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PREDICTION OF THE SHAPE CHANGES OF HYBRID LAMINATED COMPOSITE MATERIAL SHEET

HIBRĪDAS SLĀŅAINAS KOMPOZĪTMATERIĀLA LOKSNES FORMAS IZMAIŅU PROGNOZĒŠANA

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Introduction

Layered composite material sheets are widely used in the construction and transport machine-building industry, where part of the structural elements are under variable moisture conditions during the time of operation and erection. This often leads to the changes of the initial shape of these elements and to structural inadequacy regarding the requirements of the normative acts. Searching for structurally better and aesthetically more attractive solutions for the construction of various structures, non-standard anticlastic elements are used more frequently. When the anticlastic composite material sheets are used in cable roof structures as load-bearing covering elements or isolating elements in interior decoration, undesirable changes of the shape of the elements are caused by the variable moisture. The changes can be prevented partly by using reinforced plastic reinforcement. Therefore, the preservation of the initial shape of timber composite material sheets using reinforced plastic reinforcements has been investigated.

For modelling sheet deformations, the authors have used a self-developed calculation model to determine the thickness of rational reinforcement anticlastic sheet, which provides the changes of the original bending radius under variable moisture conditions [1] within the limits of preferable intervals, and the finite element method. The aim is to evaluate and compare results, collected from the previously developed and approbated calculation model [1] and the finite element method using the software package ANSYS v.11 (henceforth FEM).

Calculation model

The calculation model for an anticlastic sheet element consisting of linearly elastic orthotropic layers (henceforth *sheet*) has been developed, using the plane stress statements of laminated material mechanics in matrix form, discussed in the works [2-6]. The *sheet* layers are assumed to be tied together by a thin layer of glue and deform together. The threshold of the orthogonal coordinate system is placed in the centre of the geometrical middle plane of the *sheet*. The sample is given where the moisture content for every *sheet* layer under any moisture changes is identical. In the operating conditions, the moisture distribution along the cross-section of the element is variable, but the considered case predicts more danger because of the larger effect on the change in bending radiuses. The changes of the longitudinal deformations in the geometrical middle plane of the *sheet* and the bending radiuses of the *sheet* bottom surface are assumed as the main characteristics of invariability of the shape.

Calculation of the shape invariability characteristics under variable moisture, for the element obtained by reinforcement of the *sheet* with reinforced plastics (henceforth *element*), is carried out in several stages. In the **first stage,** the appropriate moisture change $\Delta\widehat{W}$ for straightening the anticlastic *sheet* is calculated. It is assumed that both curvature radiuses of the *sheet* become equal to ∞ almost at the same moment. Calculations are made by choosing the appropriate moisture change (reducing the moisture until the *sheet* straightens out), or using a definite moisture change, which has already provided the required curvature of the flat composite material sheet. The longitudinal deformations $\widehat{\varepsilon}$ caused by moisture changes $\Delta\widehat{W}$ on the top and bottom surfaces of the sheet are determined in this stage. To calculate the longitudinal deformations ε of the *element*, which occurs due to the moisture change $\Delta W = \Delta\widehat{W} - \Delta\widetilde{W}$, in the **second stage** a reinforced sheet without any initial curvature subjected to moisture changes $\Delta\widetilde{W}$ is inspected conditionally and longitudinal deformations $\widetilde{\varepsilon}$ are calculated. In the **third stage** the resultant longitudinal deformations ε_n of the anticlastic *element*, which has been subjected to the moisture action and changed moisture content by ΔW, are calculated using relevance:

$$\varepsilon_{n-1} = \widehat{\varepsilon}_{\widehat{n}} + \widetilde{\varepsilon}_{n-1}, \tag{1}$$

where $\varepsilon -$ longitudinal deformation;

$n -$ index which specifies the number of layers contact plane in the place where longitudinal deformation of the *element* is calculated. The planes are numbered from the top surface, starting with “0”;

$\widehat{n} -$ Index which specifies the number of layers contact plane in the place where longitudinal deformation of the *sheet* is calculated.

To define the bending radii on the top and bottom surfaces of the *element*, an equation system (2) is constructed based on the relationship between the angle and the sides of a right-angled triangle (shown in Fig.1). The system determines the bending radius $R_x|_{Zn-1}$ (2) of the bottom surface.

$$\begin{cases} tg\alpha_x = \dfrac{\widehat{h}}{\Delta l_x|_{Zn-1} - \Delta l_x|_{Z1}} \\ tg\alpha_x = \dfrac{R_x|_{Zn-1}}{\dfrac{b}{2} + \Delta l_x|_{Zn-1}} \end{cases} \Rightarrow R_x|_{Zn-1} = \dfrac{\widehat{h}\cdot(\dfrac{b}{2} + \Delta l_x|_{Zn-1})}{\Delta l_x|_{Zn-1} - \Delta l_x|_{Z1}} \quad , \quad \text{and} \tag{2}$$

$$\Delta l_x|_{Zn} = \varepsilon_x|_{Zn} \cdot \frac{b}{2} , \tag{3}$$

where $\widehat{h} -$ total thickness of the sheet;

$b -$ width of the sheet;

$\Delta l_x|_{Zn-1} -$ longitudinal elongation in the direction of X axis. Member z_n specifies the location where the elongation is calculated.

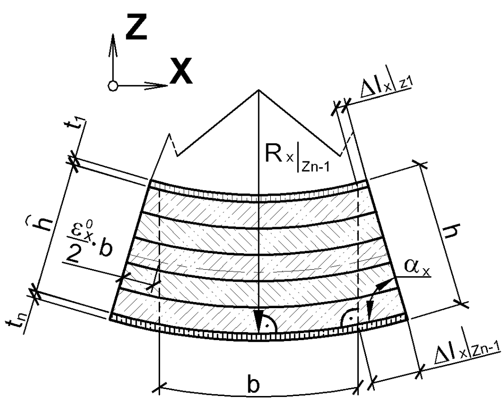

Fig.1. Calculation scheme of the bending radius in plane XZ for the *element*

The difference between the bending radiuses of the *element* $R_x|_{Zn-1}$ and *sheet* $\widehat{R}_x|_{Z\widehat{n}}$ characterizes the influence of the reinforcement at a definite moisture change. Analogical relevancies are used to calculate the bending radius $R_y\big|_{Zn-1}$. Detailed description and mathematical proof of the model can be found in [1]. The interaction of curvatures through gradual moisture changes is not considered in the developed calculation model, therefore the precision check of this model is done by comparing analytically calculated results with the results acquired using FEM.

Calculation using finite element method

One fourth of the *element* (shown in Fig.2) was modelled using FEM and applying finite element SOLID45. Layers of the *element* were meshed to cubical finite elements, with the height corresponding to the thickness of an individual layer, but for the strengthening layers – to the half of their thickness. At the bottom of the *sheet* the support was placed restricting the displacements in the directions of X, Y and Z axis. The support placed on the top was restricting the displacements in the directions of X and Y axis.
The calculation was carried out during the three loading stages by operating with the options of menu „Solution/Analysis Type/Soln Controls„ and window „Time step options”. The shape changes of the *element* through gradual moisture decreases were taken into account. The finite elements of the reinforcement layers were excluded from the calculation model by using the command EKILL, and the starting moisture content $\widehat{W}_{start}$ was defined for the *sheet* layers in the first stage. In the second loading stage, FEM calculates the deformations of the *sheet* at every step by using the command NSUBST, while moisture increases gradually by 1%, until the moisture of layers reaches $\widehat{W}_{end}$. In this stage FEM calculates the shape changes in case if the curvature of the *sheet* is produced by the changes of the moisture deformations in the layers of the *sheet*. Reinforcement layers are reactivated and included in the calculation model of the *element* by using the command EALIVE in the third loading stage. At the beginning of this stage, the moisture in the layers of the *sheet* is assumed to be $\widehat{W}_{end} = W_{start}$ by using the command TREF, and the resultant moisture W_{end} is prescribed in the end of the stage by using the command TEMP.

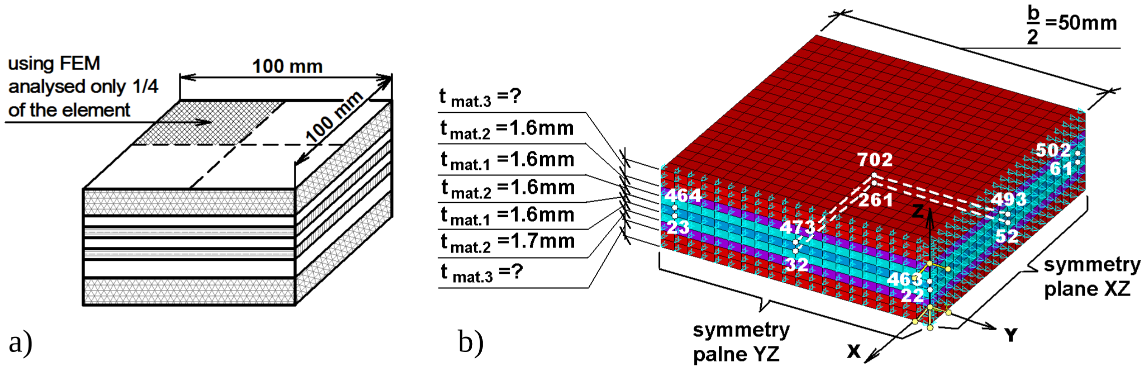

Fig.2. a) *sheet* and its dimensions b) calculation scheme of FEM supplemented with the supports, thicknesses of layers, numbers of layer materials (see. table 1) and numbers of points from which the values of main characteristics of invariability were read for the case of the sheet strengthened on both sides

Discussion of results

During exploitation under variable moisture conditions the *sheet* from composite timber materials is subjected to undesirable changes of the shape. The prevention of the changes is analytically approbated using a glass fibre sheet with oriented glass fibres and epoxy resin (henceforth GFRP). The characteristic values of GFRP rigidity are found in [7] and shown in the Table 1. A sample of the *sheet*

with unsymmetrical structure is used, consisting of five birch timber layers glued together. The properties of timber values are found in [8] – see table 1. The longitudinal fibres of the layer are oriented at right angles towards the longitudinal fibres of adjacent layers (90˚/0˚/90˚/0˚/90˚). The layer thicknesses are $\hat{t}_1 = \hat{t}_2 = \hat{t}_3 = \hat{t}_4 = 1.6\text{mm}$, $\hat{t}_5 = 1.7\text{mm}$ (see Fig.2b). The moisture change $\Delta\hat{W} = 7\%$ is the difference between the final and the initial moisture level of the timber layer, for example, when moisture in the timber changes within the limits of 10% to 17% if relative humidity of the air changes from 53% to 82%, with the air temperature of 20°C (see [9], table 3-4).
Using FEM and the developed calculation model, three cases were analytically approbated: the *sheet* curved by moisture were reinforced on the concaved surface (see Fig.3c), arched surface (see Fig.3d) and on both sides (see Fig.3b).

Table 1.

Deformative characteristics of layer properties

Characteristics	**Birch-tree[1], [8]**	**Birch-tree[2], [8]**	**GFRP S2/3501-5 $[0/90]_{2s}$, [9]**
Notation of material	mat.1	mat.2	mat.3
E_x [MPa]	17250	480	32300
E_y [MPa]	480	17250	32300
E_z [MPa]	645	645	16500
G_{xy} [MPa]	890	890	6760
G_{xz} [MPa]	1540	230	5670
G_{yz} [MPa]	230	1540	5670
ν_{xy}	0.445	0.013	0.136
ν_{xz}	0.341	0.321	0.435
ν_{yz}	0.321	0.341	0.435
β_X	0	0.0034	0
β_Y	0.0034	0	0
β_Z	0.0028	0.0028	0

[1]X axis is parallel to the direction of longitudinal fibres;
[2]Y axis is parallel to the direction of longitudinal fibres.

Indexes shown in the Table 1 indicate the properties of layer in the global coordinate system. If the X axis indicates the direction parallel to the fibres (see 2.column in the table 1), index Y indicates the direction of the property transversally to the fibres of timber layer, but Z – in the radial direction.
Declared values for modulus of elasticity E of birch are calculated by dividing the sum of the modulus of elasticity in tension and compression (found in [8]) by 2. G – shear modulus. The first index of Poisson's ratio ν indicates the direction of load, the other – the direction of transverse deformations.

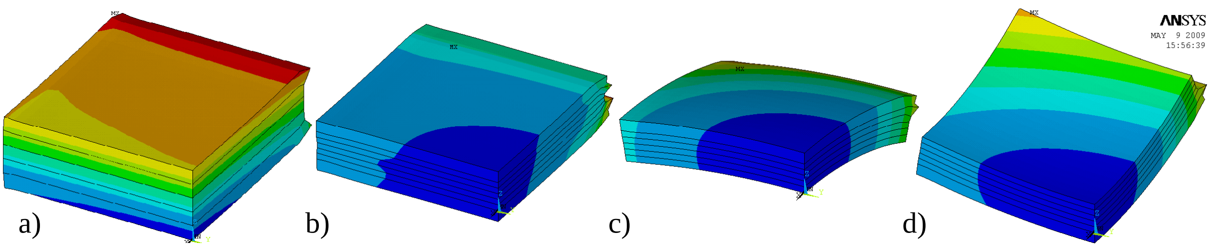

Fig.3. Visualisation of the displacements (enlargement 50×) calculated with FEM for the one fourth of the sheet. a) Displacements of the anticlastic *sheet*, with curvature obtained after the moisture growth of 7% (from $\hat{W}_{start}$ =10% to $\hat{W}_{end}$ = 17%). Displacements of the anticlastic *element* strengthened from b) both sides, c) top side and d) bottom side with the glued GFRP sheet after moisture decrease of 7% (W=10%)

A case has been analysed when the thickness of GFRP reinforcement sheets is t_{GFRP}=3.15 mm. Using double-sided reinforcement with such thickness provides the invariability of the both bending radiuses of the *element* with the precision which does not exceed 5% admissible in engineering calculations (see Fig.3b and Fig.4). In case of double-sided GFRP reinforcement with the thickness 3.15 mm (ratio of reinforcement cross-section area to the total element cross-section area æ = 0.44) for the moisture decrease of $\Delta W = 7\%$, if the developed calculation model [1] is applied, the change of the *element* bending radius parallel to the direction of X axis is -1.19%, in the direction of Y axis -4.97% (see Fig.4). If the thickness of strengthening is 1.30 mm (æ = 0.24), the change of the *element* bending radius parallel to the direction of X axis is -4.96%, but in the direction of Y axis -20.10%. The invariability is provided only for the bending radius parallel to the X axis.

The developed model can also be used if moisture-caused changes of curvature are used for the manufacturing of elements with anticlastic surface. The best accomplishment of such curvatures can be realized using one-sided reinforcement. The curvature of the *sheet* will increase or decrease depending on the placement of the reinforcement, properties and thickness. For example, when the top surface of the *sheet* is reinforced with GFRP, the curvatures tend to increase. If the moisture decrease is ~1%, the concaved curvature parallel to the direction of X axis changes and becomes arched with the greater value of curvature; the arched curvature parallel to Y axis increases more (see Fig.3c and Fig.4). When the bottom surface of the *sheet* is reinforced with GFRP, the curvatures also tend to increase. If the moisture decrease is ~0.5% (see Fig.3d and Fig.4) the concaved curvature parallel to the direction of X axis increases more, but the arched curvature parallel to Y axis changes the direction and becomes concaved with the greater value of curvature. The changes of the direction of curvatures can be explained with the changes of the placement of neutral axis following the gluing of the reinforcement. As the result, the placement of the internal forces, caused by moisture changes in layers, can change and this internal force can induce the inside moment in other direction. One-sided reinforcement is more advantageous because of smaller resulting stresses in the timber layers than in the case of double-sided reinforcement. The part of the strength left in the timber layer and also in the entire hybrid composite material is greater than in the case of double-sided reinforcement.

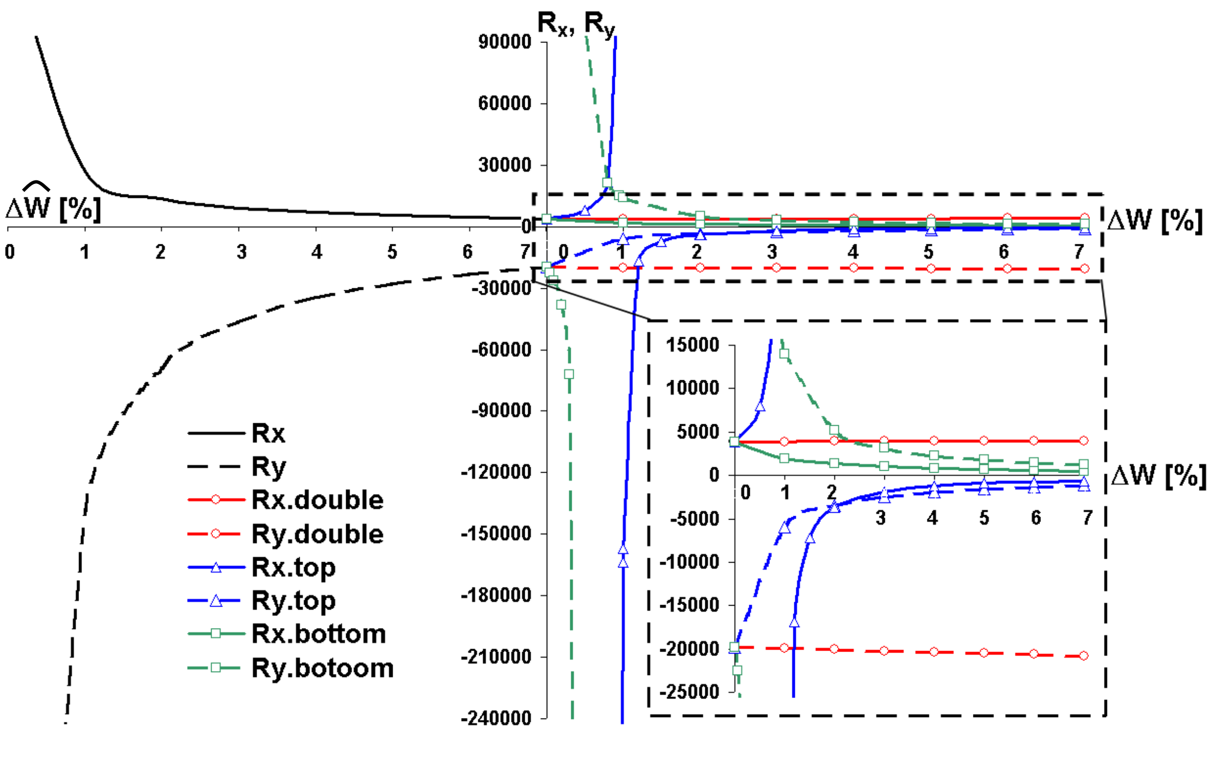

Fig.4. Change in bending radiuses in dependence of the material moisture changes for the *sheet* (on the left side of the graph) and for the *elements* (on the right side of the graph) if the thickness of the reinforcement is 3.15 mm. In the right bottom corner the enlarged part of curve is shown

Stresses are calculated by FEM and picked from the contact planes of *element* layers where the vertical axis intersects the centre of gravity. The stresses in the layers of the *sheet*, whose curvature is obtained by increasing the moisture content from 10% to 17%, are shown in the stress diagrams in Fig.5.

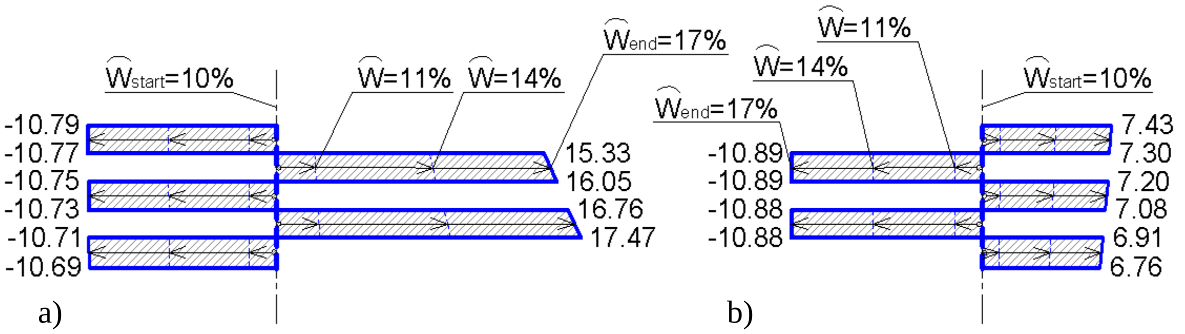

Fig.5. Stresses a) $\hat{\sigma}_x$, b) $\hat{\sigma}_y$ in the layers of the *sheet* if material moisture $\hat{W}$ changes from 10% to 17%. Patterns applied in the figure:

Line of stress diagram if moisture is 10% ($\Delta\hat{W} = 0\%$);

Line of stress diagram if moisture are 11% ($\Delta\hat{W} = 1\%$) and 14% ($\Delta\hat{W} = 4\%$);

16.76 17.47 Stress diagram with the values of the stress [MPa] if moisture is 17% ($\Delta\hat{W} = 7\%$)

Analysing the changes in stresses, for the cases of the above mentioned materials, layer thicknesses and orientations it was concluded that the highest stresses in timber layers develop when double-sided GFRP reinforcement is used (see Figs 6a and 6b), but the shape invariability is provided the best (see Figs 3b and 4). After regaining initial moisture condition, only tension stresses remain in the timber layers. Only compression stresses are present in both reinforcement layers. When strengthening the top side of the *sheet* with the GFRP reinforcement, both tension and compression stresses develop in the reinforcement (see Figs 6c and 6d). Compression stresses are larger at any moisture content. Resultant stresses in the timber layers are smaller or the same as in the case with the double-sided reinforcement. In this case, compression stresses develop in the two lower timber layers, but tension stresses – in the other layers. When strengthening the bottom side of the *sheet* with the GFRP reinforcement, both tension and compression stresses develop in the reinforcement (see Figs 6e and 6f). Compression stresses in the GFRP reinforcement are larger at any moisture content, also for this case. Resultant stresses in the timber layers are smaller or the same as in the case of the double-sided strengthening. In this case, compression stresses develop in the two topmost timber layers, but tension stresses - in the other layers.

The longitudinal deformations of the *element* are calculated in the plane which corresponds to the middle plane of the *sheet* using both FEM and developed calculation model (see Fig.7). As the developed calculation model is applicable only in the case of the uniform distribution of stresses and deformations, the edge effects were not taken into consideration during the calculation with the developed model. To compare the results, the values of longitudinal deformations calculated by FEM were derived from the zone where the distribution of stresses and deformations between adjacent finite elements are uniform, i.e. where the distance from the edge of the *sheet* is equal to the length of one finite element (2.5mm). For example, the values of the longitudinal deformations used for the calculation of the longitudinal deformation in the middle plane of the *sheet* middle layer are derived from the points 22, 23, 61, 463, 464, 502 (see Fig.2b). The difference between the longitudinal deformations calculated using the developed calculation model and FEM in all listed cases does not exceed 3.3%. Therefore, it can be declared that the developed calculation model is sufficiently accurate and does not give errors larger than 5% if the stiffness of the anticlastic surface and stress distribution between the layers of the composite material layers are not taken into account.

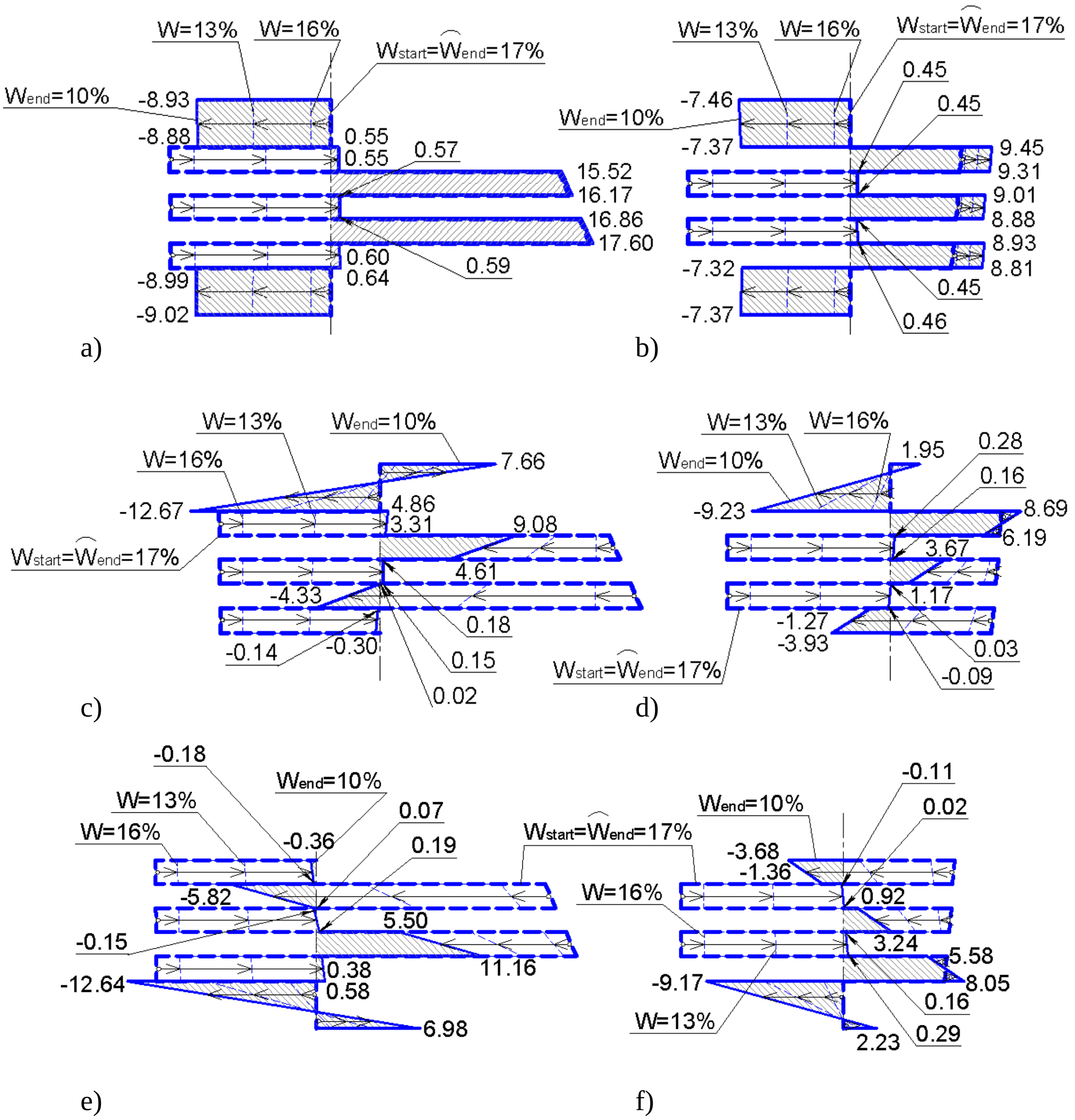

Fig.6. Stresses in the layers of the anticlastic *sheet* curved by moisture and strengthened afterwards, if timber moisture W changes from 17% to 10%. Stresses a) $\sigma_{x.double}$, b) $\sigma_{y.double}$ in the layers of the *sheet*, strengthened from both sides. Stresses c) $\sigma_{x.top}$, d) $\sigma_{y.top}$ in the layers of the *sheet*, strengthened from the top side. Stresses e) $\sigma_{x.bottom}$, f) $\sigma_{y.bottom}$ in the layers of the *sheet*, strengthened from the bottom side.

Patterns applied in the figure:

Line of stress diagram if moisture is 17% ($\Delta\widehat{W} = 7\%$ or $\Delta W = 0\%$);

Line of stress diagram if moisture are 16% ($\Delta W = 1\%$) and 13% ($\Delta W = 4\%$);

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Stress diagram with the values of the stress [MPa] if moisture is 10% ($\Delta W = 7\%$)

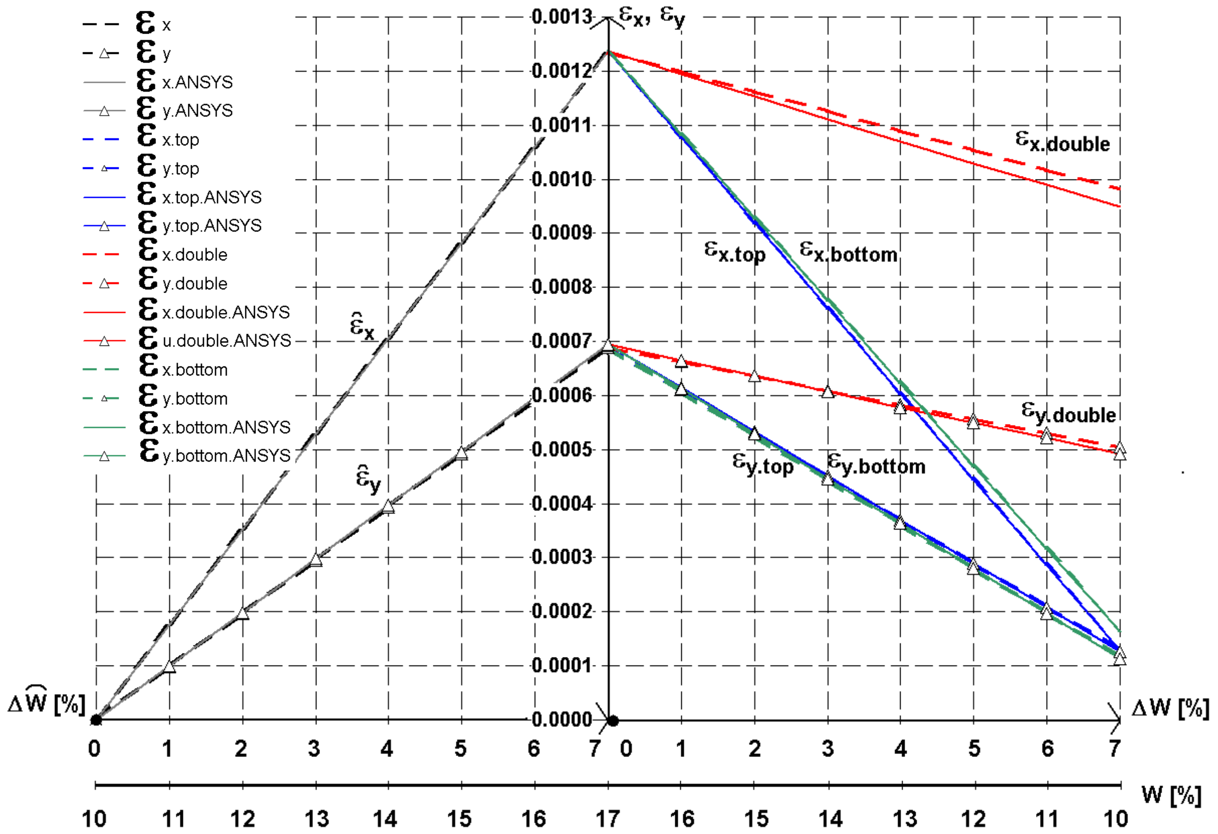

Fig.7. Longitudinal deformations calculated with FEM and the developed calculation method in the plane which coincides with the middle plane of the *sheet*.

Conclusions

Two variants for the determination of the reinforcement thickness, which provides invariability of the sheets shape, are proposed for the anticlastic composite material sheet under variable moisture conditions. Both the developed calculation model [1] and the finite element method (ANSYS v.11) can be used.

An opportunity has been demonstrated how to provide the original shape, not exceeding the difference of 5% for an anticlastic timber composite material sheet, which consists of five glued together birch-tree layers, which are oriented at right angles towards the longitudinal fibres of the adjacent layers (thickness of four top layers are 1.6mm, but of bottom layer 1.7mm) using glass fibre reinforced plastic reinforcement with thickness of 3.15mm in the case when moisture content of the layers decreases from 17% to 10%.

The comparison between the analytical results of the proposed variants has been carried out, and it has been established that the difference does not exceed 3.3% in none of the inspected three cases for all of variations – if timber composite material is reinforced on the top, bottom or both sides.

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Baikovs A., Rocēns K. Hibrīdas slāņainas kompozītmateriāla loksnes formas izmaiņu prognozēšana
Darbā pētīta izliekti-ieliektu kompozītmateriāla lokšņu sākotnējās formas saglabāšanas iespēja izmantojot stiegrota plastika pastiprinājumu. Lokšņu deformāciju modelēšanā izmantots autoru izstrādātais aprēķina modelis izliekti-ieliektu lokšņu racionāla pastiprinājuma biezuma, kas nodrošina sākotnējā loksnes liekuma rādiusa izmaiņas vēlamā intervālā mainīga mitruma apstākļos, noteikšanai [1] un galīgo elementu metode, izmantojot datorprogrammu ANSYS v.11 (turpmāk GEM).
Par formas galvenajiem raksturlielumiem ir pieņemtas loksnes liekuma rādiusu un garendeformāciju izmaiņas nepastiprinātas loksnes ģeometriskajā vidusplaknē. Ar GEM aprēķinātas spriegumu un garendeformāciju vērtības hibrīdā kompozītmateriālu elementa slāņos pie dažāda mitruma satura. Tika veikts GEM un izstrādātā aprēķina modeļa iegūto rezultātu salīdzinošs pētījums, kas parādīja, ka rezultātu atšķirība apskatītajos trīs gadījumos, ja koksnes kompozītmateriāls pastiprināts augšā, apakšā un abās pusēs, nevienam no variantiem nepārsniedz 3.3%. Parādīta iespēja, nepārsniedzot 5% atšķirību, nodrošināt sākotnējo formu izliekti - ieliektām koksnes kompozītmateriāla loksnēm mainīga mitruma apstākļos izmantojot stiegrota stikla plastika pastiprinājumu. Piedāvāts izstrādāto aprēķina modeli izmantot izliekuma prognozēšanā, ja izliekti-ieliektas formas elementu iegūšanai tiek izmantoti mitruma izmaiņu radītie pārvietojumi loksnes slāņos.
Baikovs A., Rocēns K. Prediction of the shape changes of hybrid laminated composite material sheet
The preservation of the initial shape of anticlastic composite material sheets by using reinforced plastic strengthening has been investigated in the work. For the modelling of sheet deformations the calculation model, developed by the authors, has been used for the determination of the thickness of anticlastic sheet rational strengthening, which provides changes of the original bending radius within the limits of preferable intervals under variable moisture conditions [1], as well as the finite element method, carried out by software ANSYS v.11 (henceforth FEM).
The changes of the sheet bending radii and longitudinal deformations in the geometrical middle plane of unstrengthened sheet are assumed to be the main characteristics of the shape. Stresses and longitudinal deformations have been calculated in the layers of the hybrid composite material element under variable moisture conditions using FEM. The comparative research of the results calculated with the FEM and the developed calculation model showed that the difference between the results in the inspected three cases, when the composite timber material are strengthened on the top, bottom and both sides, does not exceed 3.3 % for none of the cases. An opportunity has been demonstrated how to provide the original shape of anticlastic timber composite material sheets by using glass fibre reinforced plastic strengthening under variable moisture conditions, thus not exceeding the difference of 5%. The developed calculation model is proposed for the use in the predicting of curvature if the elements with the anticlastic shape are obtained by using the displacements of moisture changes in the layers of the sheet.

Баиковс А., Роценс К. Прогнозирование изменений формы гибридного слоистого листа из композитного материала

В работе исследована возможность использования усиления из армированного пластика для сохранения первоначальной формы у искривленного листа из композитного материала. В моделирование деформаций листов использована авторами разработанная модель определения рациональной толщины усиления, которая обеспечат изменения первоначального радиуса кривизны искривленного листа в желательном интервале [1] и метод конечных элементов, используя компьютерную программу ANSYS v.11 (далее МКЭ).

Характерными величинами приняты изменения радиуса кривизны и продольных деформаций листа в плоскости геометрической середини не-усиленного листа. Используя МКЭ вычислены напряжения и продольные деформации в слоях гибридного элемента из композитного материала для разных влажностях. Выполнены сравнительные исследования МКЭ и разработанной модели вычисления, которые показали что разница между результатами во всех трех рассмотренных случаях, если композитний материал из древесины усилен на верху, внизу и на обеих сторонах, для не-одного из вариантов не-превысила 3.3%. Показана возможность не-превышая разницу 5%, обеспечить первоначальную форму для искривленных древесных листов из композитных материалов в переменных условиях влажности, используя усиление из армированного стеклопластика. Предложено разработанную расчетную модель использовать для прогнозирования кривизны, если для получения елемента с искривленной формой используется перемещения вызванные изменениями влажности в слоях листа.