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MODIFICATION OF PHYSICAL, MECHANICAL AND STIFFNESS FEATURES OF TIMBER AND ITS INFLUENCE ON THE RESISTANCE OF A CONNECTION TIMBER-TIMBER

PART 1. THEORETICAL ANALYSIS

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ABSTRACT

Paper deals with a possibility to increase the design resistance of timber as a structural material. A part of an aspirant thesis dealing with a local strengthening of wood around a connection member is introduced in the paper as well. Basic assumptions and boundary conditions considered in the calculation are listed and results are described in the paper. This theoretical study is about to be analyzed in a laboratory and consequently the possible ways how to apply this into practice will be analyzed.

KEYWORDS: Modification, timber connection, strengthening, modulus of elasticity, density.

INTRODUCTION

To prove a possibility to strengthen wood locally by means of chemical or mechanical modification of wood around a connection element is main reason of the study. Several computational models were made whilst the whole process is described below.

This paper deals with an analysis of a two-shear plane connection of timber load-bearing elements mutually connected by a connection member – metal dowel.

Models of the analyzed load-bearing elementary system were made using a computational program based on the Final Element Method. Dimensions and the value of the acting loading had been determined according to the correspondent technical standards.

This study is figurative only and it was chosen out of many similar studies presented in the aspirant thesis by Lukáš Blesák. A laboratory analysis following the results gained in the theoretical part of the thesis is being prepared currently.

Several methods how to strengthen, increase a resistance or change characteristics of timber are known, however, most of them are being used either in the furniture industry or in the field of reconstructions and modernizations of historical and listed objects. In order to understand the principles of wood modifying in various ways and based on various principles leading to different results, it was necessary to study similar thesis to the topic in the frame of this paper. Katuščák (2006a, b) deals with the chemical principles in wood. Several papers dealing with modification of various features of wood were studied in the initial of a research. Results showing various impacts of different modification processes on wood are described in the papers (Özmen et al. 2002, Brich and Kozhin 2002, Jumaat and Murty 2004, Sawata and Yasumura 2003). It helps us to gain a certain review over the mentioned problem. Authors introduced the possible results that might be expected and also the possible modification processes that might be used within the analysis. Dutko et al. (1976) describes the determination of various material features of wood that were consequently used in the theoretical analysis.

Most of the reviewed methods lead to a modification of the certain material characteristics, such as water resistance, color, rigidity, but not strength in tension, compression, bending or modulus of elasticity that are necessary to increase the material characteristics considered in the design of load-bearing structures. From this point of view the study is unique. The results are hardly expectable and defined in advance, therefore it is necessary to apply all the assumptions into practice and consequently verify by a laboratory analysis. The method of a local strengthening might be used in several fields of a structural design of load-bearing timber structures – modern structures, historical buildings, reconstructions etc. in the case of positive results gained.

MATERIAL AND METHODS

Load-bearing connections are the certain locations in a load-bearing structure that are predisposed to collapse because of several elementary reasons – local concentration of high stresses, connection of materials with different material characteristics, the assembly aspect (load-bearing elements are often connected at a building site with imperfections), the effective dimensions of connected elements changing etc. This is one of the reasons why, it is necessary to deal with these structural parts preciously and try to improve the way of connecting load-bearing elements or trying to find a way how to strengthen these specific areas locally. Several basic ways of connecting load-bearing elements are known. The subject of this analysis is one of them. The connection is shown in Fig. 1.

Fig. 1: Two shear plane connection timber-timber – connection members are metal dowels.

The illustrated type of the connection is commonly used in the civil or road engineering

(Figs. 2, 3). Two shear plane connections steel-timber are shown in both figures. Fig. 2 shows a combination of metal dowels and bolts and Fig. 3 metal dowels used only. The Fig. 2 shows a connection of timber elements as a part of the load-bearing structure of a hangar at the airport in Vienna. The Fig. 3 shows a connection of timber elements on one of many bridges over the Austrian river Mur.

Fig. 2: Two shear plane connection steel-timber / metal dowels and bolts.

Fig. 3: Two shear plane connection steel-timber / metal dowels.

Considering the calculation of a two shear plane connection timber-timber where metal dowels are used according to the European technical standard dealing with the design of timber load-bearing structures (STN EN 1995-1-1, 2008) it is evident that the density of wood in a connected element is one of the parameter directly influences the final resistance of a connection timber-timber or steel-timber. Even though a dependence of the wood density and modulus of elasticity and vice versa is not mathematically defined, the dependence between the two parameters is evident. Looking at Fig. 4 the dependence can be seen. The function is neither linear nor exponential, but the increasing values of modulus of elasticity depending on the increasing values of the wood density are clearly evident. Following this fact, the modified material around a connection member was simulated by variable modulus of elasticity. Changing of the wood density has no influence on the stress flow in a computational program/model. Basically, an analysis of the influence of the variable material characteristics of timber around a connection member is the aim of this work. The changing of the wood density was replaced by a correspondent increasing of modulus of elasticity for the computational models in this case. The principle is described below.

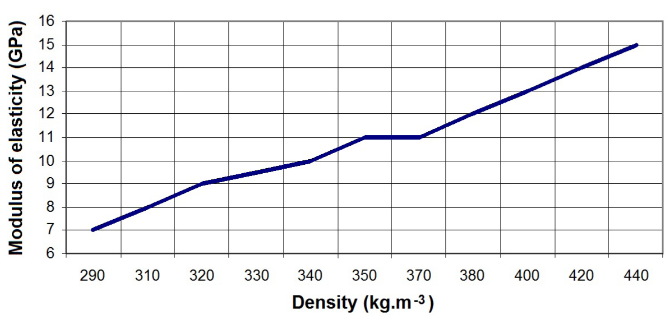

Fig. 4: Dependence of the modulus of elasticity $E_{0.05}$ on the increasing wood density ρ_k.

The own method how to modify the selected material characteristics of timber is a subject of a current study at the Department of Steel and Timber Structures at the Faculty of Civil Engineering in Bratislava. However, a chemical modification by saturation of the material around a connection member is considered in this stage of the study. A chemical agent saturated causes to gain certain and specified characteristics of timber in the specified area. Because of wood becomes a non-homogeneous material its characteristics depend on the grain flow. The direction of saturated agent only in the direction of grain flow is considered in the study. The saturation in the direction perpendicular to the grain might be negligible. The depth of saturation was varied as well. The aim of this analysis is to determine a depth which is necessary to modify the material around a connection member in order to impact the stress flow in the specified area markedly.

A part of the mentioned study (Blesák 2012) with analyze of several computational models is listed in the following. This part introduces six computational models with a simulation of the variation of the depth of chemical agent saturation and intensity of the modified material characteristics also. One of the models is a reference model. It is a comparative model with not modified material and all results are compared to its. The schemes of the particular models are shown in Figs. 5, 6 and 7. The boundary conditions for the calculation (loading, supports, orthotropic characteristics of the non-modified timber, spatial stability of the model, etc.) are not listed in the paper; however, they are the same for the each analyzed model. All the boundary conditions are described in detail in the mentioned study.

The dependence between the modulus of elasticity and the density is shown in Fig. 4. A modification of timber around a connection member in the particular models is considered, thus the values of modulus of elasticity in both directions according to the grain correspond with the values of modulus of elasticity for a chosen strength class of timber. The strength class of timber is chosen according to the assumed increasing of the density in the analyzed area. For example, if density increased twice in comparing to the material of the reference model (material of the reference model – softwood timber (spruce) / strength class C 24, ρ_k = 350 kg.m^{-3}) then a modulus of elasticity in the modified material is considered the one appertaining to timber / strength class D 60 - ρ_k = 700 kg.m^{-3}. The strength of timber D 60 give us a comparative value only to determine an expected modulus of elasticity for timber of the assumed density. The characteristics of soft wood are not replaced by the characteristics of hard wood.

The linear support and its stiffness marked as klin represents a connection member and plasticity of the material of the metal dowel is made from.

Decreasing intensity of the material modification as a function of the saturation depth is assumed thus the modulus of elasticity in the partial areas (shown in the schemes of the particular models) is multiplied by a coefficient 2/3 and 1/3.

Values of modulus of elasticity in the all models listed in this paper are considered as follows:

For the base material
(Unmodified timber)

$E_{0.05}^{C24} = 7400$ MPa

$E_{90mean}^{C24} = 370$ MPa

$G_{mean}^{C24} = 690$ MPa

For the modified material
(Modified timber)

$E_0 = E_{90} = (E_{0.05}^{D60}$ alebo E' alebo $E'')$

$E_{0.05}^{D60} = 14300$ MPa

$G_{mean}^{D60} = 1060$ MPa

$E' = E_{0.05}^{C24} + (E_{0.05}^{D60} - E_{0.05}^{C24}) * 1/3 = 9700$ MPa

$G_{mean}' = G_{mean}^{C24} + (G_{mean}^{D60} - G_{mean}^{C24}) * 1/3 = 814$ MPa

$E'' = E_{0.05}^{C24} + (E_{0.05}^{D60} - E_{0.05}^{C24}) * 2/3 = 12000$ MPa

$G_{mean}'' = G_{mean}^{C24} + (G_{mean}^{D60} - G_{mean}^{C24}) * 2/3 = 937$ MPa

Model 1 – Model is used as a reference/comparative model. It means that the gained results of the analyzed values in this model are compared with the same values of the other analyzed models. It helps to create illustrative conclusions that might be used for the analysis. The grain flow is considered in the vertical direction in all the models.

Model 2 – The area of the local modification in direction parallel to the grain of timber is bordered by two concentric circles, whilst their centre is located in the longitudinal axis of the connection member. The radiuses of the particular circles are 6 and 9 mm, i.e. the modified area is 3 mm wide. The modification in the analyzed area is based on the change of timber's modulus of elasticity. The modulus of elasticity has been changed into the value $E_{0.05}^{D60}$ = 14300 MPa in both major directions - perpendicular and parallel to the grain.

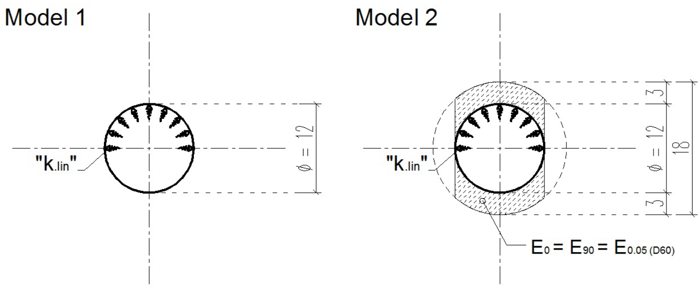

Fig. 5: Computational schemes for models 1 and 2.

Model 3 – The area of the local modification in direction parallel to the grain of timber is bordered by two concentric circles, whilst their centre is located in the longitudinal axis of the connection member. The radiuses of the particular circles are 6 and 12 mm, i.e. the modified area is 6 mm wide. The modification in the analyzed area is based on the change of timber's modulus of elasticity. The modulus of elasticity has been changed into the value E0.05D60 = 14300 MPa in both major directions - perpendicular and parallel to the grain.

Model 4 – The area of the local modification in direction parallel to the grain of timber is bordered by two concentric circles, whilst their centre is located in the longitudinal axis of the connection member. The radiuses of the particular circles are 6 and 15 mm, i.e. the modified area is 9 mm wide. The modification in the analyzed area is based on the change of timber's modulus of elasticity. The modulus of elasticity has been changed into the value $E_{0.05}^{D60}$ = 14300 MPa i in both major directions - perpendicular and parallel to the grain.

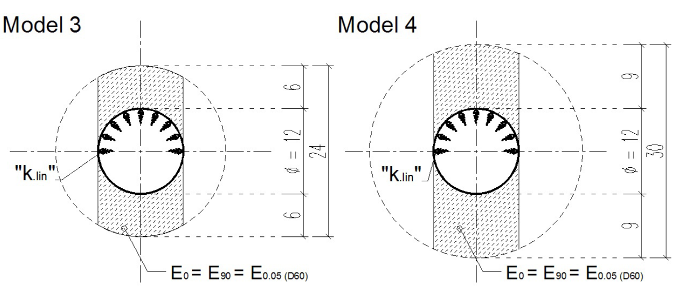

Fig. 6: Computational schemes for models 3 and 4.

Model 5 – The area of the local modification in direction parallel to the grain of timber is bordered by three concentric circles, whilst their centre is located in the longitudinal axis of the connection member. The radiuses of the particular circles are 6, 9 and 12 mm. Two modified areas are wide 3 mm each. Decrease of saturation intensity is simulated by different values of modulus of elasticity in the partial areas. These values are marked in the Model in Fig. 7 and their numerical values are listed above in this chapter.

Model 6 – The area of the local modification in direction parallel to the grain of timber is bordered by four concentric circles, whilst their centre is located in the longitudinal axis of the connection member. The radiuses of the particular circles are 6, 9, 12 and 15 mm. Three modified areas are wide 3 mm each. Decrease of saturation intensity is simulated by different values of modulus of elasticity in the partial areas. These values are marked in the Model in Fig. 7 and their numerical values are listed above in this chapter.

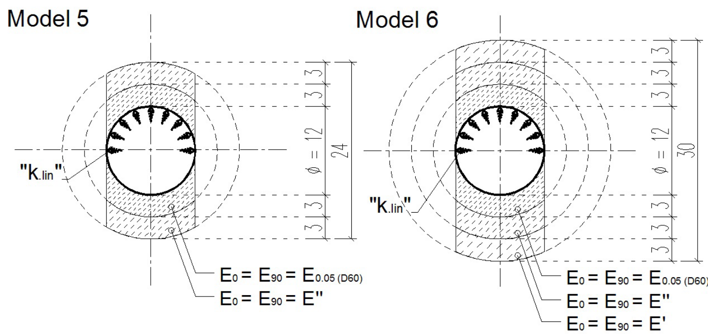

Fig. 7: Computational schemes for models 5 and 6.

The following part of this chapter introduces the way of loading in the computational models. Intensity of the linear loading was designed following the calculation of resistance for a two shear plane connection timber-timber according to the correspondent technical standard (STN EN 1995-1-1, 2008) thus, that the connection member is not deformed and its position and shape is not changed. Considering the defined dimensions and material characteristics of timber and steel elements leads to the connection failure mechanism where deformation of timber appears – deformation of the wall for the opening/cutout for the connection member.

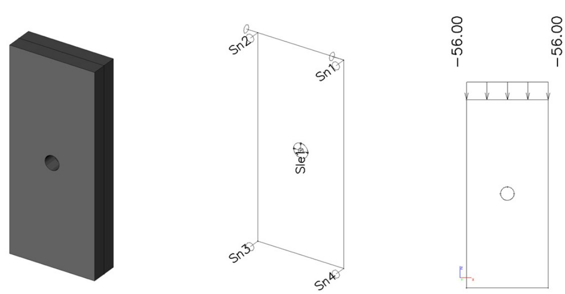

Fig. 8: Axonometric view over the model (left), linear and node supports (in the middle), outer loading (right).

The loading force was defined according to the correspondent technical standard thus, the mentioned failure mechanism is defining for the design resistance calculation - N_{Ed} = 4 kN. In Fig. 7 there is a computational model shown. The width of the computational object equals to 72 mm and the thickness equals to 24 mm. The value of linear loading is N_{Ed} / (24 mm * 72 mm) * 24 mm = 56 kN.m^{-1}. Fig. 8 shows the supports spatially stabilizing the whole system in order to be able to start a calculation in the computational program also. The node supports are located in the corners of the timber element (the middle part of the two shear plane connection). They support the system in both horizontal directions in the upper corners and in one horizontal direction in bottom corner only – perpendicular to the plane of the timber element. The system is not supported in the vertical direction and full load is transferred into the linear support. The supports located like this prevent the system from all the possible spatial movements and rotations and do not transfer any outer loading.

RESULTS

The final conclusions the laboratory testing will be based on are defined from the partial results and their mutual comparison. The results obtained are shown and described as follows. Fig. 9 shows the shapes of the deformation of the cutouts around the connection corresponding with particular models. The deformation around the connection member using the final element net is shown in the picture.

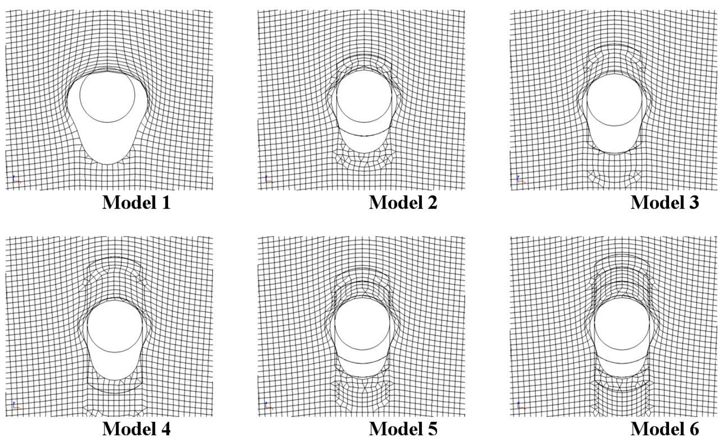

Fig. 9: Final element net's deformation around the connection member for particular models.

Fig. 10 shows the flow and intensity of the linear reaction representing the connection member in the vertical direction. A different transfer of outer loading and consequently creating the vertical reactions is obvious.

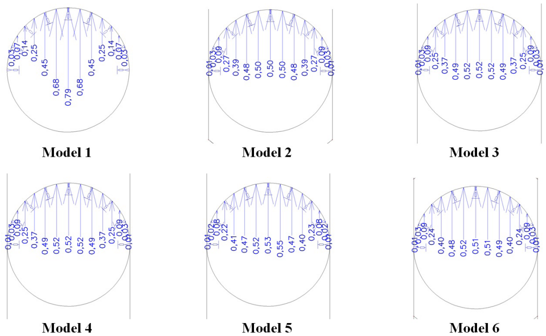

Fig. 10: Intensity of the linear reaction in the vertical direction for particular models.

Following the final element net's deformation around the connection member and intensity of the linear reaction in the vertical direction it is possible to assume the vertical stress flow in the material around the connection member. The flow of the vertical stress σ_y in the material around the connection member is shown in Fig. 11.

From Fig. 11 it is obvious that stress flow in model 1 (unmodified material) distinguishes the most from the other models (modified material). Stress flow concentrates centrically in the direction of the theoretical node centre of the load-bearing support – the linear support. This concentration appears on a relatively little area in the case of 2D model. It is a circular part, what causes local points of high stress in the unmodified material. It is shown as a dark blue color in Fig. 11 (Model 1). The darker color represents the higher pressure. The values of stress are not analyzed at this stage of the analysis. Numerical values might vary depending on the outer loading, dimension of the partial elements etc. Variation of stress flow is directive for the moment. Dark blue area in the variation of stress flow is not obvious in the case of Model 2-6. It indicates the stress spreads over a bigger circular part without local points of high stress appearing. Relatively constant stress flow without local points of high stress prevents the material around the connection member from a generating of stresses higher than the maximal standard stress of the material that might be used for a safety design of the load-bearing members. Consequently these areas do not tend to deform locally, split etc. A higher design resistance of the analyzed type of a connection is the assumed final impact of this effect.

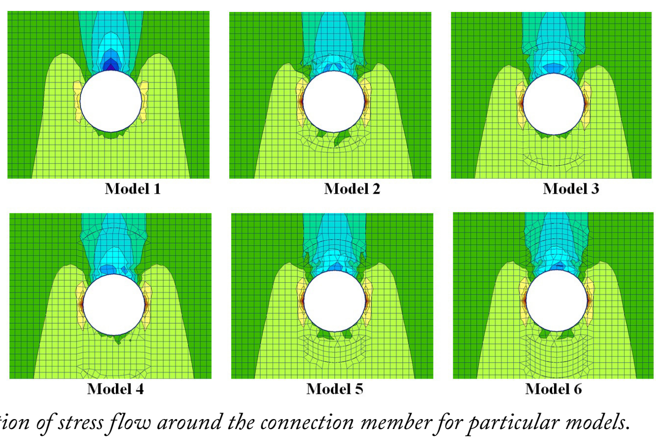

Fig. 11: Variation of stress flow around the connection member for particular models.

The results are summarized in Tab. 1. The values of maximal deformations of a point located on a circle representing the surface of the connection member – in the horizontal direction u_x, in the vertical direction uz and maximal value of vertical component of the linear reaction R_z are listed in Tab. 1. The variation of values u_z and R_z are shown in Fig. 12 also.

It is obvious that the local modification of timber around the connection member has impact over the analyzed values. The increasing depth of the chemical agent saturation has not an impact over the analyzed values in that range if the saturation is considered in a very close area only (depth 3 mm) around the connection member.

Tab. 1: Summary of the analyzed values from particular models.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Deformation u_x (mm)	0.003	0.000	0.000	0.000	0.000	0.000
Deformation u_z (mm)	0.038	0.026	0.025	0.024	0.025	0.024
Reaction R_z (kN.m^{-1})	0.790	0.500	0.520	0.550	0.510	0.530

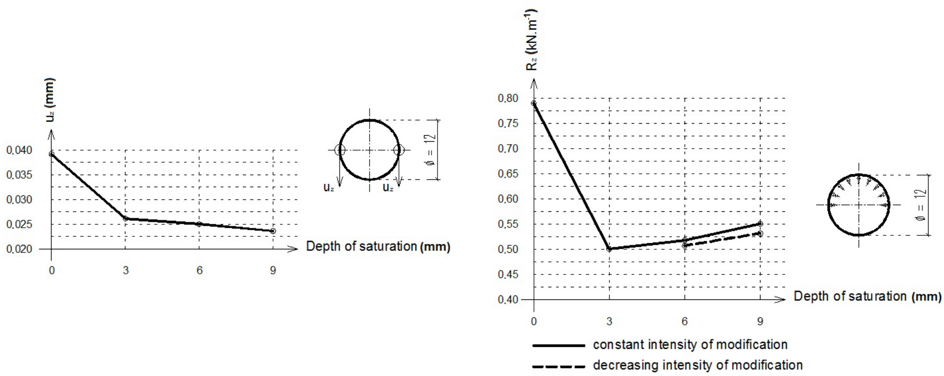

Fig. 12: Variation of the analyzed values from particular models.

Many other facts and values that might be suitable for understanding the behavior of the modified material in a very close area around a connection member have been analyzed in the study mentioned above (Blesák 2012). All results obtained to be used as an assumption for the following theoretical and laboratory study only, therefore they can not be considered and presented as definitive and final.

DISCUSSION

The results gained in the frame of this paper definitely show a positive impact of changing the stiffness conditions in wood around a connection member. Comparing the gained results to the papers mentioned above, we receive results confirming the same assumptions – physical and mechanical features increase. Özmen et al. (2002) deals with modification and consequent testing wood samples by various chemicals, for example styrene. This paper proves an increase of maximal possible load (tension) acting on the tested sample comparing to the unmodified samples. The maximal load is up to three times higher than the maximal load acting on the unmodified sample. Even in this paper decrease of stress flow is evident, what results into higher resistance of the analyzed connection.

Brich and Kozhin (2002) defines several methods how to modify wood even in bigger areas. Most of the impregnation methods consider only a surface saturation (from 1 up to 3 mm) of a chemical into the modified material. Following Brich and Kozhin (2002) we modified the analyzed area even deeper than only 1–3 mm what enables to increase the effect of wood modification around a connection member.

Katuščák (2006b) introduces wood-polymer composite materials as a combination of two materials – industrial wood and synthetic polymers. Symbiosis of wood and plastic materials has been and currently is a subject matter of various studies and a technological development. Plenty of authors have dealt with this topic trying to find to the best way how to put the theory of this interesting topic into practice. Considering the shape of wood-polymer composite materials can be divided into massive, laminated and material on the basis of lignocelluloses elements. The aim of the study presented in this paper is to develop a massive wood-polymer composite material appropriate to be used in the civil engineering practice. These materials can be modified in situ – in a defined area in a subjected element, the whole element can be modified or only a part of an element can be modified by means of react-plastics (e.g. by means of thermo-plastics polystyrene, polyester). There are basic chemical-technological processes used to prepare wood-polymer composite materials, some of them are a vacuum-pressure impregnation, applying the monomers or react-plastics on the surface of lignocelluloses materials or vaccination. All these methods prove it is possible to put the theory presented in this paper into practice and so there is a technological way how to modify the physical and mechanical features of timber used in load-bearing structures.

By a proper combination of the theoretical results gained in the study this paper represents and the practical methods of making wood-polymer composite materials in situ it is possible to reach the positive results and improve the application of timber structures in the civil engineering practice.

The other listed papers mentioned above served as the base for the analysis in this study. The self results are quite not-comparable because of different values analyzed in the particular papers. Nevertheless, all of them lead to the same point – it is possible to modify wood and improve its physical and mechanical features and consequently apply these changes into either civil engineering or furniture industry what helps to make wood even more competitive material in the field of several industries.

CONCLUSIONS

Local modification of timber around the connection member has an impact over the variation of stress flow around the connection member and other characteristics of the analyzed connection such as higher resistance against splitting, higher load-bearing resistance, etc. As it was mentioned above, all the results obtained are intended to an inaccurate assumption for the following theoretical and laboratory study; therefore they can not be considered and presented as definitive and final. This unusual way of strengthening of load-bearing timber structures is a subject of another theoretical and laboratory analyses at the Department of Steel and Timber Structures. The study deals with the questions such as: How to strengthen timber effectively in an area around a connection member - theoretically? How to put the most convenient way of strengthening into practice - practically? How to apply this method into the civil engineering industry – economically (and other) effective?

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