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OPTIMAL DESIGN OF TIMBER STRUCTERES REINFORCED WITH FIBERS

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Summary

Limited sources of material and energy rapidly affected a demand for lightweight, efficient and low cost structures, what secondly influenced the developing of new design approaches, called optimal design techniques. Authors partially deal with some problems of timber beams reinforced with different fibers, mainly the glass fibers as well as carbon fibers. The beam is modeled as a multi layered structure using the 3D brick elements in ANSYS. Some results of limit state and optimal topology of reinforcement are presented.

Introduction

In past decades people who worked in the field of structural optimization were divided into two distinct camps. On one side there was the mathematical programming camp who believed in employing the general methods of linear and non-linear programming such as penalty function techniques, the gradient projection technique and the method of feasible directions. On the other side there was the optimality criteria method camp which subscribed to the use of intuitive optimality criteria methods. The first group many times decried the lack of generality in the optimality criteria methods and the other group criticized the inefficiency of the mathematical programming approach. Recently the two approaches began to converge. This paper deals with some engineering techniques used in optimization process, well-known as structural optimization. That gives a relatively simple and easy answer on the question, how designed components obtain their shape and dimensions. These methods are mainly based on the Finite Element Method, widely used by scientists and engineers, with an implementation of optimization procedures.

1. The laminated timber structures

This paper deals with some parametrical studies of a laminated timber beam with carbon fibers compared with a laminated timber beam without carbon fibers, when asking a

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question, how much could carbon fibers contribute for an improvement of a benching capacity.

1.1 Materials of laminated timber

The timber is a structural material, usually used mainly in roof constructions, but over the last years the use of the timber in building industry is more and more observable. For this reason tighter specifications are permanently declared in codes.

Timber is a hard, fibrous, lignified structural tissue produced as secondary xylem in the stems of woody plants, notably trees but also shrubs. Timber is a heterogeneous, hygroscopic, cellular and anisotropic material, which is composed of fibers of cellulose (40%–50%) and hemicellulose (15%–25%) impregnated with lignin (15%–30%).

The glue for carrying timber elements is used as a connection of two or more parts of the wood. It works consequently as a compact static unit. A task of glue in the wood consists from a filling of the joints between wood elements and the creating of adhesive connection between elements, which has alike a compatibility and a durability like cohesive forces into elements. Layers of the glue have to be during the time of applications permanently effective. The process of gluing consists of two levels:

- In a connecting surface come into existence stick forces between the glue and the wooden molecules as a result of dab of the liquid glue.
- Passing from the liquid glue to solid state of the glue with sufficient consistency and the durability during a lifetime of construction.

This process is called hardening. Theren are three known ways as follows:

- physical process,
- chemical process,
- the combination of transition of the fusion and chemical reaction.

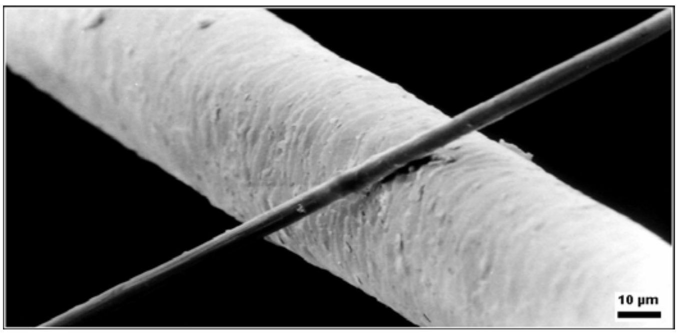

Fig.1 6 µm diameter carbon filament (thiner) compared to a human hair

The carbon fiber is a class of materials that are continuous filaments or are in discrete elongated pieces, similar to lengths of thread. Carbon fiber is also sometimes called graphite fiber. It has the highest compressive strength of all reinforcing materials, and it has a high strength to weight ratio and low coefficient of thermal expansion [1]. The density of carbon fiber is also much lower than the density of steel. Carbon fiber *(Fig. 1)* is a set of several thousand long, thin strands of material composed of mostly carbon atoms.

1.2 Laminated timber beams

The laminated timber beams (denoted LTB) *(Fig. 2),* considered in this paper, was of dimensions *b=160 mm* (width) and *h=440 mm* (height).


Fig. 2 Laminated timber beam

It consisted of 11 layers of the timber. As input values of material characteristics of LTB we used the properties of a pine-wood [2], which belongs under the class of coniferous wood as follows:

- $E_x =$ 13 650 *MPa*
- $E_y = E_z =$ 789 *MPa*
- $\upsilon_{xy} = \upsilon_{xz} =$ 0,023
- $\upsilon_{yz} =$ 0,990
- $G_{xy} = G_{xz} =$ 573 *MPa*
- $G_{yz} =$ 53 *MPa*
- $\rho_v =$ 400 $kg.m^{-3}$

As a base for strength properties the numbers by the norm [5] for a growing timber of the class SI are considered, but for our needs we adapted these values as follows:

- Flexural strength $f_{m,k} = 10$ *MPa,*
- Shear strength $f_{v,k} = 1{,}2$ *MPa* .

The LTBs, which were the subject of our research were simply supported as well as continuous *(Fig. 3)*, but in this paper we present only some results of the second ones. This LTB was loaded by two forces. The span of a half of the beam was *9,00 m*. Besides timber there were two more materials, which the beam consisted of.

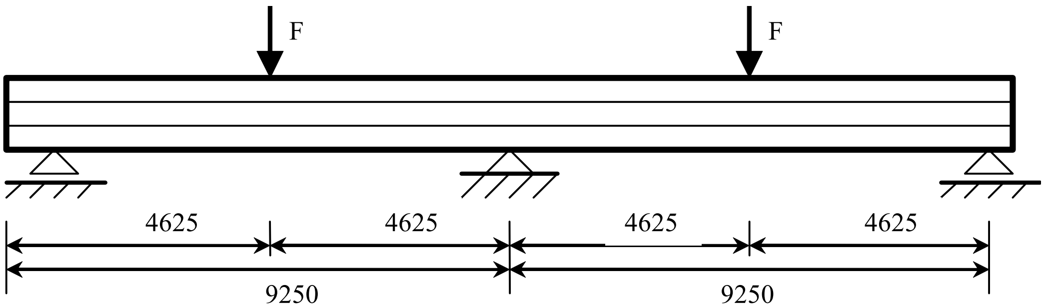

Fig.3 Continuous LTB

First of them were steel plates used for affecting the loads as well as reaction forces on the beam. They had following dimensions: the length of *160 mm* (the same as the width of the beam) and the width of *50 mm*. Their material properties were as follows:

$$E = 210\,000\ MPa, \quad \upsilon = 0.3\,, \quad G = 80\,770\ MPa, \quad \rho_v = 7\,850\ kg.m^{-3}.$$

Another material was a carbon fiber strip (*see par 1.1*) obviously used for reinforcing of material because of having the modulus of elasticity vastly higher as the modulus of elasticity of the timber. For our analysis we used its material properties given by SIKA as follows:

$$E = 164\,000\ MPa, \quad \upsilon = 0.2, \quad G = 82\,000\ MPa, \quad \rho_v = 1\,500\ kg.m^{-3}.$$

The dimensions of the carbon fiber were *50 mm* (width) and *1,3 mm* (thickness).

2. Structural Analysis

It's important to emphasize that we have to enter orthotropic properties of the timber. We considered two different directions of properties. One of them was along the fibers and another was across the fibers. Two different procedures were applied to the analysis. For a 2D model using the orthotropic matrix of stiffness we used a program [3] developed in FORTRAN, which was adapted for our LTB problem and for a 3-D model we used program ANSYS 8.1 [4]. In this paper only some results obtained by 3D will be presented.

2.1 Non-linear analysis by 3D

Several elements of ANSYS may be used for analysis of LTB reinforced with or without carbon fibers. Basic materials, of which consist LTB, are timbers lamellas of level SA [2] and glue, which connect these plies. We decided to use an element *SOLID 45* after acquaintance of some basis about its individual characteristics. This element seemed to be very suitable for our requirements. It is usually used for the 3D modeling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions [4]. The geometry, node locations, and the coordinate system for this element are shown in *Fig.4*. The element is defined by eight nodes and the orthotropic material properties. Orthotropic material directions correspond to the element coordinate directions.

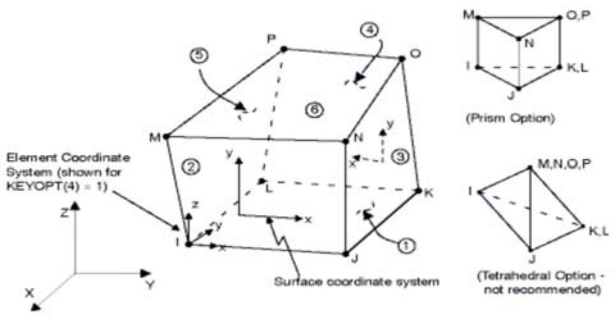

Fig.4 Element Solid 45

The important thing in term of computation was a working diagram of a modulus of elasticity in the timber. For our purpose we have chosen a bilinear diagram for both, longitudinal and transversal directions *(Fig.5)*.

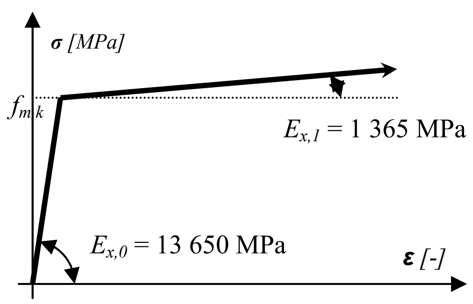

Fig.5 Working diagram of modulus of elasticity in the timber

A detail of LTB with steel sheet (red colour) and carbon fiber strip (blue colour) may be seen in *Fig.6*. The carbon fiber strip is emedded into a groove in LTB. Because of a very thin layer of the glue we replaced it in our model with a command, that substitute its effect full-value in the model.The model of LTB in ANSYS 8.1 had three variants. First of them was an unreinforced LTB, second one reinforced only on the lower side of the beam third one reinforced on both sides *(Fig.7)*.

Whole model was meshed by hexahedral elements. The width of each element was *50 mm.* The elements, which were at the edge, had not exactly *50 mm*, but they were adaptated to the model with a their real width. The unreinforced beam had 13512 elements, reinfoced LTB had 15708 elements and last of them had 17464 elements.

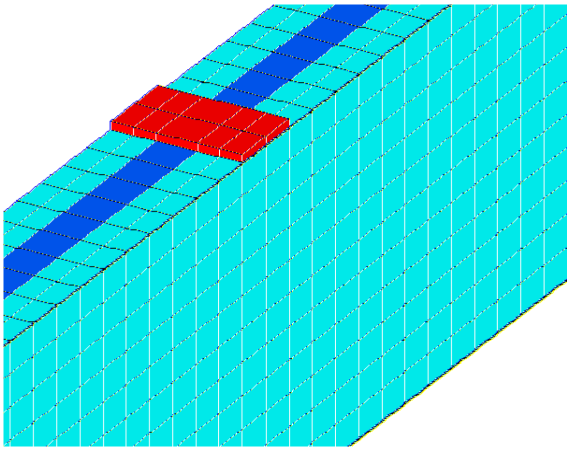

Fig.6 Detail of steel sheet, carbon fiber and LTB

Dead load was taken into into the computation with its density multplied by the gravitational acceleration of value $9{,}81\ m.s^{-2}$. The beam is loaded in two forces *(Fig.3)*. The dead load as an initial load and some increments of two concentrated forces were taken into account in the process of solution. We have chosen only two increments because of a reduction the time of analysis, but there is no problem to increase the number of increments. The values of an acting loads will be described in the next chapter.

The full Newton-Raphson (N-R) iteration procedure built in ANSYS was used for a nonlinear analysis, in which the stiffness matrix was updated at every step of iteration. The program used the tangent stiffness matrix only as long as the iterations remained stable (that was as long as the residual decreased and no negative main diagonal pivot occurred). If divergent trends were detected on iteration, the program discarded the divergent iteration and restarted the solution, using a weighted combination of the secant and tangent stiffness matrices. When the iterations returned to a convergent pattern, the program resumed using the tangent stiffness matrix. Activating adaptive descent usually enhanced the program's ability to obtain converged solutions for complicated nonlinear problems [4].

2.2 Parametrical analysis

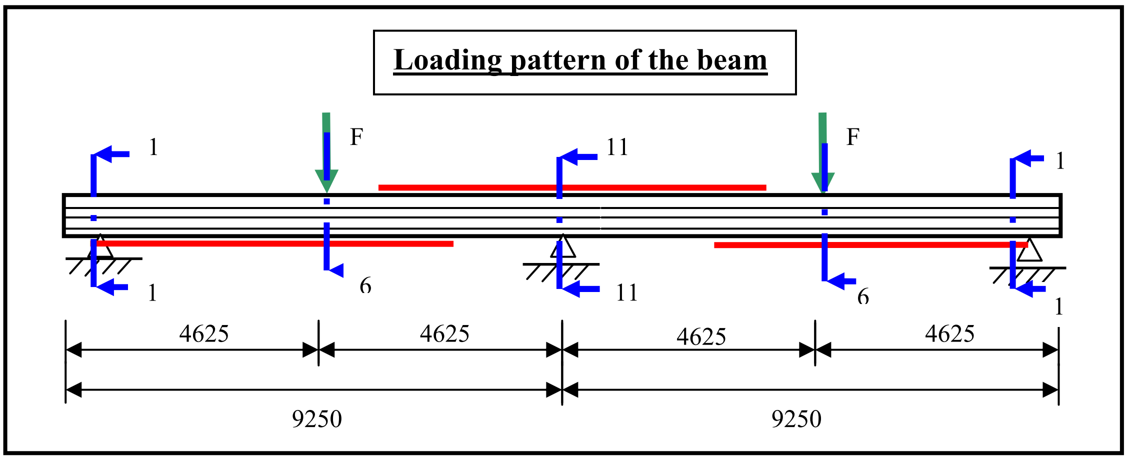

Fig.7 Loading pattern of the beam

Three different cases of reinforcement were taken into account – non-reinforced beam (denoted by 00), beam reinforced on the lower edge (denoted by 01) and beam reinforced on both edges (denoted by 02). Next figures show stress diagrams on the lower edge (denoted by SXL – *Fig. 8*), stress diagrams on the upper edge (denoted by SXU - *Fig. 9*) and deflection of the beams (denoted by w - *Fig. 10*), depending on the type of reinforcement due to a couple of forces *F = 36 kN.*

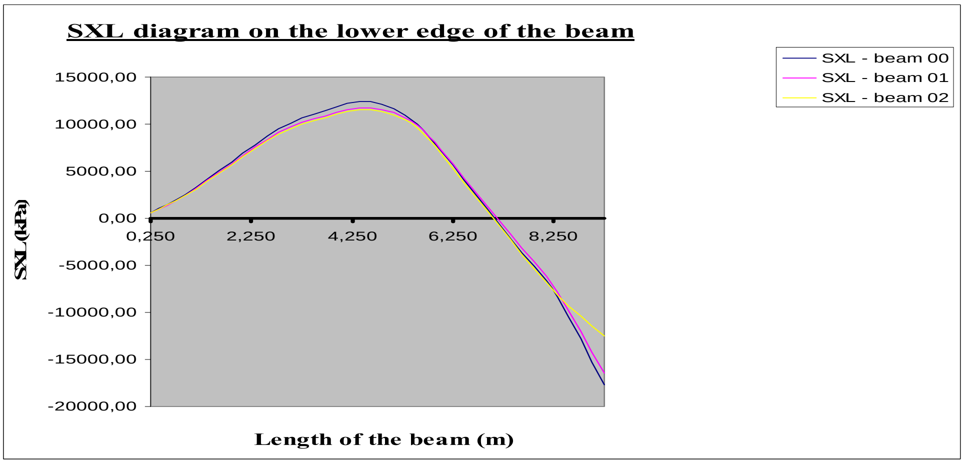

Fig. 8

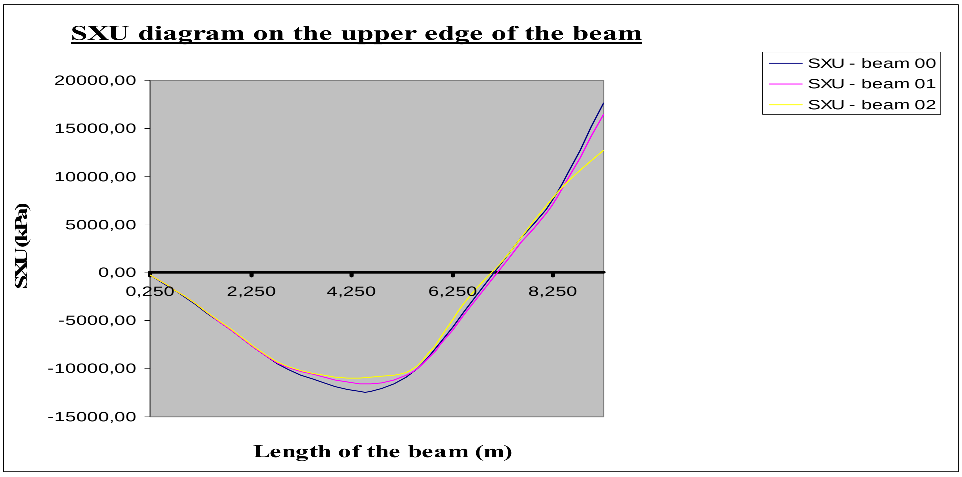

Fig. 9

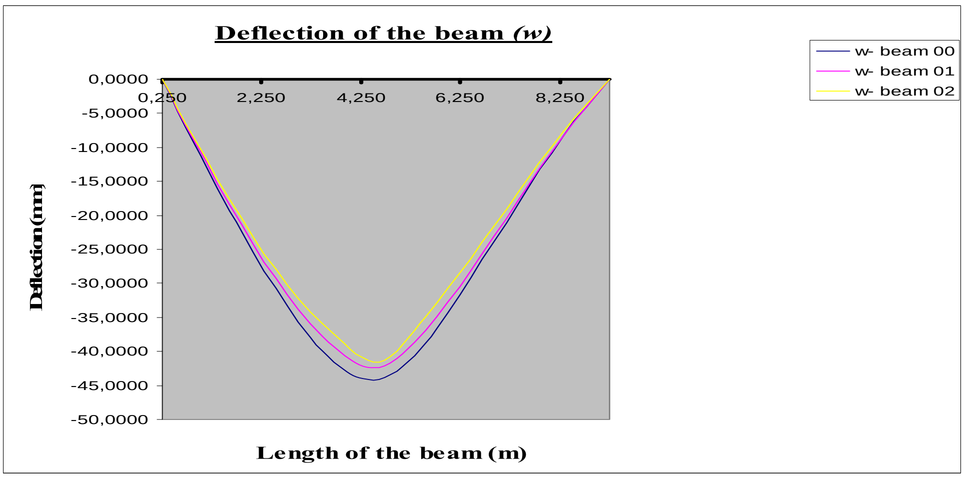

Fig.10

In next figures some results of an analysis of LTB having different length of reinforcement are presented as follows: stress diagrams on the lower edge (denoted by SXL – *Fig. 11*), stress diagrams on the upper edge (denoted by SXU - *Fig. 12*) and deflection of the beams (denoted by w - *Fig.13*), depending on the type of reinforcement due to a couple of forces *F = 36 kN.*

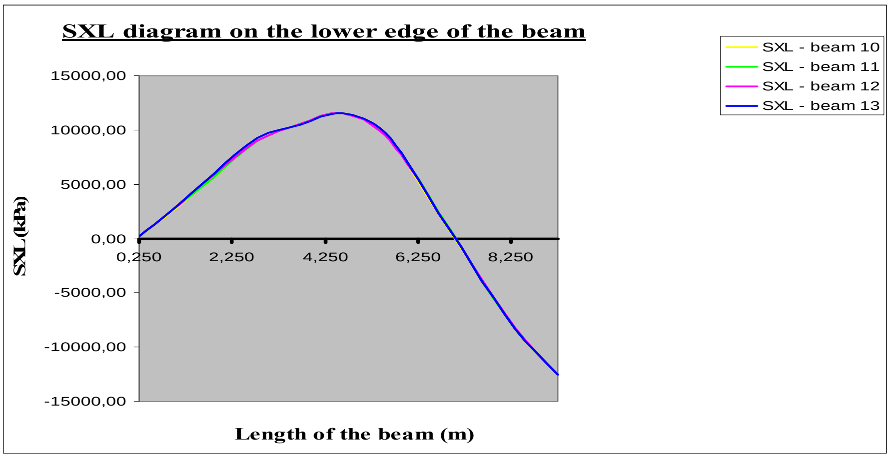

Fig. 11

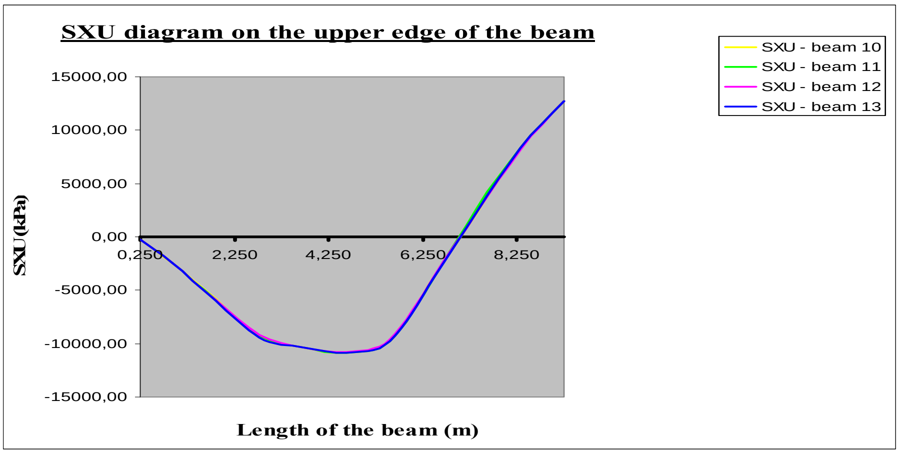

Fig. 12

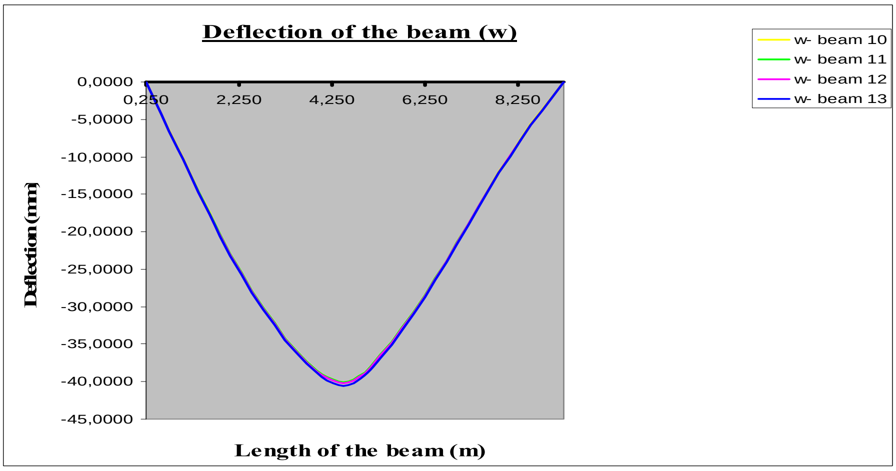

Fig. 13

In next figures some results of an analysis of LTB having different length of reinforcement are presented as follows: stress diagrams on the lower edge (denoted by SXL – *Fig. 14*), stress diagrams on the upper edge (denoted by SXU - *Fig. 15*) and deflection of the beams (denoted by w - *Fig.16*), depending on the type of reinforcement due to a couple of forces $F = 72\ kN$.

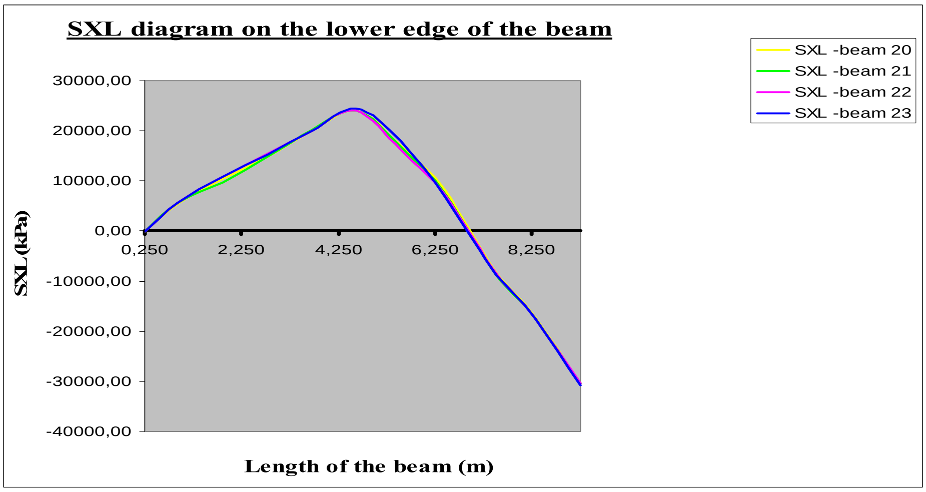

Fig. 14

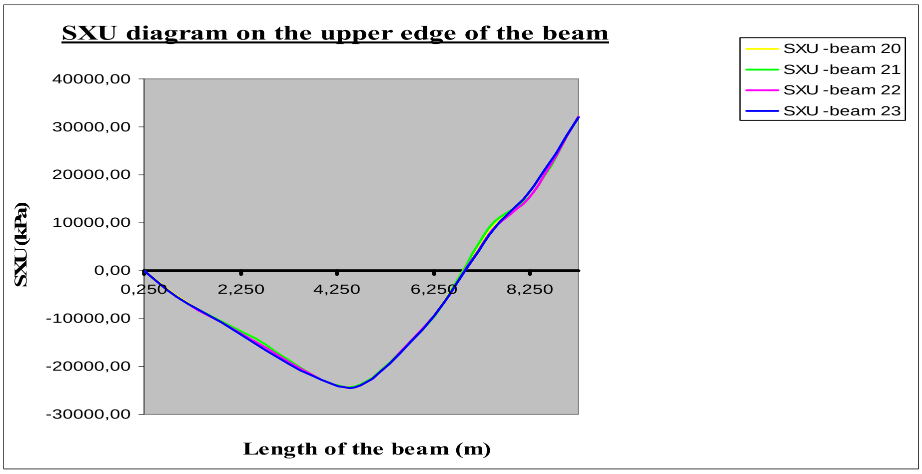

Fig. 15

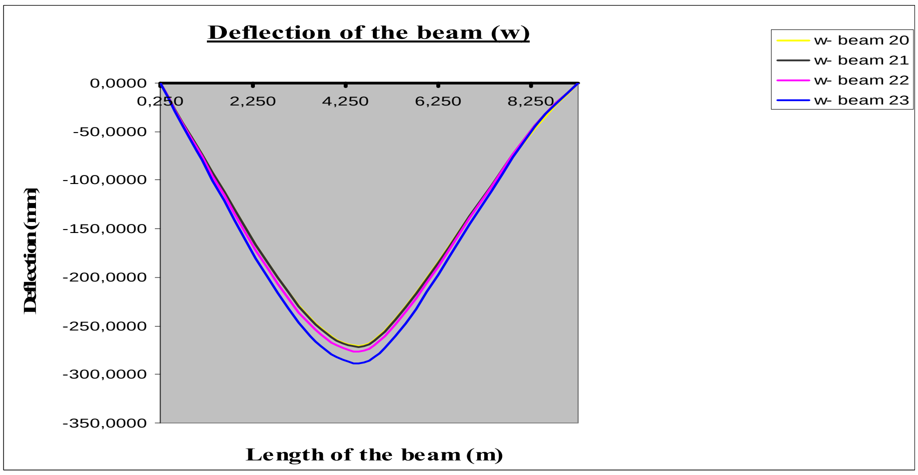

Fig. 16

3. Conclusion

As mentioned before three different cases of reinforcement were taken into account – non-reinforced beam, beam reinforced on the upper edge and beam reinforced on both edges. We did some numerical experiments due such beams in two different cases of load - a couple of forces and a couple of forces $F = 72\ kN$, when asking a question, how much could carbon fibers contribute for an improvement of a bending capacity. The results obtained by our analysis (quite well corresponding with an experiment) show, that the reinforcement by carbon fibers improves some properties of the composite beam that the maximum deflection decreases to about 90 – 95 % comparing to non-reinforced beam and maximum normal stress in timber also decreases to about 90 %. Also remarkable is the fact that carbon fibers also improve the bending capacity of the beam when they do not cover the whole length of the beam, but only parts of maximum bending moment areas. This fact may be utilized in reconstructing of timber beams.

Acknowledgement
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