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Performance assessment of wood/jute fibers reinforced polyester (JFRP) interface based on nonlinear numerical simulations

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ABSTRACT: Natural fibers used for high performance composite materials show important advantages as low density, low costs, representing a renewable resource and having bio friendly characteristics. From mechanical point of view, vegetal fibers have acceptable specific properties, less wear during processing and low energy consumption.

For timber frame structures, used to replace steel joints, the jute fibers reinforced polyester (JFRP) systems may be considered as a possibility to continuously transmit internal forces between the structural elements. Ensuring this continuity, improvement of stiffness properties both for the whole structure as for individual structural elements and a better redundancy are achieved.

For this purpose, focusing on the results obtained from shear bond strength test, a nonlinear Finite Element Analysis with contact delaminating in benchmarking is performed, for considering, in further investigations, the opportunity to using new JFRP joint systems for the enhancement of the seismic performance of timber frames structures.

1 INTRODUCTION

Emergence and development of bio-composite materials are based on thorough studies of wood, both from micro and macro structural point of view and also on its chemical composition. Wood`s fibrous structure may be encountered also in some plants whose stalks contain mainly wood fibers.

If in wood`s structure the fibers are bonded by lignin and hemicelluloses, in the plant stalks the fibers are bonded mostly by lignin. By comparing fibrous plants structures: wood, jute, hemp, cotton, flax which may be abundantly found, some composite materials made of technical fibers embedded in synthetic resins emerged. Their development is the result of the need to obtain special characteristics in construction domain: reduced weight, good physical and mechanical properties, resistance to chemical agents and ease of use for creating construction elements.

Modern composites fulfill these requirements, but with high costs. This is the reason why joining natural materials and synthetic resin is a good choice, as fibers provide enough strength at low cost and the resin plays the role of bonding agent and provides chemical resistance to the composite.

In construction domain, vegetal fibers reinforced composites are basically used for nonbearing elements. Considering that bio-composites have a lower Young modulus than glass reinforced composites but similar strengths to wood, it was stated that they can be a good substitute for wood, Ahmed & Vijayarangan (2007).

Considering the seismic activity specific to Romanian territory, failure of wood structures is concentrated in framed with a single or double notch and/or steel fastening joints. This is the effect of relatively high displacements in joining zones that lead to dangerous deformations. It is known that wood acquires plastic deformations that lead to enlargement of mounting holes for steel connections or shearing of timber elements in case of framed connections.

The work focuses on the possibility to provide fixed joints to timber structural elements by using polymeric composite materials reinforced with glass and/or vegetal fibers. The systems should be conceived so that the composite to overtake peak stresses occurring in the joint by the sufficient bond strength of polymeric matrix of unsaturated polyester resin to wood.

One of the objectives of the paper is to determine the mechanical properties of JFRP in tension, since these stresses occur in structural elements of timber frames, both in beams and columns and usually they represent the main loading causing failure. The results are than compared with wood`s mechanical properties for tension, to understand the possibilities in which this material may be used for substituting wood. Thus, JFRP may be considered an independent composite material with unitary structure. Its mechanical properties may be obtained from the design stage.

Of special interest is the shear bond strength at the interface between wood and JFRP since, for creating continuity nodes in timber frames, it plays a major role. At different scales, the interface behavior is encountered both inside JFRP composite material (jute fibers/unsaturated polyester resin) and also at structural level, by associating wood to JFRP in joint systems. By attaching a JFRP composite to a timber element a transition zone is created because resin penetrates the wood on a certain depth creating a composite material wood/synthetic resin. The mechanical properties of this wood/polyester resin material are considered to be better than those of cellulose fibers/lignin which constitutes wood. The shear bond strength at the interface between the bio-composite and dry wood is further discussed, in benchmarking, in terms of strengths and stiffness, obtained from experimental tests and nonlinear finite element analysis of specimens with contact delamination.

2 EXPERIMENTAL ANALYSIS OF WOOD AND JFRP MECHANICAL PROPERTIES IN TENSION

2.1 Wood mechanical properties in tension parallel to the grain

2.1.1 General considerations

Wood is a complex natural composite material, both because of its structure and also because of its stress/strain related mechanical properties. As for all other construction materials, wood develops both elastic and plastic deformations while loaded and, even they are very small, plastic deformations occur inside the wood even for very small stresses, so its elasticity limit may not be considered as a physical constant. Anyway, the yield limit may be perceived as the total strength of wood subjected to permanent loads, determined on long term tests. If the load is smaller than this limit, the fracture may not occur, Vanin (1953).

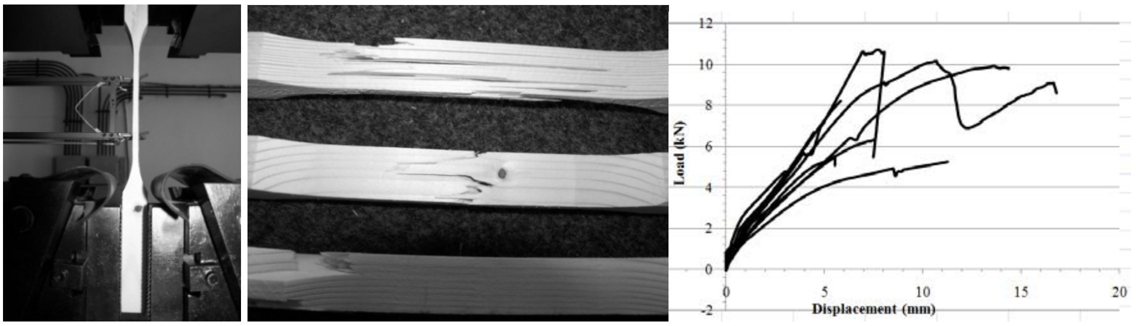
When a frame structural timber element is subjected to bending, in the upper and bottom part of the cross-section compression and tensile stresses develop, while in horizontal and vertical longitudinal sections of the element shear stresses occur. For these stresses wood withstands different values of strengths. Considering that wood`s moduli of elasticity in tension and compression are almost identical, both tensile and compression stresses uniformly develop and the neutral axis lies at the cross-section`s mid height, until they reach a value when some irreversible deformations occur, thus the yield limit being marked. In this domain, wood presents elastic properties – the relation between elastic deformations and stresses may be considered linear – and the material stands well the exterior applied loads.

After exceeding the yield point wood experiments a special qualitative state, governed by rapid growth of elastic deformations corresponding to the increasing loads, leading to a maximum deformation at yielding, the stresses corresponding to this state being in fact the wood's strengths.

2.1.2 Behavior of wood subjected to tension parallel to the grain test

For the characterization of spruce wood used in the experimental study a number of nine samples were processed and tested in tension parallel to the grain. The wood is sampled form Bucovina area, Romania.

The shape and dimensions of the samples are according to STAS 336-81 and have a rectangular section in the middle 0.004x0.020 m^2 and square section at the ends 0.02x0.02 m^2. The test set-up and results obtained are described in Figure 1.



a. b. c.

Figure 1.Tensile test of spruce wood: a. test set-up; b. failure modes; c. load displacement diagram

The failure of wood specimens in tension is produced by pull-out of the fibers from the lignin matrix and finally breaking of the fibers. The average fracture strength obtained was of $71.96 \cdot 10^6$ Pa and the corresponding characteristic strength of $16.09 \cdot 10^6$ Pa. The average value of Young modulus is $11753.74 \cdot 10^6$ Pa. Considering the values described above, the tested wood may be considered, as belonging to C27strength class, (SR EN 338:1997).

2.2 JFRP mechanical properties in tension

2.2.1 General considerations

Unsaturated polyester resin is an orthophthalic type resin with high reactivity, having maleic anhydride, phtalic anhydride and propylene-glycol components. It contains double chemical bond (- C = C -) which give unsaturated character and come from (α-β) unsaturated dicarboxyl acids – maleic anhydride. The hardening of these resins takes place by co-polymerization of monomers having double chemical bond in the unsaturated polyester chain.

Polyesterification is the main chemical reaction to reach the equilibrium. Considering that esterification of lignocelluloses fibers by maleic anhydride may produce possible cross-linking of the esterified fibers to the polymer matrix and that polyester resin contains polar groups that can form hydrogen bonds with hydroxyl groups on the surface of the lignocelluloses fibers, it may be stated that unsaturated polyester resin interacts with the natural fibers, thus the good bond strength between both wood and jute fibers being explained, Dash et al. (1999) and Decher & Lanivschi, (2012).

2.2.2 JFRP mechanical properties in tension

For determining the tensile properties of the bio-composite propose herein, a plate of 0.50x0.36 mm was poured from which a number of 13 specimens were cut and tested.

The composite plate was made of three layers of jute fabric, 140g made of untwisted yarns. The fabric is of unbalanced type: the warp is represented by one jute yarn, while weft has two jute yarns, the difference between these two being of 55% weft to 45% warp, gravimetrically measured. The fabric has 0.002x0.003 mm mesh size. The type and quantity of synthetic resin used in the experiment is NESTRAPOL 450-60 polyester resin, 709g, resulting in a 20% reinforcing percent.

The samples had the length of 0.25 m and a constant cross-section of 0.005x0.025 m^2. In the Figure 2 are presented the experimental results in terms of load-displacement diagram.

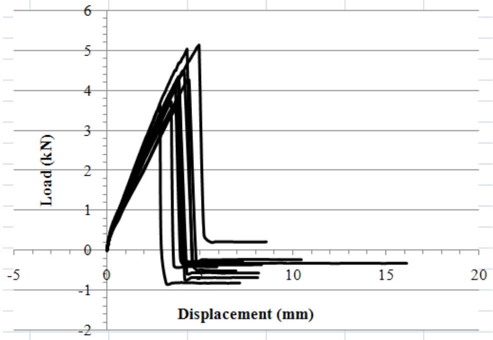


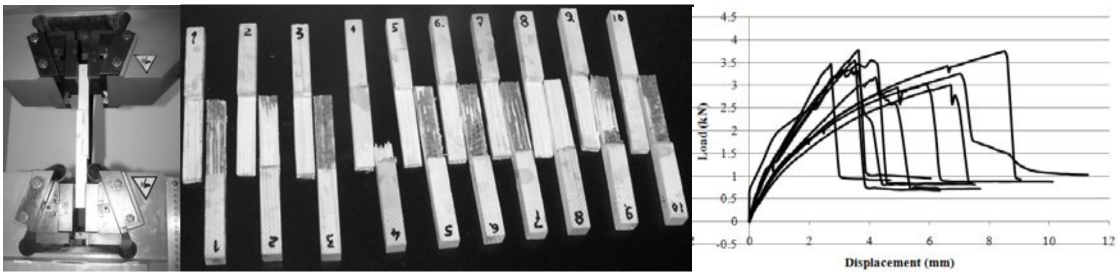
Figure 2. Load displacement diagram of JFRP strips subjected to tension

The results obtained were the average value of fracture stress of $31.21 \cdot 10^6$ Pa with a corresponding characteristic strength of $21.26 \cdot 10^6$ Pa and an average value of Young modulus of $8007.75 \cdot 10^6$ Pa.

3 JFRP/WOOD INTERFACE EXPERIMENTAL CHARACTERIZATION

The JFRP/spruce wood interface properties were determined in terms of shear bond strength.

The specimen dimensions were 0.02x0.02x0.30 m^3. At the middle third, on a length of 0.10 m, the two pieces of wood were bonded together by aid of two layers of jute fabric impregnated with polyester resin, measuring about 0.003 m thickness. Test procedure, failure modes and the obtained results are presented in Figure 3.



a. b. c.

Figure 3.Shear bond strength test: a. test set-up; b. failure modes and c. load – displacement diagram

The results obtained were the average value of shear stress of $1.67 \cdot 10^6$ Pa with corresponding characteristic shear strength of $1.29 \cdot 10^6$ Pa and the average value of shear modulus of $65.24 \cdot 10^6$ Pa.

4 NUMERICAL ANALYSIS OF THE SHEAR BOND STRENGTH TEST

4.1 General considerations

The 3D nonlinear static analysis was performed using ANSYS 12.0 software, considering the need to integrate in the model the orthotropic character of wood as well as its moduli of elasticity, different as values upon the three principal, orthogonal directions, toward the fibers position: longitudinal, tangential and radial, respectively. This feature is responsible for the manner in which the stresses are distributed along the tested specimen.

The geometry of the model respects the overall dimensions of specimens, as presented in the related chapter. For the analysis, two types of finite elements were considered, one describing the behavior of wood and JFRP as continuum media, SOLID186 and the second type aiming to describe the behavior of the interface between the two superposed materials, CONTA174. Finally, the model consisted of 84057 nodes, 17420 solid elements and 2090 contact elements. The finite element mesh, the supports and the force representation are represented in Figure 4.

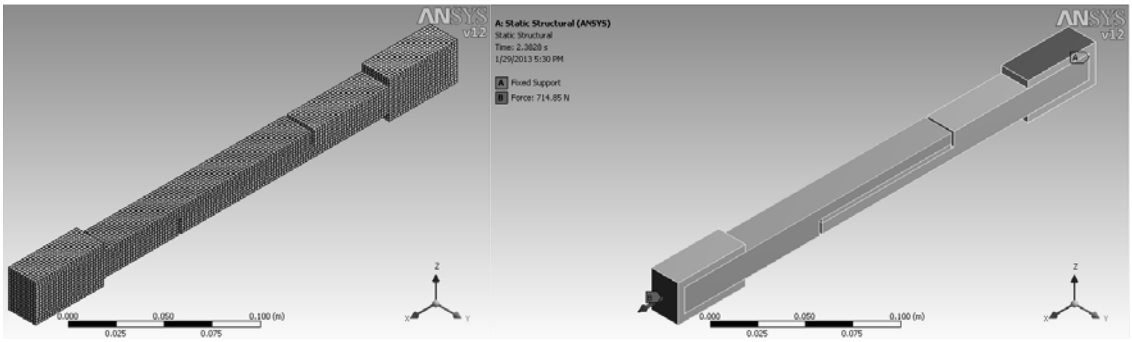


Figure 4.Finite element model used in nonlinear simulation: a. finite element mesh; b. supports and applied forces

The supports and force were applied by means of steel plates which were also modeled with SOLID186 type elements. At the bottom ends of the specimen, the steel plates were considered fixed, the applied force being gradually acting, in 13 steps of 300 N value, each. During the experiment process, the maximum force applied reached the value of 3900 N.

4.2 Material models used in the analysis

The wood pieces were modeled using an orthotropic material model. The data was considering starting from the elasticity module in tension parallel to the grain as determined in the related chapter. The other data was considered according to Green, Winandy & Kretschmann (1999) in function of E_L value. The material axes were related to the elements` axes, as global X, Y and Z axes being the corresponding longitudinal, tangential and radial respectively. For the JFRP, an isotropic material model was used and the numerical values are provided in Table 1.

For the wood/JFRP interface a bilinear material behavior with tractions and separation distances was used and it is based on the model proposed by Alfano & Crisfield (2000).

Table 1. Wood material model properties used in the finite element analysis

Material	Modulus of Elasticity ($\cdot 10^9$ Pa)	Shear Modulus ($\cdot 10^9$ Pa)	Poisson\`s Ratio
WOOD	$E_x = 11.754$	$G_{xy} = 0.752$	$\upsilon_{xy} = 0.372$
	$E_y = 0.917$	$G_{yz} = 0.035$	$\upsilon_{yz} = 0.435$
	$E_z = 0.505$	$G_{xz} = 0.717$	$\upsilon_{xz} = 0.467$
JFRP	8.000	-	$\upsilon = 0.3$

There may be defined three types of debonding. Mode I debonding defines a mode of separation of the interface surfaces where the separation normal to the interface dominates the slip tangent to the interface. The normal contact stress (tension) and contact gap behavior is plotted and it shows linear elastic loading followed by linear softening. Debonding begins when the maximum normal contact stress is achieved and is completed when the normal contact stress reaches zero value; any further separation occurs without any normal contact stress. The slope of the linear elastic range determines the contact gap at the maximum normal contact stress and, hence, characterizes how the normal contact stress decreases with the contact gap, whether the fracture is brittle or ductile. After debonding has been initiated, it is assumed to be cumulative and, any unloading and subsequent reloading occurs in a linear elastic manner at a more gradual slope. Mode II debonding defines a mode of separation of the interface surfaces where tangential slip dominates the separation normal to the interface. The normal contact stress and contact gap behavior follows the tangential contact stress and tangential slip behavior. Finally, in the mixed mode debonding, the interface separation depends on both normal and tangential components. In the finite element model proposed herein, only mode II debonding was activated by considering the elements that define this behavior and were used in the analysis, Table 2.

Table 2. Contact surface debonding parameters

Maximum equivalent tangential contact stress τ_{max} ($\cdot 10^6$ Pa)	1.69
Tangential slip at the completion of debonding u_t^c ($\cdot 10^{-3}$ m)	8.00

With the properties described above it was considered that all modes of failure that could be attributed to the element were taken into account.

4.3 *Results of the nonlinear finite element analysis considering samples with contact delamination*

The results of the finite element analysis are plotted in terms of load-displacement diagram in benchmarking, simulation vs. experiment, Figure 5.

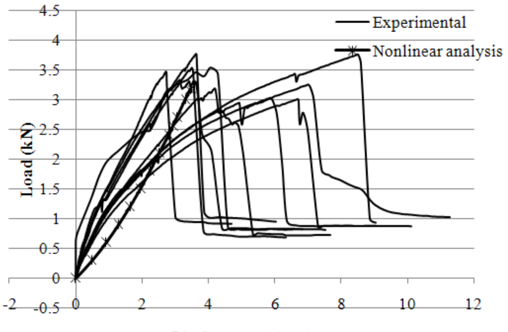
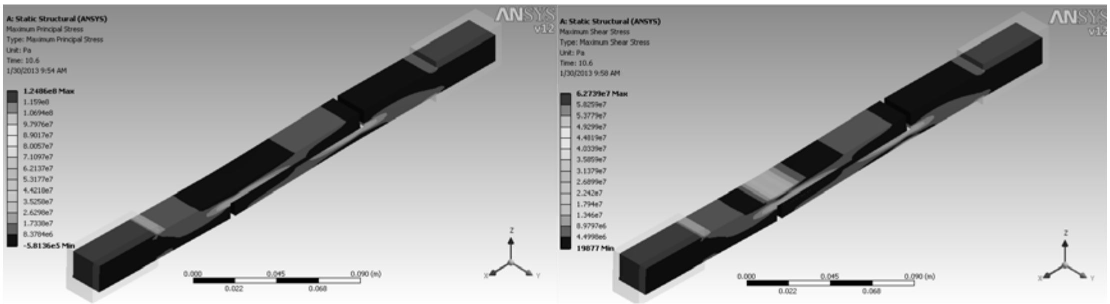


Figure 5.Load-displacement diagram of experimental vs. nonlinear analysis results.

To observe how the stresses are distributed in the materials and in which proportion, the maximum principal stresses and maximum shear stresses are mapped in Figure 6.



a. b.

Figure 6.Results of the nonlinear static analysis: a. Maximum principal stresses; b. Maximum shear stresses

5 CONCLUSIONS

With regard to the technology used for obtaining the composite material of jute fibers reinforced polyester type, some observations should be made after curing the plate. It should be pressed, so that the resin in excess could be taken out from the material. In this manner a better fiber volume fraction and a smaller percent of air gaps may be obtained, as the fabric absorbs a relatively high amount of resin. Even so, the strengths and stiffness were closed to the wood`s mechanical properties, Table 3.

Table 3. Benchmarking of experimental results in tension test of wood and JFRP

Mechanical characteristic	**WOOD**	**JFRP**
Average tension strength, $f_{t,0,m}$ ($\cdot 10^6$Pa)	71.96	31.21
Characteristic tension strength, $f_{t,0,k}$ ($\cdot 10^6$ Pa)	16.09	21.26
Young Modulus $E_{0,mean}$ ($\cdot 10^9$ Pa)	11.754	8.007

In Table 4, the comparison of the results obtained both experimentally and analytical are presented.

Table 4. Benchmarking of experimental vs. simulation of wood/JFRP shear bond strength

Property	**Experimental results**	**Nonlinear simulation results**
Displacement for $0.1T_{max}$ ($\cdot 10^{-3}$ m)	0.155	0.192
Displacement for $0.4T_{max}$($\cdot 10^{-3}$ m)	0.989	0.749
Displacement for T_{max}($\cdot 10^{-3}$ m)	4.879	3.475
Shear stress for $0.1T_{max}$ ($\cdot 10^6$ Pa)	0.169	0.255
Shear stress for $0.4T_{max}$ ($\cdot 10^6$ Pa)	0.6765	1.009
Shear stress for T_{max} ($\cdot 10^6$ Pa)	1.691	1.691

Further on, for reaching the final goal described in the introduction, it shall be considered, in order of ensuring a higher stiffness characteristic of the composite, a higher volume fraction or even the possibility to create a hybrid composite material reinforced with both glass and jute fibers.

Related to the shear bond strength at the wood/JFRP interface, it should be stated that the results may be considered as relatively closed to the experimental results, since the bond doesn't fail because of the shear stresses developed within the interface layer, but due to the fact that the wood fibers have being pulled out from the lignin matrix. This remark is valid considering both, the experimentally tested samples and, also the results obtained in numerical simulations.

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