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Design of Natural Fiber Reinforced Polymer Composite

Mario KRAJINOVIĆ , Gojko MARIĆ* and *Mateja ŠNAJDAR

Fakultet strojarstva i brodogradnje, Sveučilište u Zagrebu (Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb), Ivana Lučića 5, HR-10000 Zagreb, **Republic of Croatia**

mariokrajinovic@gmail.com

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One of the main disadvantages of composite materials like glass or carbon fiber reinforced composites in use today is their inability to be recycled. After the end of a product or part life cycle, there is no way to separate the fibers from the matrix, or to recycle them except for deposition or shredding. Bio-polymer based composites have an increasing and bright future due to their recyclability, reproduction capability, available sources and economic factors without the fundamental loss of mechanical properties. This paper deals with natural – bamboo fiber reinforced composite material design and its basic mechanical properties testing.

Izrada polimernog kompozita ojačanog prirodnim vlaknima

Izvornoznanstveni članak

Jedan od velikih nedostataka sadašnjih kompozitnih materijala poput kompozita sa staklenim ili ugljičnim vlaknima jest nemogućnost njihova recikliranja. Nakon isteka vijeka trajanja proizvoda ili dijela, iz kompozitnih materijala trenutno nije moguće razdvojiti vlakna i matricu, niti ih reciklirati drugim metodama osim deponiranjem ili usitnjavanjem za agregat pri polaganju cesta. Bio-polimerni kompoziti imaju sve veću primjenu i svijetlu budućnost upravo iz razloga recikličnosti, lake obnovljivosti, dostupnih izvora i ekonomičnosti, bez znatnih gubitaka mehaničkih svojstava. U ovom radu pokazana je izrada kompozitnog materijala, poliesterske matrice, ojačanog prirodnim, bambusovim vlaknima, te ispitivanje osnovnih mehaničkih svojstava ispitnog uzorka.

1. Introduction

Bamboo is a group of evergreens in the true grass family lat. Poaceae which abundantly grows in most tropical areas. Due to its specific structure made of cellulose fibers distributed in lignin matrix it presents a type of natural composite. Orientation of cellulose fibers which provide maximum tensile strength in the same direction is determined by the fiber growth line. Over 1200 species of bamboo, which is one of the oldest construction materials, have been indentified worldwide. When comparing bamboo to the normal wood stem some differences arise.

First one relates to its structure i.e. structure of vascular bundles radially scattered throught the stem instead of cylindrical arrangement specific for hardwood stem.

Bamboo stem is hollow and can have a very thin wall which sometimes makes joining very difficult unlike hardwood joining. Bamboo is a good alternative for many materials due to its low price, renewability and very good physical and mechanical properties. Current high demand for environmentally friendly materials makes natural composites very acceptable considering the wide range of their dismantling and recycling possibilities.

Chemical composition of bamboo and wood are similar. Main constituents such as cellulose, hemicelluloses and lignin make 90 % of its overall mass. Resin, tannin, waxes and inorganic salts are less present components. Other organic ingredients besides cellulose and lignin, such as 2 - 6 % of starch, 2 % of saccharides, 2 - 4 % of fat and 0,8 - 6 % of proteins are also present in bamboo composition.

Sensibility of bamboo to fungal diseases and pests is well known while its natural durability varies between 1 and 36 months dependant on the species and climatic conditions. High ash content of some bamboo species can negatively affect mechanical processing.

Individual samples of natural material such as bamboo timber can display significantly different physical and mechanical properties which makes use of standards and classification by WBO-a (World Bamboo Organization) very important for shops with bamboo products. Value of bamboo as material can be illustrated with mechanical properties comparison to wood and other omnipresent materials such as steel and concrete (Table 1). In comparison to its mass bamboo possesses better mechanical properties than wood and many other materials. With 1 % change of moisture content bamboo timber contracts or swells by about 0,14 % and has

Symbols/Oznake

b	- specimen width, mm - širina epruvete	h_2	- lower position of Charpy striker, m - donja pozicija bata
E	- impact energy, J - udarna radnja loma	l	- specimen length, mm - duljina epruvete
E_f	- flexural modulus, N/mm² - savojni modul elastičnosti	L	- length of the support span, mm - razmak između oslonaca
F	- force, N - sila	m	- mass of Charpy striker, kg - masa bata
F_{max}	- force at maximum load, N - maksimalna sila	R_{ms}	- flexural strength, N/mm² - savijna čvrstoća
G	- flexural modulus, N/mm² - savijni modul elstičnosti		**Greek letters/Grčka slova**
g	- acceleration due to gravity, ms^{-2} - gravitacija	ΔF	- force increment, N - prirast sile
h	- specimen hight, mm - visina epruvete	Δf	- specimen deflection, mm - progib
h_1	- highest position of Charpy striker, m - gornja pozicija bata	Δh	- difference in height between two positions of Charpy striker - visinska razlika između dva položaja udarnog bata

moisture balance content of 10 % at 20 °C and 65 % of relative humidity. [1]

Table 1. Bamboo tensile strength and Young's modulus comparison to other materials [2]

Tablica 1. Usporedba čvrstoće i modula elastičnosti bambusa u odnosu na ostale materijale [2]

Material / Materijal	Strain / Naprezanje, N/mm²	Density / Gustoća, kg/m³	Ratio / Omjer
	Strength / Čvrstoća		
Concrete / Beton	8	2400	0,003
Steel / Čelik	160	7800	0,020
Wood / Drvo	7,5	600	0,013
Bamboo / Bambus	10	600	0,017
	Young's modulus / Youngov modul, N/mm²		
Concrete / Beton	25 000	2400	10
Steel / Čelik	210 000	7800	27
Wood / Drvo	11 000	600	18
Bamboo / Bambus	20 000	600	33

2. Natural fiber reinforced polymer composite

Design of natural fiber reinforced composite requires a relatively small amount of equipment and raw material. Dried 25-30 cm long and 3 cm in diameter bamboo chucks were used as raw material.

Due to lack of fiber extraction apparatus, the best method for manual fiber extraction needed investigation. High strength of bamboo made shredding with hammer and soaking in water necessary to separate the stem and enable manual extraction of individual fibers. Manual extraction is a complex procedure which often results in uneven fibers. During extraction, fibers with very good cross-section surface/length ratio were often broken or bent at lengths of approximately 4 cm which proved to be too short for producing samples in 20x20 cm mould. Figure 1 shows manually extracted fibers. All specimens were obtained at the Laboratory for non-metals at Faculty of Mechanical Engineering and Naval Architecture in Zagreb.

A very simple and economical procedure for obtaining hand-laid composite material specimens has been used. Hand-laying is a process during which fibers are manually placed in a weaving pattern inside a mould. Resin which is placed on top of prepositioned fibers is impregnated into fibers with rollers or brushes. Resin solidification occurs at atmospheric conditions. Polyester and epoxy resins are most common matrix materials, but other sorts such as vinyl ester and phenol resins can be used. A wide range of materials can be used for fiber production.

Some advantages and disadvantages of described production method are:

Figure 1. Fibers after drying

Slika 1. Vlakna nakon sušenja

Advantages:

- quick and simple procedure used for some time now
- production without size, geometric and volume constraints
- good surface quality
- low tool design cost
- great variety of materials and suppliers

Disadvantages:

- procedure quality is highly dependent on worker skills
- difficulty of producing composites with low resin content without cracks
- resins with low viscosity have to be used which influences final product properties

Overall extracted fiber mass was 40,3 grams. To obtain sufficient specimen thickness a set of fibers was divided into four parts of equal mass in order to obtain layers used for fiber weaving. Orientation of 0-90^0 was used during this experiment as shown in Figure 2 due to small amount of fibers, their nonuniformity and lack of weaving apparatus. Described fiber orientation reduces negative effects of one-way orientation and enables a wider range of mechanical properties testing.

Due to lack of better procedures such as vacuum bonding which provides possibility of eliminating air trapped between composite layers and uniform fiber positioning, manual fiber depositing was slowly and carefully conducted in a way that minimizes its negative features.

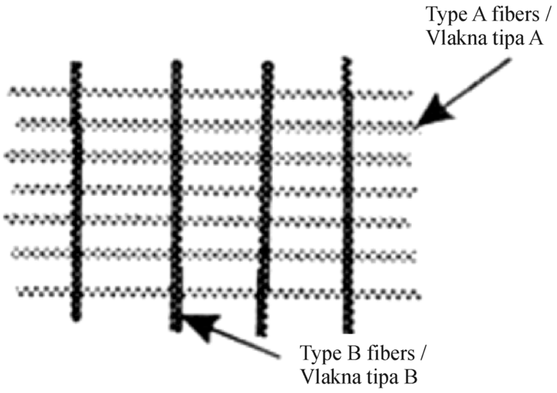

Figure 2. Schematic representation of fiber orientation [3]

Slika 2. Shematski prikaz usmjerenosti vlakana [3]

In order to create a good base for fibers which will hold them in place, resin deposition was conducted as a first phase of composite production. Without resin first introduced fibers would stick to the brush and not be oriented in a desired way. Depositing first composite layers proved to be difficult due to low resin viscosity and previously mentioned issues.

Desired fiber orientation had to be done on almost every fiber individually but due to fiber nonuniformity special attention was given to the general orientation of one layer and not an individual fiber (Figure 3).

Figure 3. Resin and fibers layer deposition

Slika 3. Polaganje sloja vlakana i smole

Incomplete coverage of the entire mould surface is another problem specific to manual extraction and fiber laying which is particularly evident at the edges of specimen. This negative feature was later eliminated by removing that part of a specimen.

In order to secure uniform resin distribution and eliminate as much air from the mould as possible it was necessary to provide sufficient pressure on the mould. This was achieved by positioning 35 kg weights on top of the mould and providing enough time during 3 days for drying, solidification and structure crosslinking. By cutting the panel fifteen specimens divided in three groups of five were obtained for mechanical properties testing purposes (Figure 4).

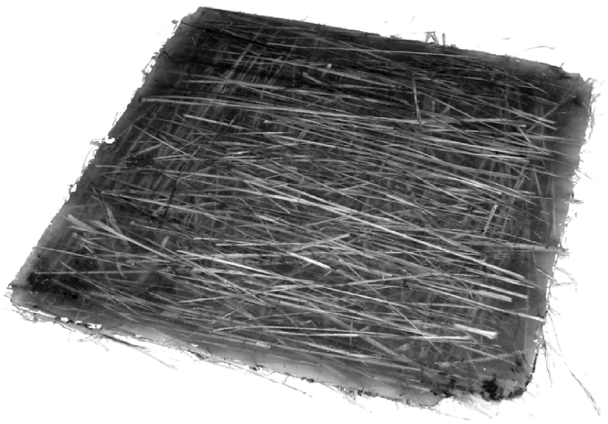

Figure 4. Composite product

Slika 4. Kompozitni izradak

3. Mechanical properties testing

Testing of mechanical properties was conducted on fifteen specimens of three different shapes in order to obtain information about the following properties:

- impact energy
- flexural modulus
- laminar flexural strength

Impact energy measures energy absorbed for deformation and fracture of notched specimen. This energy can be calculated with the following expression:

$$E = mg\Delta h. \quad (1)$$

with:

E, J- impact energy (impact toughness)

m, kg - Charpy striker mass

$g = 9{,}81$, m/s^2 - gravity acceleration

$\Delta h = h_1 - h_2$, m-difference in height between two positions of striker mounted at the end of a pendulum

The Charpy test is the most commonly used to evaluate the relative toughness or impact toughness of materials and as such is often included in the majority of material standards and specifications. Nine instead of five specimens were prepared for testing according to Charpy.

Four specimens showed significant deviation of measured values. Measurement variations occurred due to very low fiber content or presence of very wide fiber in the tested area which is a consequence of manual deposition procedure. These results were therefore excluded and eight new specimens were prepared which provided sufficient number of viable results.

V-notched specimens are shown in Figure 5, their dimensions and test results are given in Table 2.

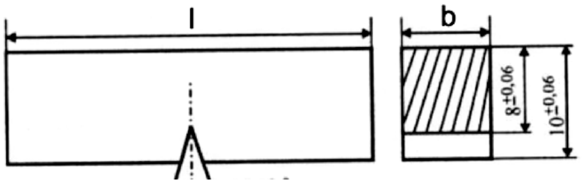

Figure 5. Schematic representation of V-notched specimen [4]

Slika 5. Shematski prikaz savojne epruvete s V zarezom [4]

Table 2. Specimen dimensions and impact energy testing results

Tablica 2. Dimenzije epruveta i rezultati dobiveni ispitivanjem udarne radnje loma

Specimen / Uzorak	**Specimen dimensions / Dimenzije uzorka, mm**			**Impact energy / Energija udara**	
	b	***h***	***l***	**Kp**	**J/mm² (*)**
C1	10,1	8,02	80	1,8	
C2	10,2	8,2	80	1,1	
C3	9,88	8,16	80	4,0	0,0392
C4	9,54	8,04	80	4,1	0,0402
C5	9,82	8,1	80	8,0	
C6	9,98	8,07	80	5,9	0,0579
C7	9,91	8,2	80	4,1	0,0402
C8	9,96	7,98	80	9,5	
C9	9,95	7.97	80	2,6	0,0255
* 1 J = 9,80665 kp/m					

Table 3. Comparison composite plate: Matt glass 300g/m^2, tix-scot bader resin (CHROMOS) [5]

Tablica 3. Usporedbena ploča: Mat stakleni 300g/ m^2, smola tix- scot bader (CHROMOS) [5]

Specimen / Uzorak	***b*, mm**	***h*, mm**	***L*, mm**	**J**	**J/mm²**
1	10,00	4,60	62	3,43	0,075
2	10,30	4,60	62	3,57	0,075
3	10,50	3,90	62	3,10	0,076
4	10,30	4,40	62	3,10	0,068
5	10,20	4,70	62	3,55	0,074

Table 4. Dimensions and flexural strength values of tested specimens

Tablica 4. Dimenzije i vrijednosti savojne čvrstoće ispitivanih epruveta

specimen / uzorak	Specimen dimensions / Dimenzije uzorka, mm			Flexural strength / Čvrstoća na savijanje	F_{max}, N
	b	*h*	*l*	N/mm^2	
B1	9,16	10,04	120	95,27	352
B2	9,12	9,86	120	55.31	252
B3	9,08	9,62	120	66,72	294
B4	9,10	9,52	120	90,42	396
B5	9,08	9,7	120	63,47	282

Table 5. Comparison composite plate: Matt glass 300g/m^2, tix-scot bader resin (CHROMOS) [5]

Tablica 5. Usporedbena ploča: Mat stakleni 300g/ m^2, smola tix- scot bader (CHROMOS) [5]

Spec. / Uzorak	*h*, mm	*b*, mm	*F/f*	*L*, mm	*E*, N/mm^2	R_{ms}, N/mm^2	F_{max}, N
1	2,9	10,5	32,052	64	8202,6	243,5	224
2	3,2	10,2	44,622	64	8749,4	220,6	240
3	3,2	10,3	42,61	64	8273,8	249,4	274
4	3,4	10,3	42,831	64	6933,7	211,2	262
5	3,5	10,1	42,014	64	6358,4	190,9	246

Mechanical properties of materials in bending stress conditions are determined by means of a bend test machine with the help of specimen positioning apparatus.

Five rectangular cross-section specimens were chosen for this testing with dimensions given in Table 4. Forces under which specimen fracture occurred are also presented. In order to determine laminar flexural strength a 3-point bending test has been conducted (Figure 6).

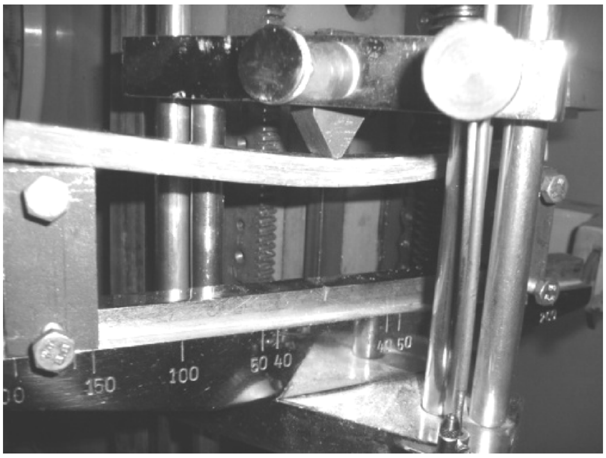

Figure 6. Specimen undergoing 3-point bending test

Slika 6. Savijno ispitivanje epruvete

Table 6. Specimen dimensions and deflection obtained for corresponding force increment

Tablica 6. Dimenzije epruveta i dobiveni progibi za odgovarajući prirast sile

specimen / uzorak		A1 *		A2 **		A3		A4		A5	
Dimensions / Dimenzije, cm		b_1=15,24	h_1=9,9	b_2=15,22	h_2=9,9	b_3=15,33	h_3=9,2	b_4=15,2	h_4=9,4	b_5=15,34	h_5=9,6
Deflection / Progib, cm	Force increment / Porast sile, N	0,74	20	0,05	4	0,29	10	0,34	10	0,26	10
		1,54	40	0,18	8	0,87	20	0,59	20	0,65	20
		1,82	60	0,33	12	1,03	30	0,79	30	0,82	30
		2,18	80	0,57	16	1,19	40	1,00	40	0,92	40
		2,78	**100**	0,71	20	1,38	50	1,22	50	1,17	50
				0,81	24	1,61	60	1,45	60	1,29	60
				0,87	28	1,84	70	1,67	70	1,48	70
				0,96	32	2,08	80	1,91	80	1,66	80
				1,03	36	2,32	90	2,12	90	1,97	90
				1,07	40	3,02	100	2,39	100	2,14	100
				1,17	44	3,37	110	2,64	110	2,35	110
				1,24	48	3,73	120	2,94	120	2,57	120
				1,34	52...	4,35	**130**	3,22	130...	2,80	130...
				1,58	**186**			3,81	**210**	3,03	**214**

Flexural modulus was tested on five specimens with dimensions given in Table 6. Testing was conducted in the same way as the bending test but with different measurements which are also shown in Table 6.

Due to the fact that force increment needed for flexural modulus testing was still unknown, the first two specimens were used for obtaining flexural stress increment range. An increment of 20N has been proved to cause specimen fracture after five steps, while an increment of 4 N led to increased number of steps which were not relevant for measuring. The remaining specimens were subjected to force increment of 10N in each step, which resulted in adequate results.

Flexural modulus can be calculated by the following expression:

$$E = \frac{l^3}{4 \cdot b \cdot h^3} \cdot \frac{\Delta F}{\Delta f}. \tag{2}$$

With:

E_f, N/mm^2 –flexural modulus

l, mm – specimen length

b, mm – specimen width

h, mm – specimen thickness

ΔF, N – force increment

Δf, mm – specimen deflection

Table 7. Measured results for flexural modulus

Tablica 7. Rezultati mjerenja savojnog modula elastičnosti

specimen / uzorak	***h*, cm**	***b*, cm**	***F/f*,**	***l*, cm**	**E_f, kN/mm^2**	**F_{max}, N**
1	9,9	15,24	35,791	18,5	3,831	100
2	9,9	15,22	117,721	18,5	12,618	186
3	9,2	15,33	29,885	18,5	3,963	130
4	9,4	15,2	55,118	18,5	6,911	210
5	9,6	15,34	70,627	18,5	8,237	214
					∑=7,112	

Table 8. Comparison composite plate: Matt glass 300g/ M^2 tix-scot bader resin(CHROMOS) [5]

Tablica 8. Usporedbena ploča: Mat stakleni 300g/ m^2, smola tix- scot bader (CHROMOS) [5]

specimen / uzorak	***h*, mm**	***b*, mm**	***F/f*,**	***L*, mm**	***E*, N/mm^2**	**R_{ms}, N/mm^2**	**F_{max}, N**
1	2,9	10,5	32,052	64	8202,6	243,5	224
2	3,2	10,2	44,622	64	8749,4	220,6	240
3	3,2	10,3	42,61	64	8273,8	249,4	274
4	3,4	10,3	42,831	64	6933,7	211,2	262
5	3,5	10,1	42,014	64	6358,4	190,9	246
				S	**7703,6**	**223,1**	

Results given in Table 6 are comparable to the ones gathered during testing glass fiber reinforced polymer composite at the Faculty of Mechanical Engineering and Naval Architecture (Table 7). It is important to mention significant dispersion of flexural strength testing results which is again a consequence of manual fiber laying and their extraction during bending load.

4. Conclusion

The main goal of this research was design and testing of composite material made from polyester resin matrix reinforced with natural bamboo fibers. The main problem of obtaining described composite was lack of all necessary production steps. During fiber production mechanical and chemical fiber extraction is necessary for obtaining uniform fiber distribution. Also automatic fiber weaving would provide higher composite quality. During manual fiber depositing it was not possible to influence the amount of air trapped inside the specimen. With production procedure being crucial for all material properties it can be concluded that values of tested properties do not fully present all possibilities of this bio-polymer fiber reinforced composite. Nevertheless, material produced in described way shows great potential when compared with other materials and their impact energy, flexural strength and flexural modulus values.

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