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ANALYSIS OF HYBRID POLYMERIC COMPOSITE-TIMBER BEAMS USING NUMERICAL MODELLING

BY

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Abstract. A preliminary analysis of different hybrid beams based on strengthening solutions of wood beams using fibre reinforced polymeric (FRP) composite products is presented. The carbon fiber reinforced polymeric (CFRP) composite materials utilized to strengthen the wood beams have been selected in several shapes like plates, round bars, or narrow strips. A comparison between several solutions utilizing different strengthening schemes has been done on certain criteria such as materials consumption, maximum deflection, and normal stress at mid span.

Key words: hybrid beam; wood beam; strengthening methods; FEM analysis; CFRP.

1. Introduction

Structural strengthening of load bearing elements is needed because of changed service conditions, new functional requirements, new safety requirements, new code precisions and deficient or lack of maintenance (Isopescu *et al.*, 2010).

The well known advantages of composite materials have ensured their

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intensive use in strengthening works of reinforced concrete elements for the last three decades. As an extension of this application, fiber reinforced polymeric (FRP) composites have been introduced in strengthening of wood elements as well.

Timber constructions, that represent a remarkable cultural value are in need of special care and the strengthening works applied to them need to firstly respect the aesthetical criterion. This condition involves preserving most of the original timber parts, while making it possible for them to fulfill design constraints (Oprişan *et al*., 2004).

Strengthening with FRP composite materials can fulfill this need of aesthetical preservation, also reducing the structural alterations to a minimum in a rapid and efficient manner.

There are several strengthening solutions and they depend on the final purpose of the intervention, the elements and materials involved, and the importance and intended appearance of the work.

In what follows a preliminary analysis of several strengthening solutions is presented, to reveal the effects and advantages that different FRP composite products and alternatives can bring in strengthening wood beams. This analysis has been carried out using ANSYS software and the information resulted from the numerical modeling helped in drawing certain preliminary conclusions that will be improved and refined in the following research works.

2. Hybrid Beams Conceived in Strengthening with FRP Composite Products

2.1. Strengthening Alternatives Considered in the Analysis

Six strengthening solutions were considered for this analysis (Stănilă *et al.*, 2010; Wan *et al.*, 2005). These strengthening solutions can be grouped in two categories, depending on the place where the composite product is applied, as follows:

1. On the surface of the beam element
   - 1.1. CFRP plate (100 mm width, 1.4 mm thickness) on the bottom of the wood beam;
   - 1.2. CFRP plates (50 mm width, 1.4 mm thickness) on lateral sides of the beam.
2. Near Surface Mounted (NSM) composite products placed in bottom slots and laterally inserted
   - 2.1. CFRP narrow strips (15 mm width, 1.4 mm thickness);
   - 2.2. CFRP round bars (10 mm diameter).

The CFRP products which are placed at the bottom of the wood beam have the length equal to the distance between the supports, L = 2 m. On the other hand, the elements that are placed on the lateral sides of the beam have the length equal to L = 2.2 m.

The three-dimensional models for the considered solutions are presented in Figs. 1,…,3 (Reh *et al.*, 2006; Gomey & Svecova, 2008).

a

b

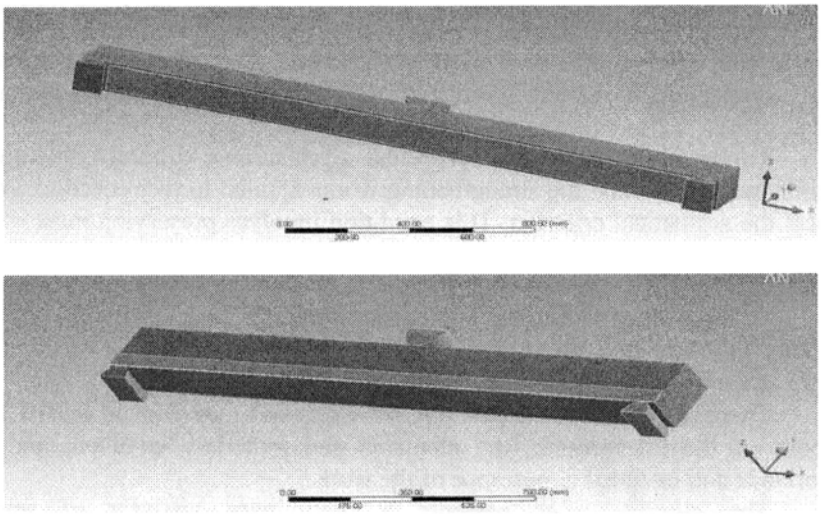

Fig. 1 – Strengthening solutions for wood beams with CFRP plates:
a – with bottom plate; *b* – with lateral plates.

a

b

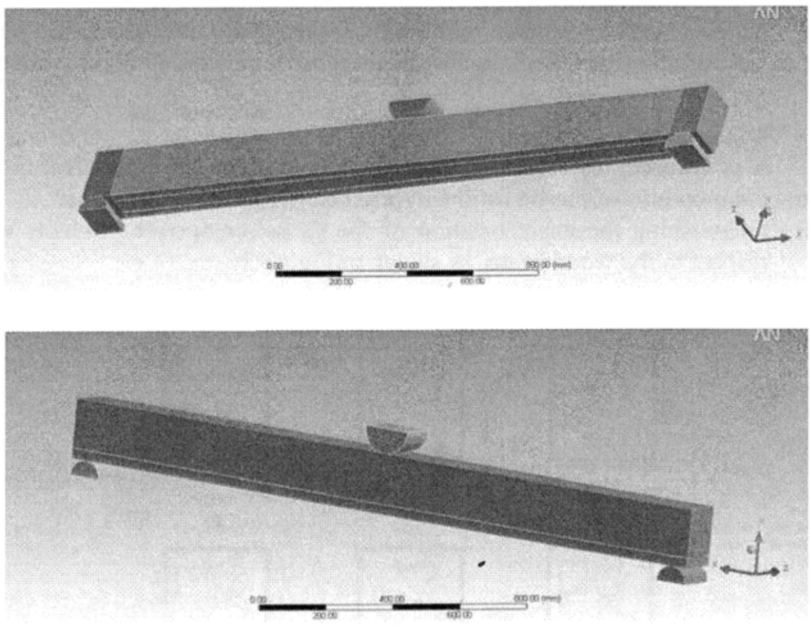

Fig. 2 – Strengthening solutions for wood beams with NSM composite products:
a – bottom narrow strips; *b* – lateral narrow strips.

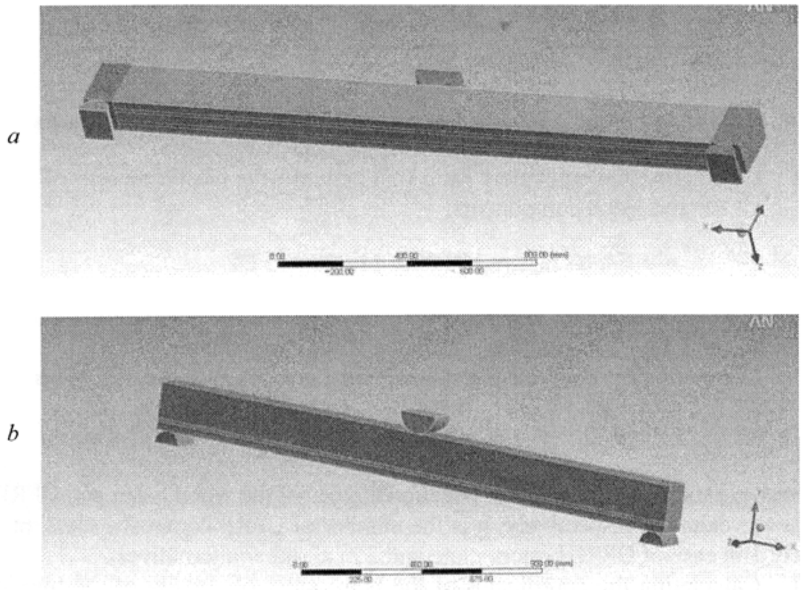

Fig. 3 – Strengthening solutions for wood beams with NSM composite products:
a – bottom round bars; *b* – lateral round bars.

All polymeric composite reinforcing products are attached to the beam using an epoxy adhesive especially formulated for wood rehabilitation systems.

2.2. Calculus of the Equivalent Characteristics for the Hybrid Beam

A preliminary calculus has been done to evaluate the equivalent cross-section and moments of inertia for the hybrid beam, applying the following steps:

1. Establishing the exact location of the CFRP composite products with respect to the wood beam, as shown in Fig. 4.
2. Calculating the equivalent ratio (n') between the elastic moduli of the CFRP and wood components

$$n' = \frac{E_{\text{CFRP}}}{E_{\text{wood}}} = \frac{170{,}000}{11{,}300} = 15.04, \tag{1}$$

where $E_{\text{CFRP}} = 170{,}000$ MPa and $E_{\text{wood}} = 11{,}300$ MPa are the longitudinal elastic moduli for the CFRP composite material and wood, respectively.

3. Computing the equivalent cross-sectional area (A_{eq}) of the hybrid beam

$$A_{\text{eq}} = A_{\text{wood}} + n' A_{\text{CFRP}}\, n, \tag{2}$$

where A_{wood} and A_{CFRP} are the cross-sectional areas of the wood beam and CFRP composite element, respectively; n – the number of CFRP composite elements, namely 1 in case of CFRP bottom plate and 2 in all other alternatives.

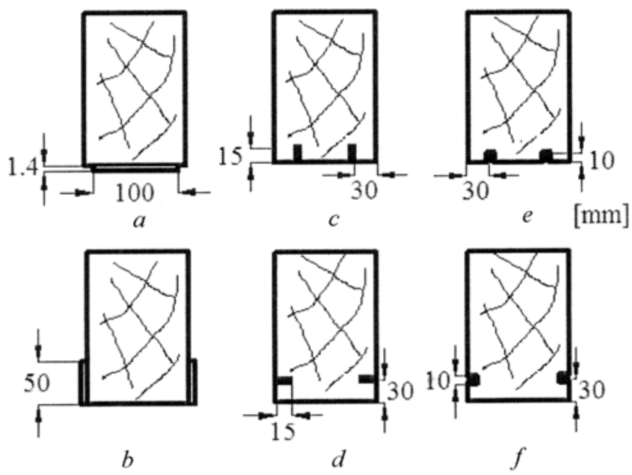

Fig. 4 – Hybrid beam cross-sections: *a*, *b* – plates;
c, *d* – narrow strips; *e*, *f* – round bars.

4. Calculating the coordinates of the new center of rigidity of the hybrid beam.

5. Calculating the distances between the new center of rigidity and the centers of rigidity of the components of hybrid system – the wood beam and CFRP composite products.

6. Computing the equivalent moments of inertia (I_{eq}) using the classic formulas.

The characteristics of the hybrid beams obtained from the calculus are presented in Table 1, where h_g stands for the vertical coordinate of the new center of rigidity, measured from the bottom of the wood beam.

Table 1
Characteristics of the Hybrid Beams

Case		A_{eq}, [mm^2]	h_g, [mm]	I_{eq}, [mm^4]
Reinforcement applied on the surface of the beam				
On the bottom	Beam+ plate	23,705.6	82.07	74,103,855.7
On the lateral sides	Beam+ plates	23,705.6	84.23	66,645,310.9
Reinforcement inserted in the beam, using NSM composite products				
On the bottom	Beam+ narrow strips	22,231.7	87.66	62,503,134.1
	Beam+ round bars	23,962.5	84.08	65,993,796.8
On the lateral sides	Beam+ narrow strips	22,231.7	88.30	60,529,486.4
	Beam+ round bars	23,962.5	84.08	65,993,796.8

3. Establishing the Model for Unstrengthened and Strengthened Wood Beams

The analysed beam has been considered as part of a floor system and its design has firstly been done according to NP 019-97 (Kim & Harries, 2010). The basic model chosen for this simulation was a soft wood (fir) beam with the dimensions presented in Table 2.

Table 2
Geometric Characteristics of Beams

Parameter	Dimension, [mm]
Length, *L*	2,000
Width, *b*	120
Height, *h*	180

Material consumption represents an important factor when choosing a strengthening method; therefore the used volumes of CFRP composite products have also been evaluated.

Table 3
Consumption of CFRP Composite Elements

Solution	Type of material	Nr. of elements	Dimensions		Volume mm^3
			length, [mm]	area, [mm^2]	
Reinforcement applied on the surface of the beam					
On the bottom	plate	1	2,000	140	280,000
On the lateral sides	plates	2	2,200	70	308,000
Reinforcement inserted in the beam, using NSM composite products					
On the bottom	narrow strips	2	2,000	21	84,000
	round bars	2	2,000	78.5	314,000
On the lateral sides	narrow strips	2	2,200	21	92,400
	round bars	2	2,200	78.5	345,400

The ANSYS software used for this numerical modeling is a Finite Element Method (FEM) based program. All the models were firstly drawn using AutoCAD 3D and then exported to ANSYS Workbench (Isopescu, 2002).

3.1. Engineering Data

The selected materials have been introduced in the Mechanical Model: Engineering Data section of ANSYS Workbench (Green *et al.*, 1999; Moses *et al.*, 2004). The physical properties and strength values for wood in this preliminary analysis were chosen for Douglas fir and are presented in Table 4 (NP 019-97; Kim & Harries, 2010). Wood is an orthotropic material and it is considered to have orthotropic properties on the longitudinal (X), transversal (Y) and radial (Z) directions (Schober & Rautenstrauch, 2006).

Table 4
Material Properties of Wood

Property	Value
Density, [kg/m^3]	450
Young's modulus, I_X , [Mpa]	11,300
Young's modulus, I_Y , [Mpa]	565
Young's modulus, I_Z , [Mpa]	769.4
Poisson's ratio, ν_{XY}	0.449
Poisson's ratio, ν_{YZ}	0.374
Poisson's ratio, ν_{XZ}	0.292
Shear modulus, G_{XY} , [Mpa]	881.4
Shear modulus, G_{YZ} , [Mpa]	79.1
Shear modulus, G_{XZ} , [Mpa]	723.2
Ultimate tensile strength, [Mpa]	3.6
Ultimate compressive strength, [Mpa]	14.4

In a similar manner, the material properties for the CFRP composites as well as for the epoxy adhesive are introduced in the program.

Table 5
Material Properties for CFRP Composites and Epoxy Adhesive

Property	Value
CFRP composite material	
Density, [kg/m^3]	1,610
Elastic modulus, I_X, [Mpa]	170,000
Poisson's ratio, ν_{XY}	0.3
Tensile strength, [Mpa]	3,100
Epoxy adhesive	
Density, [kg/m^3]	1,080
Elastic modulus, I_X, [Mpa]	4,000
Poisson's ratio, ν_{XY}	0.4
Tensile strength, [Mpa]	30
Compressive strength, [Mpa]	45

The CFRP plates have been fabricated by pultrusion; their characteristics are given in Table 5. In addition, they are extremely light weight, easily applied and commonly used in strengthening works. The same characteristics are met in the case of CFRP narrow strips and round bars.

The epoxy adhesive used in the numerical simulations is a paste especially formulated for restoration of wood structural elements and its characteristics are also given in Table 5.

3.2. Interfaces

Connections between wood–adhesive and adhesive–CFRP plates or rods are considered "bonded" for these linear analyses. In addition, the contact regions between the wood beam and the steel supports and force device are also considered bonded. A normal stiffness factor of 10^{-2} for the contact area between wood and steel supports has been introduced, to simulate the rubber band that would normally be placed in a real testing situation.

3.3. Loads and Boundary Conditions

All beam models are considered simple supported on the steel supports which are fixed to the ground. The force has been applied on the beam as illustrated in Fig. 5.

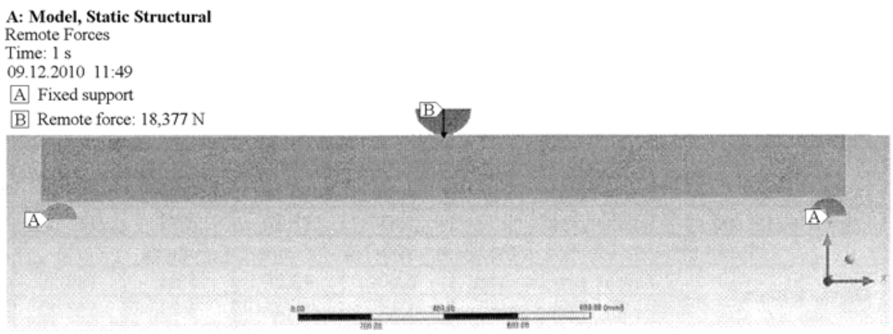

Fig. 5 – Load application and boundary conditions.

A numerical calculus for the unreinforced wood beam has been done to evaluate the load capacity corresponding to ultimate limit state of strength. As a result of this calculus, the force applied on the beam element resulted with a magnitude equal to 27,000 N. This value was kept unchanged for the numerical modeling analyses for all cases of strengthened beams.

3.4. Discretization Mesh

The fineness of the mesh is an important factor in the accuracy of the results and it influences the needed time for running the analysis (Fig. 6).

The discretization of the model has been made by body sizing it into elements of 10 mm sizes. The chosen element size enabled for a relatively short period for the analysis to be carried out without negatively affecting the quality of the results.

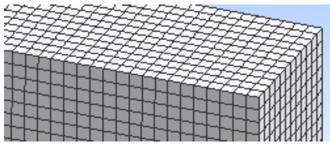

Fig. 6 – Part of the meshed model.

4. The Numerical Modeling Results

The purpose of this preliminary analysis was to compare the chosen strengthening solutions between them and with the unreinforced wood beam on certain criteria like use of materials, maximum deflection, and normal stress (on the longitudinal axis, *X*-direction) at middle span.

4.1. Stresses and Deflections from the Numerical Modeling

After running the analysis on the unreinforced and then strengthened beam, the obtained results have been synthesized in Table 6.

Table 6
Maximum Deflections and Normal Stresses Eesulted

Case		f_{max} mm	σ_{wood} MPa	$\sigma_{adhesive}$ MPa	σ_{CFRP} MPa
Simple beam		6.23	14.184	–	–
Reinforcement applied on the surface of the beam					
On the bottom	Beam + plate	5.59	10.19	3.93	163.00
On the lateral sides	Beam + plates	5.83	12.30	4.53	185.20
Reinforcement inserted in the beam, using NSM composite products					
On the bottom	Beam + narrow strips	6.00	13.20	5.64	190.00
	Beam + round bars	5.68	11.40	5.75	157.23
On the lateral sides	Beam + narrow strips	5.58	12.50	3.64	106.20
	Beam + round bars	6.00	12.90	5.02	111.21

4.2. Influence of CFRP Composite Products

The maximum deflection, f_{max} , has firstly been determined to analyse the influence of CFRP composite products on the stiffness of the hybrid composite/wood beam. As it can be noticed, the stiffness can be improved by using strengthening with CFRP composite products technique that reduces the maximum deflection within the range of 3.7…10.4%.

When comparing the normal stresses developed in the beam, for an applied load of 27,000 N, the simple wood element reaches at mid-span its limit strength of 14.18 MPa. Therefore, the wood beam is loaded up to its failure condition.

An important result of all the considered strengthening solutions is the improvement of the hybrid element load–bearing capacity. It can be observed that the used CFRP products are taking over a part of the stresses developed in the wood beam.

In addition, regardless of the strengthening solution, stresses in the adhesive layer and in the CFRP products do not reach their limit strength, namely 18 MPa, and 3,100 MPa, respectively.

5. Conclusions

According to the quantity of CFRP material needed for each strengthening solution, the methods that utilize the largest volume of composite product are the ones that involve rods while the ones that contain narrow strips are the most economical. The most inefficient methods, from all points of view, are the ones that utilize CFRP rods.

The largest stiffness gain is of 10.4%, in the case of the strengthening solution that involves the CFRP plate placed under the wood beam.

Based on simulation results it can be stated that this composite product is also most efficiently loaded, leaving for the wood beam only a normal stress of 10.19 MPa.

As a conclusion of this preliminary analysis, taking into consideration only the mentioned criteria, reinforcing the wood beam with a CFRP plate on its bottom is considered to be the most efficient strengthening alternative.

The second valuable solutions in terms of efficiency are those involving CFRP narrow strips and CFRP plates applied on the lateral sides of the beam.

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ANALIZA UNOR GRINZI HIBRIDE DIN COMPOZITE POLIMERICE ŞI LEMN FOLOSIND MODELAREA NUMERICĂ

(Rezumat)

Se prezintă o analiză preliminară a unor grinzi hibride obţinute prin soluţii de consolidare a grinzilor din lemn folosind produse din compozite polimerice armate cu fibre de carbon (CPAFC). Materialele compozite utilizate pentru a arma grinzile au fost selectate sub formă de platbenzi, benzi înguste şi bare rotunde. S-a efectuat o comparaţie între metodele alese, folosindu-se diferite produse, după anumite criterii cum ar fi cantitatea necesară de materiale, săgeata maximă şi tensiunea normală măsurată la mijlocul deschiderii.