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REINFORCEMENT PREDESIGN OF COMPOSITES USED TO STRENGTHEN TIMBER MEMBERS LOADED IN BENDING

BY

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Abstract. Using timber for construction of frame structures is opportune due to low density and good strength properties of wood. The main drawback of wood is given by its reduced modulus of elasticity parallel to grain that negatively affects structural elements` stiffness.

Consequently, it would be an important achievement to have the possibility to determine the cross-section dimensions of timber frame structural elements from load bearing capacity criteria.

The increasing of structural elements` stiffness may be achieved by using wood-composite hybrid cross sections in specific “target” locations along timber bars.

From the methods that may be used to compose hybrid wood-composite cross-sections of timber bars are chosen, for analysis, multilayered composite strips of matrix-unidirectional fabric type.

The attempt to determine a predesign formula for the warp yarns` quality of the reinforcing unidirectional fabric is based on the principles of constituent composite lamella structure and work hypotheses of timber – composite strip hybrid assembly.

Accepting that, the tensile strength of the constituent composite lamella is function of only fiber volume fraction and tension strength of reinforcing phase, a simple and efficient criterium is proposed, in order to predesign materials` quality used for reinforcement yarns.

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1. Introduction

Using timber in structural applications in construction domain is recommended by its low density and good mechanical characteristics of wood.

The main drawback of wood is given by its reduced parallel to the grain modulus of elasticity that, consequently, negatively affects the verifications of structural elements' stiffness.

Some of the possibilities to decrease the effects of the low modulus of elasticity of wood (Secu & Roşu, 2013) are:

a) creating timber bars joints in order to achieve continuity of stress transfer between structural elements that enter the node;

b) introducing multilayer composite strips in some specific "target" locations along timber bars (Alann André & Kliger, 2009).

For obtaining wood-composite cross-sections for timber bars some steps are required:

i) predesign of composite lamella inside the multilayer material used for creating the hybrid cross-section, further named constituent composite lamella;

ii) predesign of the multilayer composite, by determining the thickness, width and length of the composite strip.

Predesign of the constituent composite lamella may differ depending on the method used to attach the multilayer composite to the timber bar element.

Currently, a number of two technologies are used in order to attach the composite strip to the timber element: by gluing, using adhesives and manual "contact" technology (Ţăranu *et al*., 1992).

In this paper the constituent composite lamella is analysed, considering that the composite strip is applied using manual contact technology. The main elements required for lamella predesign are [A*]:

a) Type of material to be used as reinforcement yarns.

b) Unidirectional fiber type.

c) Matrix with double compatibility, both to unidirectional fabric and to wood from which the structural elements are made of. The resulted hybrid cross-sections will be considered for the structural elements.

d) The thickness of the lamella.

e) Volumetric fractions (proportions).

The main objective of the paper is the predesign of material quality to be used in the reinforcing phase of the composite used for obtaining hybrid cross-sections for timber structural elements.

2. Composing Principles of Constituent Composite Lamella

The included study refers to timber members loaded in bending to which, in the tension part a multilayer composite strip is attached by hand layout. The resulted wood/composite hybrid cross-section is considered in order to decrease the deflection and to increase timber beam`s load bearing capacity.

In the case of simply supported beams with rectangular cross-section and gravitationally loaded, in the upper and bottom part of the transverse cross-section, compression and tension parallel to grain stresses occur. In the horizontal and vertical longitudinal sections of the beam, shear stresses occur. Inside the beam, the fibers that are not subjected to compression nor to tension form the neutral axis of the structural element.

Because of wood`s parallel to the grain moduli of elasticity are almost equal in tension as in compression, both types of stresses uniformly develop and the neutral axis lies at the mid-height of beam`s transverse cross-section. When the proportionality limit is overcome, in the fibers mostly loaded in compression some remnant stresses occur, their value reaching wood`s parallel to the grain compression strength. These stresses are than progressively transmited toward the neutral axis. Thus, the stress diagram in the compressed part of the beam`s cross-section has trapezoidal shape. In the tension part of the cross-section, after the compression proportionality limit is exceeded, the stress diagram has triangular shape, due to the fact that tensile strength parallel to grain is much higher than corresponding compression strength of wood. The deformation in the compressed part of the cross-section is higher than in tension part and the neutral axis moves towards the tension part until the tensile stresses reach the wood tensile strength parallel to grain.

Considering these arguments, the composing principles of the constituent composite lamella are basic elements used for predesign of material that reinforcing yarns are made of and may be overviewed as following:

a) The composite strip and consequently the constituent composite lamella are attached to the tension side of timber bar`s cross-section.

b) The lamella with the highest efficiency is of matrix-unidirectional fabric type. The reinforcement is laid parallel to wood grain and the fiber volume fraction (V_f) is considered the maximum from technological point of view.

c) In practice, from technological point of view, unidirectional reinforcement may not be used due to geometrical instability, so that unidirectional fabrics are used instead, the warp being parallel to wood grain and prevailing in the fabric from fiber volume point of view. The weft is only used to maintain the position of the yarns that constitute the warp.

d) The composite constituent lamella`s modulus of elasticity along warp direction ($E_1$) should be at least twice the wood parallel to the grain modulus of elasticity ($E_{0,mean}$), a principle that takes into account both economic and efficiency considerations concerning stiffness and cross-section`s characteristics.

e) In the multilayer composite, the constituent lamellae have identical orientation.

3. Working Assumptions

The following assumptions are considered in the analysis:

1º The composite strip behavior is considered only in parallel to the grain direction of wood, and deformations are assumed to be constant on the strip thickness; the assumption is sustained by the reduced thickness of the strip, that is of maximum 4 mm, considering economical aspects. Thus, the resulting ratio between height of timber element`s cross-section and composite strip thickness is high.

2º The timber structural element and the composite strip are considered to perform as perfectly bonded, with no separations or detachments at their interface, due to matrix being chosen for the case of using manual “contact” technology and/or the adhesive used in the case of gluing the composite strip on the timber structural element.

3º Inside the constituent composite lamella the weft influence on the mechanical properties of the lamella may be neglected. Thus, the composite lamella micromechanics relationships may be applied, (Altenbach *et al*., 2004) considering the case of an unidirectional fabric reinforced matrix composite material type.

4. Analytical Determination of the Reinforcing Predesign Formula

In the constituent composite lamella, along its principal direction that coincides with the warp direction that is parallel to the wood`s grain, normal stresses occur due to bending of the timber bar with hybrid cross-section. The normal stresses are described, according to composite lamella micromechanics (Altenbach *et al*., 2004; Secu, 1997), by:

$$\sigma_1 = E_1\varepsilon_1, \quad (1)$$

where: σ_1 represents the normal stress along the main direction 1; E_1 as it is defined in the second chapter of the paper; ε_1 is the specific deformation in the lamella, in the main direction 1.

At the wood – composite strip interface, in limit conditions, along parallel to the grain direction of wood (direction 1), the specific deformations that occur in wood are described by:

$$\varepsilon_{0,\lim} = \frac{f_{m,d}}{E_{0,\text{mean}}}, \tag{2}$$

where: $\varepsilon_{0,\lim}$ is the maximum specific deformation of wood parallel to the grain that corresponds to the main direction 1 of the attached composite lamella, $f_{m,d}$ – the design value of bending strength of wood parallel to the grain that corresponds to the main direction 1 of the attached composite lamella and $E_{0,\text{mean}}$ as it is defined in section 2 of this paper.

Due to the stated properties of wood–composite strip interface, for the multilayer composite structure, resulted from identical lamellae identically oriented, and considering the assumed behavior of the constituent composite lamella, plane stress state respectively, the relationship described by eq. (3) is valid:

$$\sigma_{1,\lim} = E_1 \frac{f_{m,d}}{E_{0,\text{mean}}}, \tag{3}$$

where: $\sigma_{1,\lim}$ is the maximum normal stress along main direction 1 in the constituent composite lamella. In the case of higher stresses, the bending strength of wood would be overcome.

The tension strength of the constituent composite lamella, denoted f_t, in main direction 1, has to fulfill, evidently, the relation stated in:

$$f_t \geq \sigma_{1,\lim}, \tag{4}$$

According to Secu (1997), the tension strength f_t is computed using the formulae given in:

$$\begin{cases} f_t = f_{t,f} V_f + \sigma^*_{t,m} V_m, \\ \varepsilon_{1,u,f} < \varepsilon_{1,u,m}, \end{cases} \tag{5}$$

$$\begin{cases} f_t = f_{t,f} V_f, \\ \varepsilon_{1,u,f} > \varepsilon_{1,u,m}, \end{cases} \tag{6}$$

where: $f_{t,f}$ is the tension strength of the yarns in the moment of breaking the constituent composite lamella, $\sigma^*_{t,m}$ – the average stress that occurs in the matrix in the moment when the fibers from the constituent composite lamella break; V_f – the fiber volume fraction of the reinforcement, V_m – the matrix volume fraction, $\varepsilon_{1,u,m}$ is the ultimate specific deformation of the matrix, along to main direction 1 and $\varepsilon_{1,u,f}$ – the ultimate specific deformation of the reinforcing yarns, along main direction 1.

As the $(V_m\sigma^*_{t,m})$ product has much lower value compared to $(f_{t,f}V_f)$ product, from eqs. (3),…,(6) results, accordingly, the relationship:

$$f_{t,f}V_f \geq E_1\frac{f_{m,d}}{E_{0,\text{mean}}}, \tag{7}$$

According to the principles stated in chapter 2 of the present paper, the inequalities written in Eq. (8) and (9) may be stated.

$$V_f = V_{f,\text{max,th}}, \tag{8}$$

$$\frac{E_1}{E_{0,\text{mean}}} \geq 2, \tag{9}$$

where: $V_{f,\text{max,th}}$ is the maximum fiber volume fraction of the reinforcing yarns, that may be achieved from technological point of view. In the case of using manual "contact" technology it has the value of 0.5.

From eqs. (7),…,(9), for the "contact" technology, results:

$$f_{t,f} \geq 4f_{m,d}. \tag{10}$$

Eq. (10) is the obtained predesign criterium for the material quality to be used for tailoring the reinforcing yarns inside the constituent composite lamella.

5. Case Study

For a structural system composed of timber bars of C24 softwood strength class, subjected to a fundamental load combination consisting of deadloads and long term variable loads and considering the design requirements, results that:

1. The characteristic bending strength of C24 strength class of wood, $f_{m,k}$, according to BS EN 338:2003, has the value of 24 N/mm^2;

2. Modification factor for duration of load and moisture content, k_{mod}, is considered as provided by SREN 1995-1-1-2004, Table 3.1, page 28. Thus, for a structural element subjected to loads with different load durations, deadloads and long term variable loads respectively, the modification factor`s value is chosen for the long duration load case. Moreover, this factor takes into account the service class that characterizes the climatic conditions that timber elements are exposed to and that lead to certain values of moisture content of wood. Thus, for structural elements of service class 1, characterised by a moisture content in the materials corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 65% for a few weeks per year,

with the wood moisture content value not higher than 12%, the determined value of k_{mod} is 0.70;

3. Partial safety factor for material properties, γ_M, with the value of 1.3 is corresponding to the ultimate limit state design, for fundamental combinations of actions and for solid softwood cross-sections.

The design value of the bending strength is determined using the formula:

$$f_{m,d} = k_{\text{mod}} \frac{f_{m,k}}{\gamma_M}, \tag{11}$$

and results in a value of 12.92 N/mm^2.

It may be concluded that, in order to attach composite strips to C24 strength class timber structural elements, fibers with tensile strength of at least 51.68 N/mm^2 should be considered.

It is obvious that most technical fibers used in composites for construction domain, such as steel, glass, carbon or aramide fibers, show tensile strengths much higher to those needed for wood-composite strip hybrid cross-sections of structural elements and their use is not entirely justified both from mechanical characteristics point of view and economical reasons.

6. Conclusions

The wood-composite strip interconditionality, the composition principles and the accepted assumptions leaded, in analytical manner, to the formulation of a simple and efficient predesign criterium of material`s quality to be used for tailoring of reinforcing yarns inside the constituent composite lamellae.

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PREDIMENSIONAREA FAZEI DE ARMARE A LAMELELOR COMPOZITE DIN STRATIFICATELE UTILIZATE LA HIBRIDAREA BARELOR DIN LEMN SOLICITATE LA ÎNCOVOIERE

(Rezumat)

Utilizarea lemnului la alcătuirea structurilor din cadre este recomandată de densitatea sa redusă şi de caracteristicile mecanice ale acestui material.

Punctul slab al lemnului este dat de valoarea redusă a modulului de elasticitate longitudinal cu implicații negative în verificările de rigiditate ale structurii.

Ideal este ca mărimile secțiunilor transversale ale barelor din lemn, utilizată într-o structură din cadre, să rezulte din predimensionările realizate din criterii de capacitate portantă.

Mărirea rigidităților barelor astfel obținute poate fi realizată prin hibridarea unor zone ”țintă”.

Dintre modalitățile de realizare a hibridării barelor din lemn, s-a ales spre analiză, utilizarea platbandelor din stratificate compozite de tip matrice-țesătură unidirecțională.

Pentru determinarea unei relații de predimensionare a calității firelor de urzeală din cadrul țesăturii unidirecționale, s-a pornit de la principiile de alcătuire ale lamelei compozite constituente şi de la ipotezele de lucru ale ansamblului hibrid (secțiune din lemn - platbandă compozită).

Acceptând, în mod acoperitor, că rezistența la întindere a lamelei compozite constituente este funcție numai de fracțiunea volumetrică a firelor şi de rezistența la întindere a fazei de armare, se propune un criteriu simplu şi eficient de predimensionare a calității firelor de armare.