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The Effect of Sheathing Material on Racking Performance of Plywood Shear Wall

Utjecaj materijala za oblaganje na svojstva posmičnog zida od furnirske ploče

ABSTRACT • *Wooden buildings are intensely preferred especially in earthquake regions due to their many advantages such as lightness, durability, environmental friendliness, insulation and aesthetics. Shear walls provide the lateral resistance needed for light-frame wood structures to withstand earthquake loads. When sheathed with wooden structural panels such as plywood, shear walls can be strong, stiff, and ductile. This study focuses on the effects of production factors (wood species, thickness of panels) of plywood and fibre direction of sheathing material on the racking performance of the shear wall. The displacement at ultimate load decreased with increasing the thickness of plywood panels. It was also concluded that the black pine plywood panels were the best sheathing materials for the shear walls among wood species in terms of ductility. Scots pine plywood panels are the best sheathing materials for the shear walls among wood species in terms of load carrying capacity. Moreover, it was found that the wall formed perpendicular to fibre direction of sheathing materials could carry more load than the wall formed parallel to fibre direction.*

KEYWORDS: *shear wall; structural plywood; racking performance, fibre direction*

SAŽETAK • *U potresnim su područjima osobito zastupljene drvene građevine zbog njihovih brojnih prednosti kao što su lakoća, trajnost, ekološka prihvatljivost, izolacija i estetika. Posmični zidovi osiguravaju bočnu otpornost kako bi lagane drvene konstrukcije izdržale potresna opterećenja. Kada su obloženi drvenim strukturnim pločama kao što je furnirska ploča, posmični zidovi mogu biti jaki, kruti i duktilni. Ovo je istraživanje fokusirano na učinke proizvodnih čimbenika furnirske ploče (vrstu drva, debljinu ploče) te na smjer vlakanaca materijala za oblaganje na svojstva posmičnog zida. Pokazalo se da se s povećanjem debljine furnirske ploče smanjuje pomak pri krajnjem opterećenju. Također je zaključeno da su sa stajališta duktilnosti furnirske ploče od drva crnog bora bolji izbor za oblaganje posmičnih zidova nego furnirske ploče od ostalih istraživanih vrsta drva. Sa stajališta nosivosti, za oblaganje posmičnih zidova najboljima su se pokazale furnirske ploče od drva bijelog bora. Osim toga, utvrđeno je da zid formiran okomito na smjer vlakanaca materijala za oblaganje može nositi veće opterećenje nego zid formiran paralelno sa smjerom vlakanaca materijala za oblaganje.*

KLJUČNE RIJEČI: *posmični zid; strukturna furnirska ploča; svojstva nosača; smjer vlakanaca*

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1 INTRODUCTION
1. UVOD

In recent devastating earthquakes around the world, many buildings suffered severe damage, leading to huge social and economic losses (Li *et al.,* 2018). Because of the unique structural characteristics of wood, the use of wood construction has been becoming widespread in the world. Wooden buildings are intensely used especially in earthquake regions due to their many advantages such as lightness, durability, environmental friendliness, insulation and aesthetics. They have also traditionally performed well during past earthquakes and provided a good performance during earthquakes. The investigation on performance of platform-frame wood construction showed a remarkably low fatality level (only 34 people) in the 1964 Alaska earthquake (Magnitude-M: 6.4), 1971, 1989 and 1994 California earthquakes (M: 6.7, 7.1 and 6.7, respectively), 1987 New Zealand earthquake (M: 6.3), 1988 Quebec earthquake in Canada (M: 5.7), 1995 Kobe earthquake in Japan (M: 6.8). Also, a few buildings collapsed, but many buildings (about 375.000) survived strong shaking almost unscathed or with various degrees of superficial and structural damage (Rainer and Karacabeyli, 2000). In addition, Carrero *et al.* (2018) analysed in detail the damage level of light-framed timber buildings during three major contemporary earthquakes, namely the 1994 Northridge Earthquake (M: 6.7), the 2010 Chile Earthquake (M: 8.8), and the 2011 Christchurch Earthquake (M: 6.3), all happening in regions with significant stock of platform-framing timber buildings. They stated that light-framed timber buildings can withstand severe earthquakes with low collapse risk (Carrero *et al.,* 2018). Contrarily, the 1999 Izmit earthquake in Turkey (M: 7.4) unfortunately caused 18 000 deaths, mostly from building collapse, and nearly 300 000 buildings damaged, since concrete and masonry are the primary building materials in Turkey. Therefore, focus has been placed on the awareness of earthquake and development of earthquake-resistant structures in Turkey since 1999. In the last 10 years, approximately 70 earthquakes with the magnitudes between 5 and 7 have occurred in Turkey (AFAD, 2019). The officials predict that there might be a big earthquake in the near future, especially in the Marmara region. Even though Turkey is an earthquake country, the new developments and studies about the wooden buildings have not been sufficiently followed in the country. One of the reasons for that is insufficient research on wood construction in Turkey (Caliskan *et al.,* 2019).

The most important components affecting the structural performance of wooden buildings are shear walls and horizontal diaphragms (Skaggs and Martin, 2004). The shear walls are commonly used to provide stiffness and strength to the structure to resist lateral wind and seismic forces in wood-frame buildings. As a shear wall transfers the wind and earthquakes loads from the roof to the foundation, the wall-to-foundation connection is a critical component in transferring the loads from the wall to the foundation. Failures of this connection can occur due to overturning or sliding of a structure (Shadravan and Ramseyer, 2018). A wood shear wall consists of dimensional lumber sheathed with plywood, oriented strand board (OSB), or other sheathing material (van de Lindt and Walz, 2003). Sheathing material has considerable in plane shear strength. Plywood is a good product as sheathing material in wood shear wall because it is much more rigid when loaded along the thin edge (in plane) as opposed to the large flat surface (out of plane) (Bott, 2005). Additionally, plywood is the best for resisting earthquake loads, since it is able to tolerate the greatest amount of displacement before failing (Demirkir *et al.,* 2013). Li *et al.* (2007) also determined that plywood performs well as a sheathing material in terms of stiffness. There are some studies about the performance of plywood, OSB or other sheathing materials used in different shear wall types (Guíñez *et al.,* 2019; Shadravan *et al.,* 2019; Xiao *et al.,* 2015). However, there are few studies about how plywood manufacturing factors affect structural performance of shear wall sheathed with them. It is known that manufacturing factors of the panels such as wood species, adhesive types, number of layers and pressing parameters affect the mechanical properties of plywood (Bal and Bektas, 2014). It should not be ignored that this might be causing the changing of structural performance of shear wall.

The aim of the study is to investigate the effects of some production factors (wood species, thickness of panels) of plywood and fibre direction of sheathing material on the racking performance of the shear wall.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Wood materials and manufacturing of plywood
2.2. Drvni materijali i proizvodnja furnirskih ploča

Three coniferous tree species were used in this study: Scots pine *(Pinus sylvestris),* black pine (*Pinus nigra*) and spruce (*Picea orientalis* L.). The logs for veneer manufacturing, with an average size of 40 cm, were supplied by Trabzon, located at the northern point of the Black Sea Region of Turkey.

The production of plywood was planned to be carried out in a facility capable of producing large size panels that can be used in shear wall construction. For this aim, veneer peeling, veneer drying, gluing and

pressing were carried out in a factory under controlled conditions. A rotary peeler with a maximum horizontal holding capacity of 80 cm was used for veneer manufacturing. The logs were steamed for 12-16 hours at a temperature of 80 °C before the peeling process and veneer sheets with dimensions of 120 cm by 240 cm by 2 mm were clipped. The vertical opening was 0.5 mm and the horizontal opening was 85 % of the veneer thickness in the veneer manufacturing process. After rotary peeling, the veneers were dried at 110 °C in a veneer dryer until reaching 6-7 % moisture content.

The Eurocode 5 states that the minimum thickness of the plywood boards to be used in shear walls should be 9 mm EN 1995-1, -2:2004). Therefore, five and seven-ply plywood panels, 10 mm and 14 mm thick, were manufactured by using phenol formaldehyde (PF) glue resin with 47 % solid content. The glue was applied at a rate of 160 g/m² to each surface of veneer by using a four-roller spreader. The assembled samples were pressed in a hot press at a pressure of 8 kg/cm² (785 kPa) and at 140 °C for 10 min (five-ply plywood) and 14 min (seven-ply plywood). Five replicate plywood panels were manufactured from each group. Before the tests, the density of plywood panels was determined according to EN 323:1993. The results of density according to wood species are given in Table 1.

Table 1 Density results of plywood panels
Tablica 1. Gustoća ispitivanih furnirskih ploča

Wood species *Vrsta drva*	Thickness of panel, mm *Debljina ploča, mm*	Density, g/cm³ *Gustoća,* g/cm³	
		X	S
Scots pine	10	0.59	0.03
drvo bijelog bora	14	0.66	0.04
Black pine	10	0.57	0.14
drvo crnog bora	14	0.61	0.07
Spruce	10	0.51	0.07
smrekovina	14	0.49	0.03

2.2 Modelling and sheathing of shear wall
2.2. Modeliranje i oblaganje posmičnog zida

Standard wood frame dimensions for each group of panels and the positioning, mounting and fastening of the produced plywood in this frame are given in Figure 1 according to ASTM E 72 (2014) standard.

All shear walls, 2.4 m x 2.4 m in size were constructed with 50 mm x 100 mm spruce framing members. The upper element and the edges were made of twin pieces of timber beam. Two repetitive frame systems were installed for each group. Each frame was nailed by 2 plywood panels in size of 1.2 m x 2.4 m. Power driven nails (6d) of 3.1 mm in diameter and 63
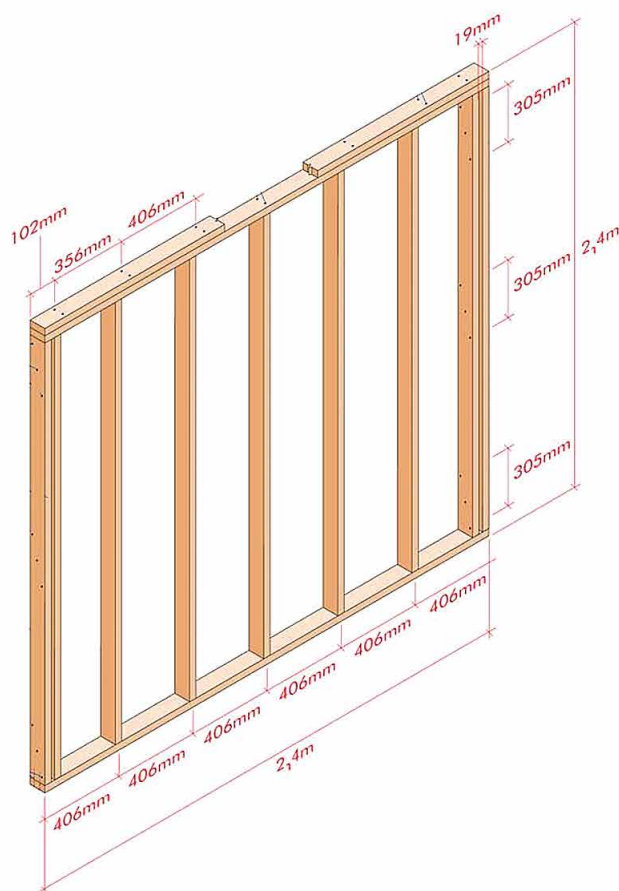

Figure 1 Standard wood frame (ASTM E 72, 2014) and shear wall sheathing with plywood
Slika 1. Standardni drveni okvir (ASTM E 72, 2014) i posmični zid obložen furnirskom pločom

Figure 2 Shear walls formed according to fibre direction (a: perpendicular, b: parallel)
Slika 2. Posmični zidovi formirani prema smjeru vlakanaca (a: okomito, b: paralelno)

Figure 3 Mounting of shear wall to floor
Slika 3. Montaža posmičnog zida na pod

mm in length were used to connect the framing material and the plywood panels. 76 mm nail spacing along the panel edges and 152 mm spacing along the interior studs were used. The plywood of each frame group was tested in two different fibre directions (Figure 2). Connections to the floor of the frame system were made with fittings suitable for concrete floors (Figure 3).

In order to achieve the aim of the study, the description of the shear wall models formed according to the wood species, thickness of plywood and fibre direction of shear wall is given in Table 2.

2.3 Determining racking performance of shear walls
2.3. Utvrđivanje svojstava posmičnih zidova

Shear wall analysis test was carried out under linear load according to ASTM E 72 (2014) standard. The experimental test setup is given in Figure 4.

The shear walls were loaded in three stages to 3.5 kN, 7 kN and 10.5 kN at a uniform rate. After the load of 3.5 kN was placed on the walls, all of the load was removed and any residual displacement in the panel was noted. Then the walls were loaded to 7 kN and again the load was removed and any additional displacement was noted; after this the loading was increased to 10.5 kN, the load was removed again, and the displacement was noted. After the shear wall was loaded as specified to 3.5 kN, 7 kN and 10.5 kN, it was loaded again to failure or until the total displacement of the panel reached 100 mm. As a result of the analysis, maximum load and displacement values were obtained to determine the racking performance of each shear wall group.

Multivariate analysis of variance was performed for statistical evaluation of the changes in the maximum loads and displacements at ultimate load depending on the wood species, thickness of panel and fibre directions of the shear wall. After multivariate analysis, Student–Newman–Keuls test with 95 % confidence level was used to compare the mean values of variance sources.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Racking performance of shear walls
3.1. Svojstva posmičnih zidova

The wall groups were tested according to ASTM E 72 (2014) and some calculations were made for the racking performance of the walls in the current study.
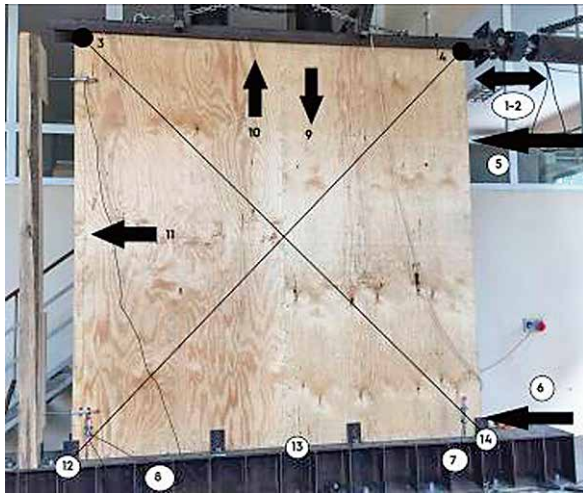
Table 2 Description of models formed within scope of study
Tablica 2. Opis modela izvedenih u sklopu istraživanja

Wall number *Broj zida*	Wood species *Vrsta drva*	Thickness of panel, mm *Debljina ploče,* mm	Fibre direction *Smjer vlakanaca*
Wall 1	Scots pine *drvo bijelog bora*	10	Perpendicular / *okomito*
Wall 2			Parallel / *paralelno*
Wall 3		14	Perpendicular / *okomito*
Wall 4			Parallel / *paralelno*
Wall 5	Black pine *drvo crnog bora*	10	Perpendicular / *okomito*
Wall 6			Parallel / *paralelno*
Wall 7		14	Perpendicular / *okomito*
Wall 8			Parallel / *paralelno*
Wall 9	Spruce *smrekovina*	10	Perpendicular / *okomito*
Wall 10			Parallel / *paralelno*
Wall 11		14	Perpendicular / *okomito*
Wall 12			Parallel / *paralelno*

1: Applied load / *Primijenjeno opterećenje*
2: Applied load / *Primijenjeno opterećenje*
3: Diagonal displacement / *Dijagonalni pomak*
4: Diagonal displacement / *Dijagonalni pomak*
5: Displacement at the top / *Pomak na vrhu*
6: Sliding on the floor / *Pomak na podu*
7-8: Upward movement in floor connections / *Kretanje prema gore u podnim spojevima*
9-11: Plywood movements / *Kretanja furnirske ploče*
12-14: Displacement of beams / *Pomak greda*

Figure 4 Experimental test setup
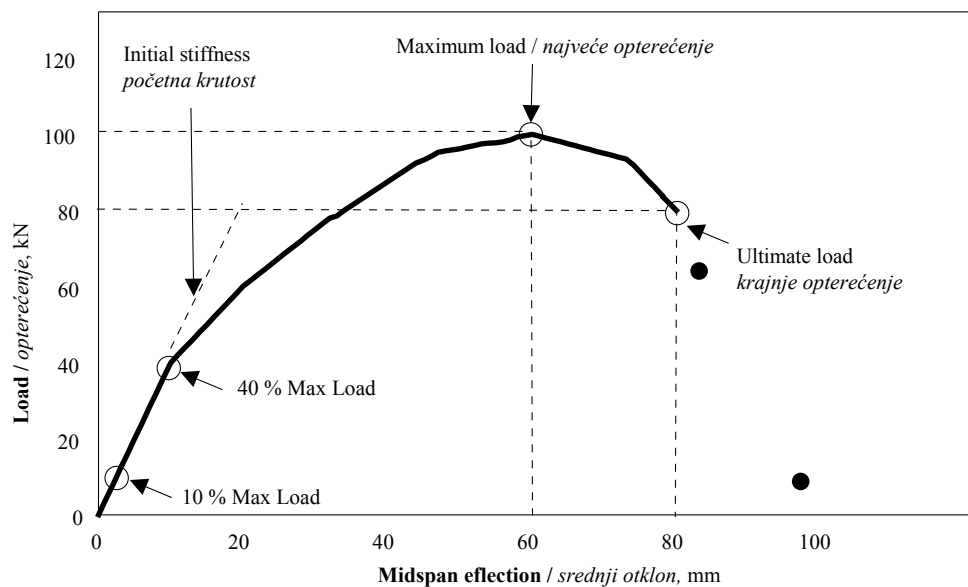**Slika 4.** Postavka eksperimenta

Figure 5 Analysis of a load-displacement curve (Pirvu, 2008)
Slika 5. Analiza krivulje opterećenje – pomak (Pirvu, 2008.)

The following properties shown in Figure 5 were calculated according to Figure 6 for each wall tested and the results are given in Table 3 together with the maximum load and displacement at the maximum load:

- Initial stiffness, by selecting the points closest to 10 % and 40 % of the maximum load and fitting a straight line to the intervening points;
- Ultimate load, as 80 % of the maximum load;
- Displacement at ultimate load; identified based on the calculated ultimate load.

Stiffness is one of the most important parameters for structural panels. If the panels are used as sheathing material in a shear wall that has higher stiffness, they will be more resistant to earthquake loads (Demirkir and Colakoglu, 2015). As shown in Table 3, Wall 3 manufactured with Scots pine seven ply-plywood perpendicular to the fibres showed the highest stiffness, whereas Wall 10 manufactured with spruce five ply-plywood parallel to the fibres showed the lowest stiffness value. In addition to stiffness, ductility is also an important factor, being defined as the ability to deform structures especially under the effect of load. The displacement values at ultimate load can be compared in determining the ductility properties of the walls. According to Table 3, Wall 8 manufactured with black pine seven ply-plywood perpendicular to the fibres showed the highest displacement value at ultimate load, whereas Wall 3 manufactured with Scots pine seven ply-plywood perpendicular to the fibres showed the lowest value. Xiao *et al.* (2015) examined the shear walls sheathed with bamboo plywood at 9 mm thickness and they found stiffness values between 0.89 kN/mm and 1.09 kN/mm. In another study on shear walls sheathing plywood panels, the stiffness value of

Table 3 Results of racking performance of shear walls
Tablica 3. Izmjerene vrijednosti svojstava posmičnih zidova

Wall number Broj zida	Maximum load, kN Najveće opterećenje, kN	Displacement at maximum load, mm Pomak pri najvećem opterećenju, mm	Ultimate load, kN Krajnje opterećenje, kN	Displacement at ultimate load, mm Pomak pri krajnjem opterećenju, mm	Stiffness, kN/mm Krutost, kN/mm
Wall 1	44.80	75.95	35.84	89.99	0.88
Wall 2	42.98	84.98	34.38	87.26	0.69
Wall 3	39.99	48.24	32.00	64.99	1.48
Wall 4	42.26	66.17	33.81	67.23	0.73
Wall 5	42.06	75.84	33.65	89.98	1.15
Wall 6	39.73	95.77	31.78	99.96	0.97
Wall 7	42.01	74.65	33.61	89.98	1.13
Wall 8	39.88	94.78	31.91	100.17	0.98
Wall 9	27.01	84.99	21.60	85.02	0.93
Wall 10	30.69	80.44	24.55	87.75	0.61
Wall 11	37.68	85.65	30.15	87.68	0.93
Wall 12	26.51	63.25	21.21	87.75	0.70

1.3 kN/mm was found (FEMA, 2001). Okabe *et al.* (2000) found the stiffness of shear walls sheathing Canadian Softwood Plywood between 0.38 and 0.7 kN/mm. In this study, the stiffness values were found in between 0.61 and 1.48 kN/mm, which is similar to those of literature studies.

As a result of the statistical analysis, the effects of wood species, thickness of panel and fibre directions of the wall groups on the maximum load and displacements at ultimate load were found significant. Student–Newman–Keuls test with 95 % confidence level was used to compare the mean values of variance sources and the results are given in Table 4.

When the effect of wood species on the maximum load carried by the walls is examined, the walls sheathing Scots pine plywood gave higher results than other species (Table 4). It can be explained by density values of plywood panels. As can be seen from Table 1, Scots pine has the highest values in density among all wood species. Demir *et al.* (2019) stated that there was a positive correlation between the maximum load carried by the shear wall and density.

Table 4 Racking performance results of Student–Newman–Keuls test at 95 % confidence level
Tablica 4. Rezultati Student-Newman-Keulsova testa za svojstva posmičnog zida pri razini značajnosti od 95 %

Properties Svojstva	Factors Činitelji	LS Mean Srednja vrijednost LS	Homogenous groups* Homogene grupe*
Maximum load, kN najveće opterećenje, kN	Wood species of plywood / vrsta drva furnirske ploče		
	Scots pine / drvo bijelog bora	42.51	c
	Black pine / drvo crnog bora	40.92	b
	Spruce / smrekovina	30.47	a
	Thickness of panel, mm / debljina ploče, mm		
	10	37.88	a
	14	38.01	a
	Fibre direction of wall / smjer drvnih vlakana na zidu		
	Perpendicular / okomito	38.93	b
	Parallel / paralelno	37.00	a
Displacement at ultimate load, mm pomak pri krajnjem opterećenju, mm	Wood species of plywood / vrsta drva furnirske ploče		
	Scots pine / drvo bijelog bora	77.37	a
	Black pine / drvo crnog bora	95.02	c
	Spruce / smrekovina	87.05	b
	Thickness of panel, mm / debljina ploče, mm		
	10	89.99	b
	14	82.97	a
	Fibre direction of wall / smjer drvnih vlakana na zidu		
	Perpendicular / okomito	84.61	a
	Parallel / paralelno	88.35	b

*Different letters denote statistically significant differences. / Različito slovo označuje statistički značajnu razliku.
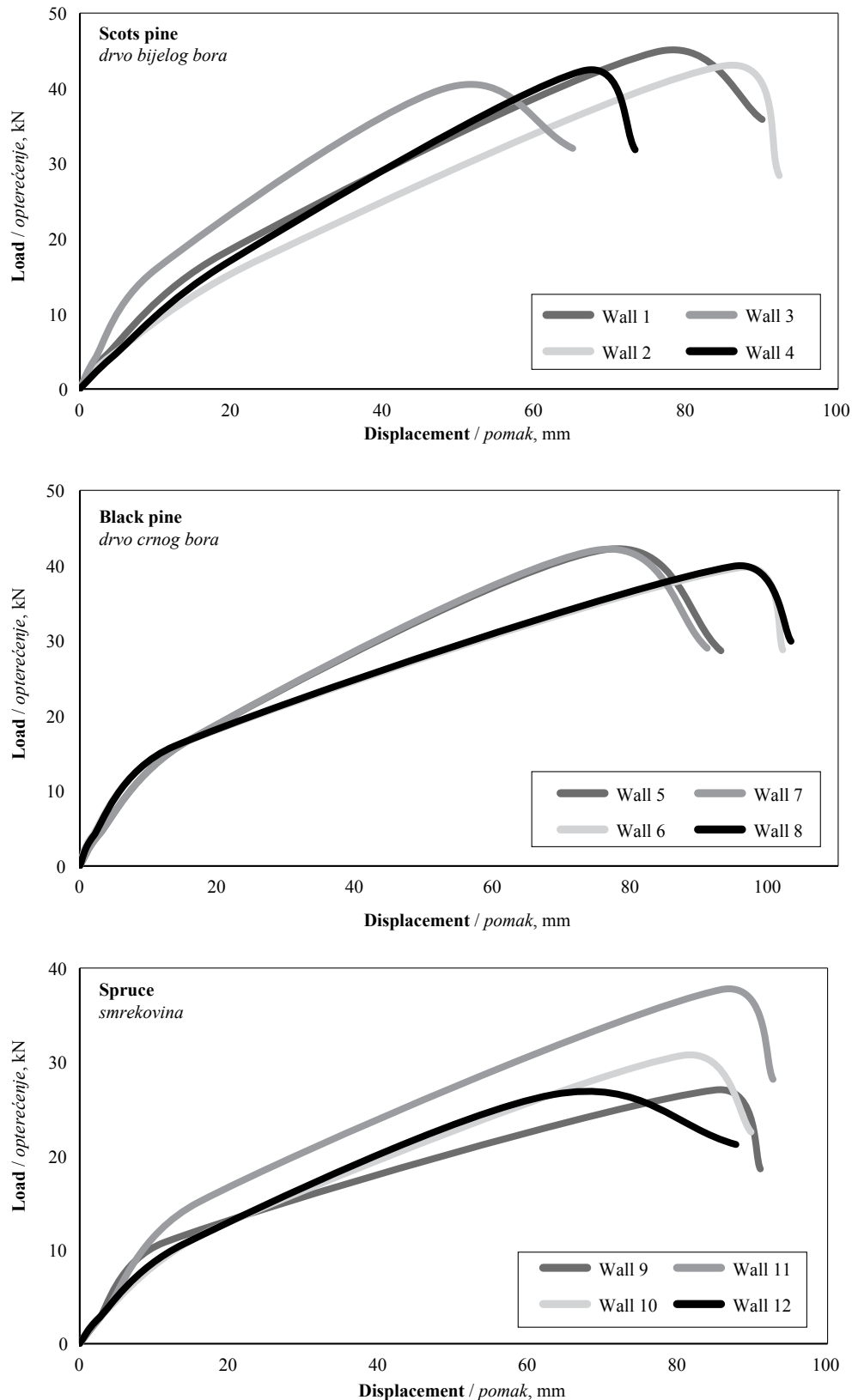
Figure 6 Load-displacement relationship for shear walls sheathed with plywood
Slika 6. Odnos opterećenje – pomak za posmične zidove obložene furnirskom pločom

It is stated that the lateral load resistance of a timber frame system depends on the rigidity of the timber, the sheathing material and the connecting elements used on the shear wall (Li *et al.*, 2007). Demirkir *et al.*

(2013) stated that the effect of veneer wood species on maximum load was significant and the difference in wood species was determined to have a small but significant effect on resistance and stiffness. The highest
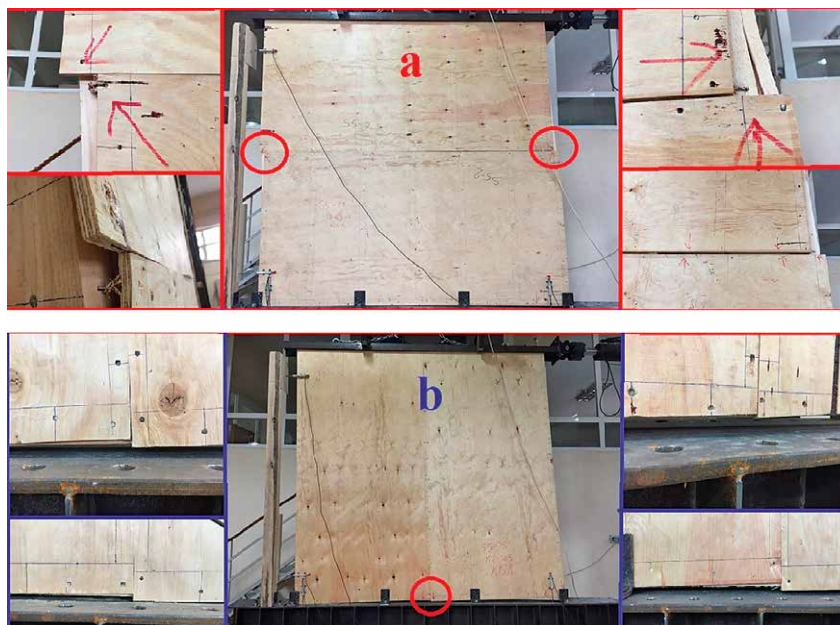
Figure 7 Failure modes of shear walls formed according to fibre direction (a: parallel, b: perpendicular)
Slika 7. Načini loma posmičnih zidova nastali s obzirom na smjer drvnih vlakanaca (a: paralelno, b: okomito)

displacement value at ultimate load was obtained from the shear wall sheathing black pine plywood as compared to other groups (Table 4).

There is no statistically significant difference between the maximum load value of the shear walls with seven and five ply-plywood panels. However, the mean of maximum load of the seven ply-plywood panels was slightly higher than that of the five ply-plywood panels. Han *et al*. (2018) stated that thicker sheathing panels could bear larger lateral shearing loads compared with thinner ones. Also, plywood thickness tends to increase the load carry capacity and stiffness of the hybrid system (Kho *et al.,* 2018). In Table 4, the highest displacement value at ultimate load was obtained from the shear wall sheathing five ply-plywood. Wang *et al. (*2017) examined the lateral loading performance of two different thickness bamboo plywood (6 mm and 9 mm) and they found that increases in thickness of sheathing panels increased the deformability of some groups of shear walls. The size, thickness and material property of the sheathing material have to be designed for effectively resisting the lateral forces and they are critical in providing enough resistance, stiffness and ductility to the system when subjected to earthquake ground motions (Jayamon, 2017).

As shown in Table 4, the maximum load values of shear wall sheathing perpendicular to the fibre directions were higher than those parallel to the fibre directions. Similar results were obtained in the study by Kho (2018). In Table 4, the highest displacement value at ultimate load was obtained from the shear wall sheathing parallel to fibre directions. Similarly, it was found that displacement values of shear wall produced paral-

lel to face grain were larger than those of shear wall produced perpendicular to face grain (Han *et al.,* 2018). The connections nailed perpendicular to grain had significantly lower ultimate displacement due to the tendency of plywood splitting, thus leading to 12 – 45 % lower ductility than the connections nailed parallel to grain (Kho, 2018).

3.2 Failure modes of shear walls

As shown in Figure 9, with the monotonic loading process going on, the nail joints failed as consequence of relative displacement between the sheathing panels and the timber frame. The wall formed perpendicular to fibre direction was less deformed than that formed parallel to fibre direction. Especially, the failure mode of the wall formed parallel observed in all the walls was due to the cutting of sheathing nails, pull out of the nails in the edges of the wall sheathing and crushing of plywood panel by nails head (Figure 7a). The walls formed parallel to fibre direction were displaced more at ultimate load. The main failure mode of the wall formed perpendicular included the dislocation of the panels (Figure 7b). When the loading exceeded the maximum bearing capacity of the nail joints between studs and bottom plate, the relative displacement uplifted the studs and shear walls were wrecked when the nails were withdrawn from the adjacent studs (Han *et al.,* 2018).

The predominant failure mode of the walls was the failure of sheathing to framing nail connections on either side of the wall. The failure never occurred simultaneously on both ends of the wall. The shear wall sheathed with spruce plywood panels failed more than the walls

sheathed with other species. Moreover, the wall covered with five ply-plywood was damaged more, because it had larger displacement at ultimate load than the wall covered with seven ply-plywood panels.

4 CONCLUSIONS
4. ZAKLJUČAK

The effects of production factors (wood species, thickness of panel) of plywood and fibre direction of sheathing material on the racking performance of the shear wall were investigated in this study. The maximum load capacity of the wall increased with increasing the density values of plywood panels. It was determined that the Scots pine plywood panels are the best sheathing materials for the shear walls among wood species in terms of load carrying capacity. Moreover, it was found that the wall formed perpendicular to fibre directions sheathing materials can carry more load than the wall formed parallel to fibre directions. The thickness of panel had no statistically relevant impact on the maximum load capacity. The displacement at ultimate load of the wall is significant for determining the ductility of the shear walls. It was also concluded that the black pine plywood panels were the best sheathing material for the shear walls among wood species in terms of ductility. In addition, the wall formed parallel to fibre directions sheathing materials could carry more load than the wall formed perpendicular to fibre directions. The displacement at ultimate load decreased with increasing the thickness of plywood panels. When analysing the failures modes at the end of the test, it was determined that the walls formed parallel to fibre directions were more damaged than the walls formed perpendicular to fibre directions. However, it was seen that the walls were able to withstand loads undergoing displacement for a long time.

This study shows that plywood panels manufactured from softwood species growing in Turkey can be used in wood frame buildings as a sheathing material in shear walls designed to withstand lateral loads such as earthquakes.

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