15: 585-603. https://dx.doi.org /10.1007/BF02639957.
11. Huckfeldt, T.; Eichhorn, M.; Koch, G.; Welzbacher, C. R.; Brischke, C., 2010: Bewertung von Schäden an dauerhaften Hölzern am Beispiel von Bongossi (*Lophira alata*). Eur. Sanierungskalender, 2010: 95-108.
12. Lachenbruch, B.; Johnson, G. R.; Downes, G. M.; Evans, R., 2010: Relationships of density, microfibril angle, and sound velocity with stiffness and strength in mature wood of Douglas-fir. Canadian Journal of Forest Research, 40: 55-64. https://dx.doi.org /10.1139/X09-174.
13. Niemz, P.; Sonderegger, W., 2003: Untersuchungen zur Korrelation ausgewählter Holzeigenschaften untereinander und mit der Rohdichte unter Verwendung von 103 Holzarten [Analysis of the correlation between selected wood properties among each other and the density of 103 wood species]. Schweizerische Zeitschrift für das Forstwesen, 154: 489-493.
14. Rapp, A. O.; Brischke, C.; Welzbacher, C. R.; Nilsson, T.; Björdal, C., 2008: Mechanical strength of wood from the Vasa shipwreck. Document IRG/WP 08-20381. International Research Group on Wood Protection, Stockholm.
15. Rapp, A. O.; Brischke, C.; Welzbacher, C. R. 2006: Interrelationship between the severity of heat treatments and sieve fractions after impact ball milling: a mechanical test for quality control of thermally modified wood. Holzforschung, 60: 64-70. https://dx.doi.org /10.1515/HF.2006.012.
16. Sandak, J.; Sandak, A.; Riggio, M., 2015: Characterization and Monitoring of Surface Weathering on Exposed Timber Structures With a Multi-Sensor Approach. International Journal of Architectural Heritage, 9: 674-688. https://dx.doi.org /10.1080/15583058.2015.1041190.

17. Schweingruber, F. H., 2012: Tree rings: basics and applications of dendrochronology. Springer Science & Business Media.
18. Ulvcrona, T.; Lindberg, H.; Bergsten, U., 2006: Impregnation of Norway spruce (*Picea abies* L. Karst.) wood with hydrophobic oil and dispersion patterns in different tissues. Forestry, 79: 123-134. https://dx.doi.org /10.1093/forestry/cpi064.
19. von Pechmann, H., 1953: Untersuchungen über die Bruchschlagarbeit von Rotbuchenholz. Holz als Roh- und Werkstoff, 11: 361-367. https://dx.doi.org /10.1007/BF02607465
20. Welzbacher, C. R.; Rassam, G.; Talaei, A.; Brischke, C., 2011: Microstructure, strength and structural integrity of heat treated beech and spruce wood. Wood Material Science and Engineering 6: 219-227. https://dx.doi.org/10.1080/17480272.2011.622411.
21. Willems, W.; Lykidis, C.; Altgen, M.; Clauder, L., 2015: Quality control methods for thermally modified wood. Holzforschung, 69: 875-884. https://dx.doi.org/10.1515/hf-2014-0185.
22. Yang, J. L.; Evans, R., 2003: Prediction of MOE of eucalypt wood from microfibril angle and density. Holz als Roh- und Werkstoff, 61: 449-452. https://dx.doi.org /10.1007/s00107-003-0424-3.
23. ***DIN Deutsches Institut für Normung 1978: DIN 52186. Prüfung von Holz; Biegeversuch. [Testing of wood; bending test].
24. ***DIN Deutsches Institut für Normung 1981: DIN 52189-1. Prüfung von Holz; Schlagbiegeversuch; Bestimmung der Bruchschlagarbeit. [Testing of wood; Impact bending test; Determination of impact bending strength.]
25. ***ISO International Standardisation Organisation 1996: ISO 5223. Test sieves for cereals. Geneva: International Organization for Standardization.

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