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NUMERICAL SOLUTION STRESSED DEFRESSED CONDITION OF MULTILAYER COMPOSITION BLADES IN THE FIELD OF CENTRIFUGAL FORCES

Abstract. One of the main tasks of the mechanics of composite materials (CM) is the calculation of the effective characteristics of the elasticity of CM based on information about the physicomechanical properties of their components and the laws of the distribution of components over the volume of the material. The possible scattering of the properties of a layer of multilayer CM is not taken into account when constructing models of structurally inhomogeneous media and when calculating their effective characteristics. Therefore, it is necessary to assess the influence of the properties of the layer on the effective characteristics of the material, as well as on the reliability of the structure as a whole.

The paper considers program, allowing numerically determine stress and strain state of a layered composite blade in the centrifugal force field, has been compiled using proved engineering torsion theory of the random section composite layered rod. The naturally twisted layered composite blade lies under combined action of stretching forces, bending and twisting moments or under the influence of centrifugal forces. The program has solved engineering problem on cutting of the blade to leaves (these leaves appear in a result of variable section along the blade length) in planes, parallel to the rod axis. The blade, studied in this paper, is presented by eight sections.

Keywords: blade, torsion, stretching, bend, deformation, strain, cutting.

Introduction. Rotodynamic machine blade outline in potential engines becomes more complex. There is a change from outlines, close to the rods with twist and high relative elongation, to outlines like plates with low relative elongation, high twist and flexure, in the blade structures of fans, compressors and turbines. Intermetallic compounds, metal-matrix composites and ceramic-matrix composites come into use instead of modern metal alloys. With development of analysis methods of modern jet engines, geometrical characteristics, aerodynamic and thermal loads of bladed disks and drums become more specific. This allows use numerical method to determine the blades' stress and strain state [1, 6-21].

Research. Prospective models of air screws have blades with high sweep angle, twisted by the span and bended towards the axis of rotation. These blades should function in rather complicated and heavy aeromechanic conditions.

Similar designs are known for a long time, however, up till now there were no methods for their calculation and materials for their manufacture. Currently, the emergence of high-performance computers and complicated engineering software, as well as the availability of modern composite materials allow carry out more thorough and detailed analysis of the prospective turboprop engine blades. Therefore, using materials, received in [1], the analysis computer program, allowing numerically determine stress and strain state of the blades from the composite material, has been compiled.

The program is designed for investigation of the stress and strain state of naturally twisted layered rod structures, which lie under combined action of stretching forces, bending and twisting moments or under the influence of centrifugal forces. Each layer of the rod section under the investigation consists of orthotropic material with 9 independent elastic constants. At that, purposeful general property regulation of the specific material can be carried out by choice of both fiber pattern in a separate layer and layer arrangement with known properties in section. This is achieved by alteration of angles φ_i between the material elastic symmetry principal directions in the layer and axes, where the body's stress and strain state is investigated. At that, amount of independent elastic constants (elastic modulus, shearing modulus, Poisson's constants, etc.) of the layer material in the general case will be equal to 13 [1].

The relevant rod structure cross section is arbitrary. The input program parameters are coordinates of the line, limiting separate arbitrary plane section, usually set in the working drawings of projects. This line is divided into two parts (further conditionally called "back" and "backet"), to which two outer lines are adjacent in the layer section. Coordinates of the layers' superficies are specified. Proceeding from these data, with the help of special procedure, the arbitrary configuration section is divided into separate layers by defined thickness t_c of the monolayer [3]. At that, numbers of each layer origin and end are formed. Such designs are carried out for a series of following one after another rod sections (figure 1). As dimensions of the section may vary along the rod length, then number of the layers in each section can be different. This predetermines the emergence of short layers inside the section. Taken from different sections, the coordinates of origin and end of one layer determine the leaf length in the current rod section.

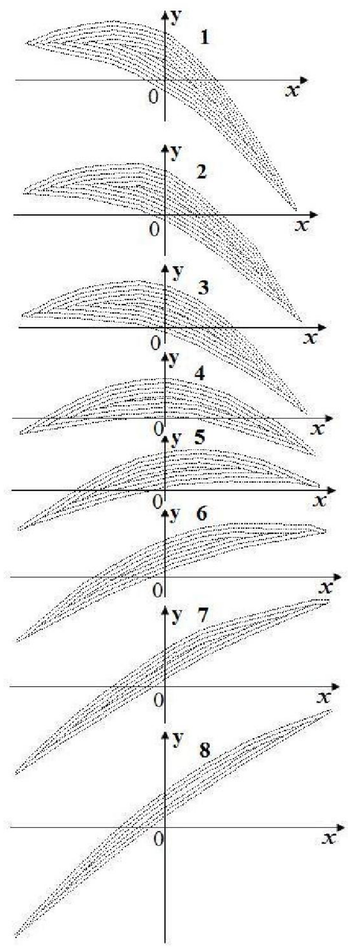

Figure 1 –
The compressor blade cross section set layers; numbers of the blade sections correspond to the sections, distant from its root section

Therefore, the program has solved the engineering problem of "cutting" of each rod layer on the leaves in planes, parallel to the rod axis.

Basic relations of the developed engineering theory on layered rods [1-6] are used to investigate the layered rod stress and strain state. Based on this theory, stretching strain ε, curvature changes χ_1, χ_2 and unwinding τ, as well as strains $\sigma_{11}^{i}, \sigma_{22}^{i}, \sigma_{33}^{i}, \sigma_{23}^{i}, \sigma_{13}^{i}, \sigma_{12}^{i}$ in separate points of the layer i are calculated for each section.

The input program parameters are stretching force P, bending M_1, M_2 and twisting M_t moments, as well as 13 elastic constants of each layer [1] for the current layer. The layers' set points coordinates and numbers are also input parameters for the current section.

To investigate the rod stress and strain state in the centrifugal force field, stretching force, applied in the current section, is calculated by formula:

$$P_r = P = \omega^2 \int_r^R \Big(\int_{F(r_1)} \rho dF \Big) r_1 dr_1 , \qquad (1)$$

where $F(r_1)$ – cross sectional area; r, R – distance from the rotational axis to the gravitational center of the current r and peripheral R section respectively (figure 2); $\omega=\pi\cdot N/30$ – angular velocity (rad.turns/sec.), where N – rotational velocity (turns/min); r_1 – integration variable; ρ - the section layer material density.

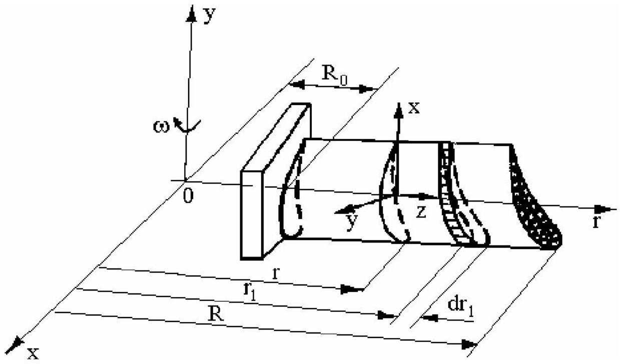

Figure 2 – The distance from the rotation axis to the center of gravity of the current r and peripheral R section

Thus, the force P in the current section r is equal by the centrifugal inertial force value, to the developed layered rod part, concluded between the considered section r and peripheral section R [22].

Data about geometrical characteristics of all sections are necessary to calculate the centrifugal effort by formula (1) and the current section gravity center coordinates. To this end, with the help of special procedure, 15 geometrical characteristics and set densities of all sections are calculated at first [22].

The centrifugal effort for the current section r by the approximate value for (1) is calculated by formula:

$$P_r = \omega^2 \sum_{i=1}^{R} \int_{r_i}^{r_{i+1}} F \rho r_1 dr , \qquad (2)$$

where the current section area and density are measured linearly towards the previous section. i.e.

$$F = F_i + (r_1 - r_i)(F_{i+1} - F_i)/(r_{i+1} - r_i),$$
$$\rho = \rho_i + (r_1 - r_i)(\rho_{i+1} - \rho_i)/(r_{i+1} - r_i). \qquad (3)$$

Further, the layered rod stress and strain state is studied for the current section. The stretching strain ε, curvature changes χ_1, χ_2 and unwinding τ are determined, physical and geometrical characteristics of the layer and the whole section are calculated.

The program for described lower calculations is currently used to analyze the blade stress and strain state at the preliminary design stage.

1. The studied blade description. The considered blade model is a reduced version of the full scale compressor blade. This blade has been designed and manufactured with a view to follow the real blade structural and aerodynamic equivalency. The blade, studied in the paper, is presented by eight sections (figure 1). Figure 3 presents changes in the area (curve 2 on figure 3), in the highest thickness (curve 1 on figure 3), in the chord в (curve 3 on figure 3) of the blade and relation $c_{max}/в$ depending on r/R_0. The root

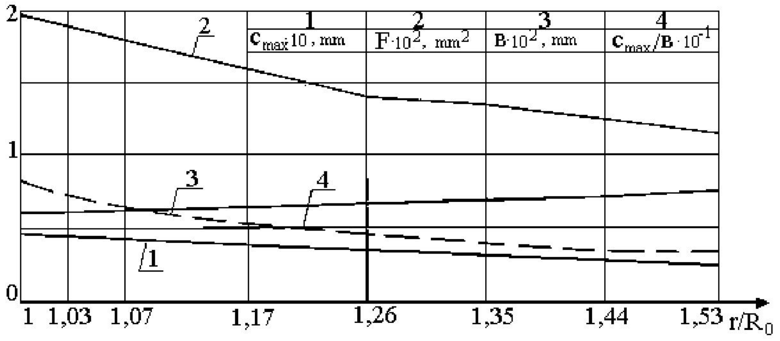

Figure 3 – Change of c_{max}, area F, chord в and c_{max}/в by the compressor blade length

blade section consists of 12 layers of uniform thickness t_c=0,4 mm, however, the peripheral section consists of 6 layers. The reference swirl angle per one unit of the blade length τ_0 – is equal to 0.006 rad./mm.

2. Calculation variants. As an example, the blade from the composite material in the centrifugal force field has been calculated by the described program. At that, investigation for three different combinations of the elastic constants in the package of the composite blade layers has been carried out.

The blade consisting of boron aluminum (BAL) layers interstratified from the side of back and backet has been considered.

3. Calculation result analysis. The stretching force P in the blade rotation has been calculated by formula (1) for each its section r/R_0. Averaged values of the tension stresses σ_{cp} in the conditional untwisted blade achieve the highest value in the third section. This is related to the fact that the force P in the third section differs from the force in the root section on 17%, while their areas differ on 45%.

W, U, V displacement pattern isograms by the blade length for the back and backet (figure 4) have been drawn by the calculation results. As is clear from the Figure, normal displacements W on the peripheral section have maximal values (MX point). W displacements rise on 4-5 times on the entry edge of the back from the root section to the third section. They rise on 10 times on the feathered entry edges. W normal displacement and U, V displacement patterns on the back are more proportional in comparison with the blade backet. On the backet, concentration of the high displacements W is already observed in the fourth blade section. Therefore, to increase the blade strength, it is necessary to change the layers from the backet side by materials more rigid in the stretching.

Figure 5 gives deformation of the blade U_x, V_y, W_z towards the axis 0x, 0y, 0z. The highest changes occur in the second blade section. The compressing deformation value towards the axis 0x on the trailing edge on 3-4 times higher than on the entry blade edge. As a consequence, local strength loss may occur in the tailing feathered layers' edge. Therefore, these layers should be changed by materials with higher compression-resisting properties. The highest blade deformation changes towards the axis 0y occur on the third blade section. The stretching strain value towards the axis 0y in the trailing edge is 2 times higher than in the entry edge of the second blade section and by its value is 3 times higher than the compressing deformation towards the axis 0x. Consequently, to avoid the strength loss from the compressing and stretching strains in the tailing feathered layers' edge, these layers should be changed by materials with higher tensile and compression-resisting properties.

Figure 6 gives distribution of stresses σ_{xx}, σ_{yy}, σ_{zz} on the back and backet by the blade length. The highest normal stress is distributed on the root blade section (MX point), as the root blade section is rigidly fixed. If not to consider it, then the maximum stress is achieved on the third blade section and concentration of the normal stresses on the backet is higher on 1.5-2 times in comparison with the normal stresses on the back. Concentration of the normal stresses on the third section is lower on 4-5 times in comparison with its values on the root section. The compression stresses, conditioned by bending, twisting and stretching interconnectivity, occur on the peripheral back sections. The average stresses in comparison with the stresses σ_{xx}, σ_{yy}, σ_{zz} on 1.5-2 times higher and it is impossible to determine the compression stresses' fields by them (figure 7). Therefore, to determine the blade stress and strain state it is necessary to calculate all components of the stresses σ_{xx}, σ_{yy}, σ_{zz}.

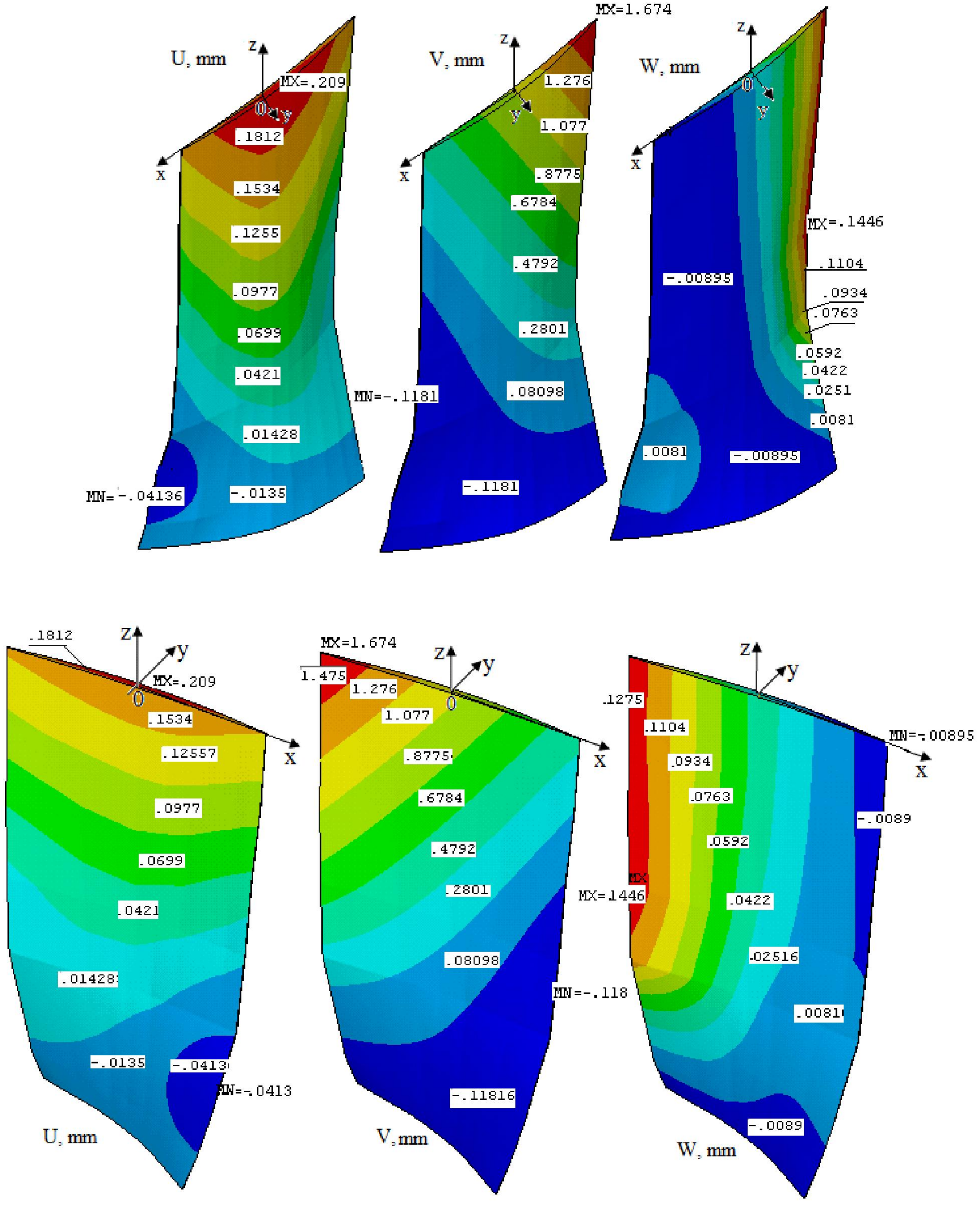

Figure 4 – U, V, W displacement patterns on the back and backet by the boron aluminum blade length

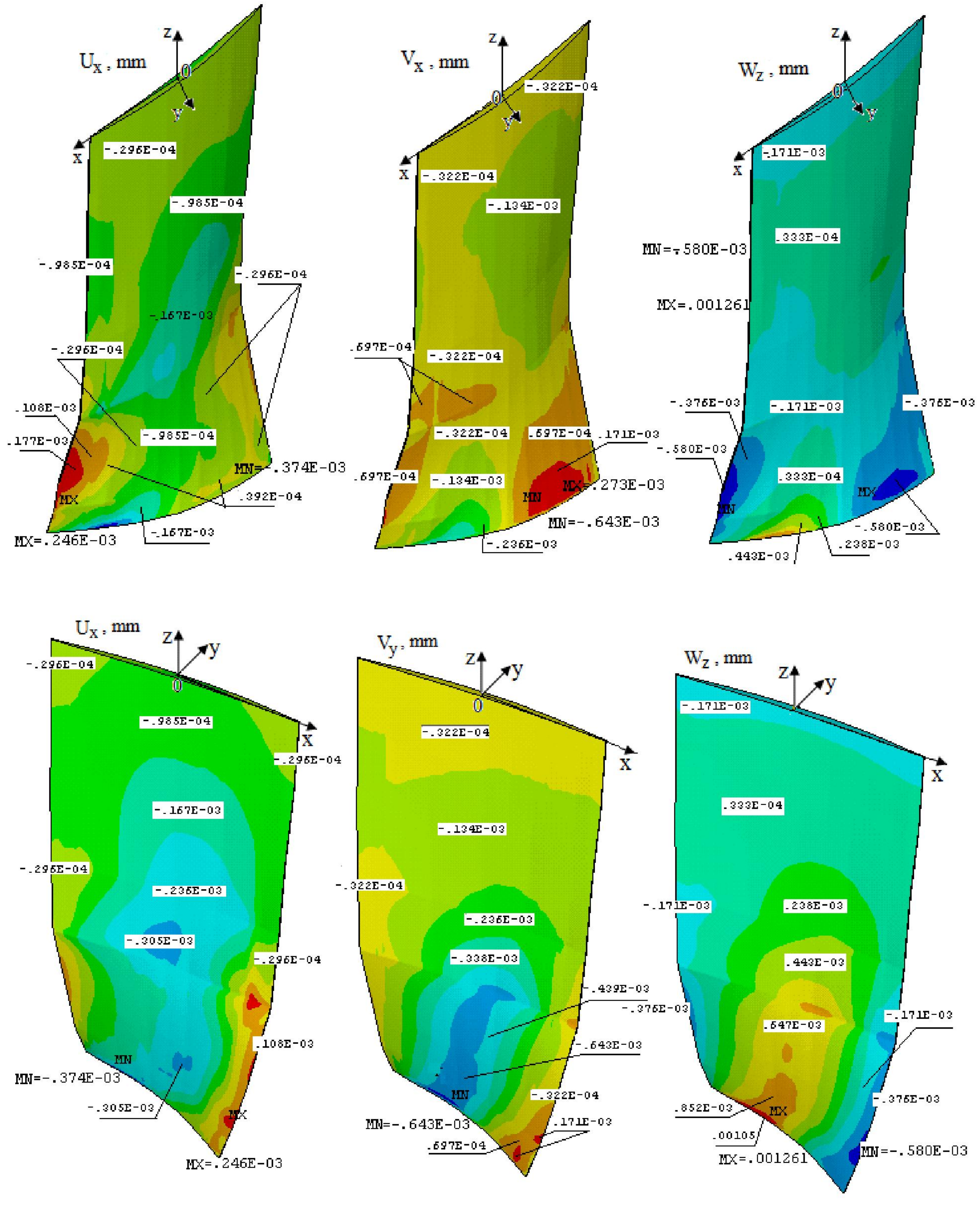

Figure 5 – U_x, V_y, W_z displacement patterns on the back and backet by the boron aluminum blade length

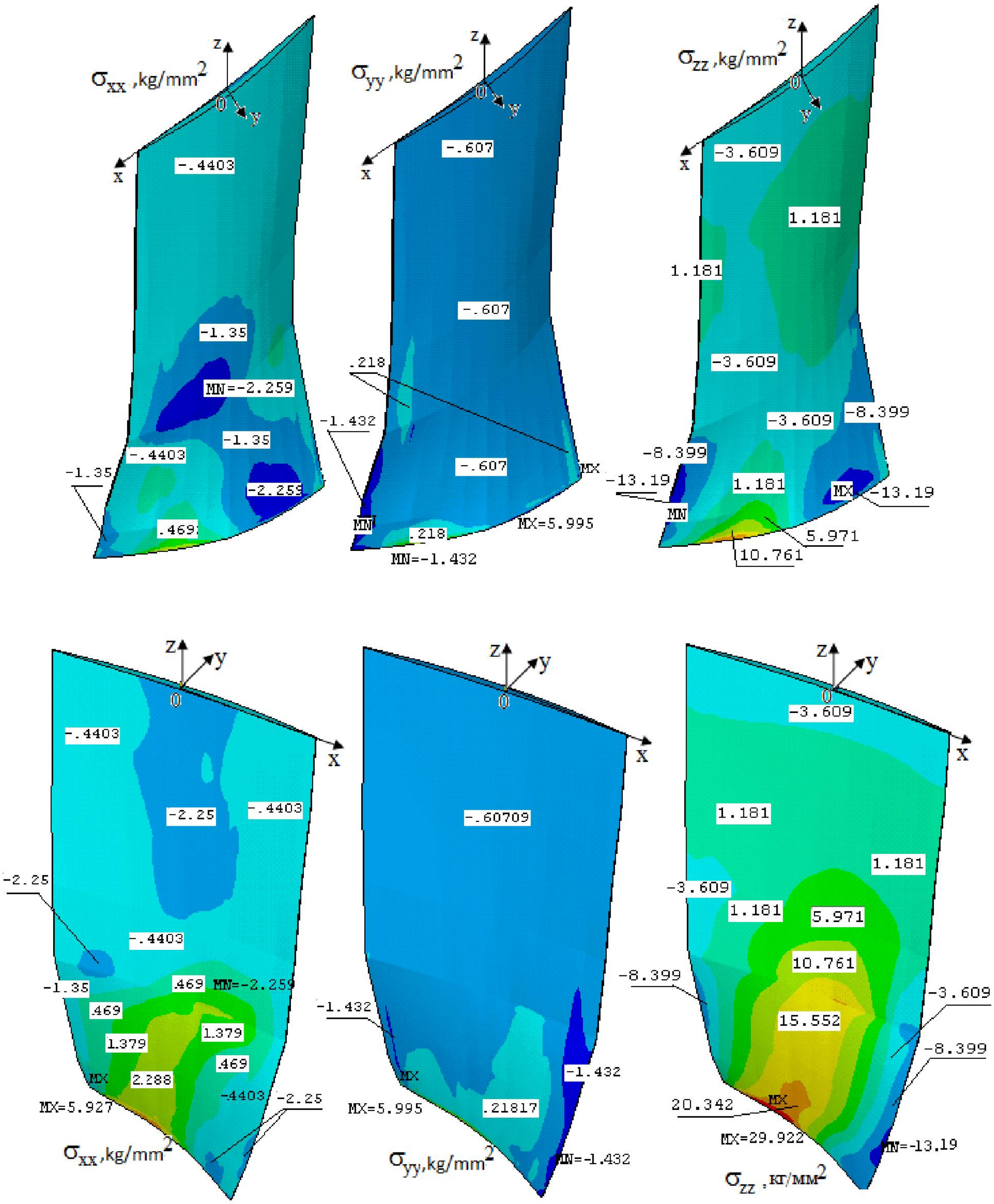

Figure 6 – Distribution of the stresses σ_{xx}, σ_{yy}, σ_{zz} on the back and backet by the boron aluminum blade length

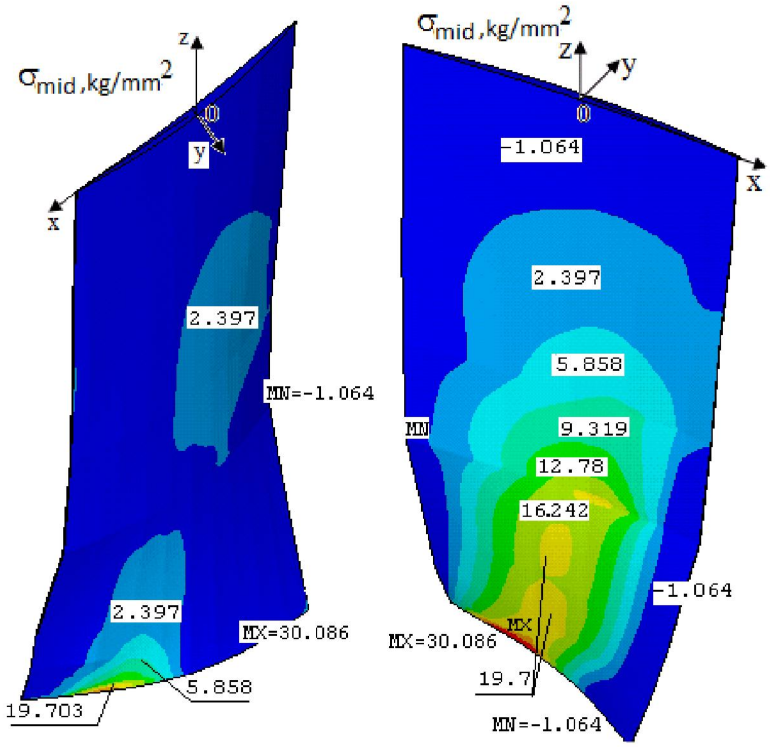

Figure 7 – Distribution of the averaged stress σ_{avg} on the back and backet by the boron aluminum blade length

Figure 8 gives distribution of tangential stresses σ_{xz}, σ_{yz}, σ_{xy} on the back and backet by the blade length. The highest tangential stress is distributed on the third blade section. The local highest tensile tangential stress σ_{xz} is achieved on the third section near the entry back edge, and the compression one – on the tailing backet edge and its value (MN point) is higher on 2 times in comparison with values of σ_{xz} near the entry back edge (MX point). As is known, in the feathered layers such concentration of the tangential stresses may result in the blade's local strength loss. As a consequence, the emergence of the above values of the tangential stresses in the blades may be inadmissible. It has been deduced from the experiments that the strength margin by the tangential stresses between the layers currently should not be less than 3 [3]. The tangential stress σ_{yz} by the value is 2 times lower than the tangential stress σ_{xz} and is distributed respectively on the thick back and backet layers. Therefore, in comparison with the tangential stress σ_{xz}, its influence on the general blade strength is insignificant. The highest value of the tangential stress σ_{xy} is achieved in the third section (MX point) (figure 8). In comparison with the values of the tangential stresses σ_{yz}, σ_{xz} the tangential stress σ_{xy} is insignificant. Therefore, it may not be considered in the calculations.

Figure 9 gives the displacement pattern isograms on the fourth blade section. As is seen from the Figure, displacement area on the backet is higher by its value on 25% from displacement on the back. The highest displacements occur in the middle of the blade back section. The highest displacement U occurs in the back layers neighboring to the gravitational center. V, W displacements occur on the tailing blade edge (MX point). Consequently, it is necessary to select materials of the layers neighboring to the gravitational center and tailing section edges with the tensile properties.

Figure 10 gives distribution isograms of the stresses σ_{xx}, σ_{yy}, σ_{zz} on the fourth blade section. As is seen from the figure, displacement area of the normal stress σ_{zz} on the backet is higher by its value on 20 times from the normal stress σ_{zz} on the back. The highest normal stresses occur in the middle of the blade backet section. The highest normal stress σ_{zz} occurs in the points neighboring to the backet layers' gravitational center and comparable to the values of the average stress (figure 12). Consequently, it is necessary to select materials of the layers neighboring to the gravitational section center with the tensile properties.

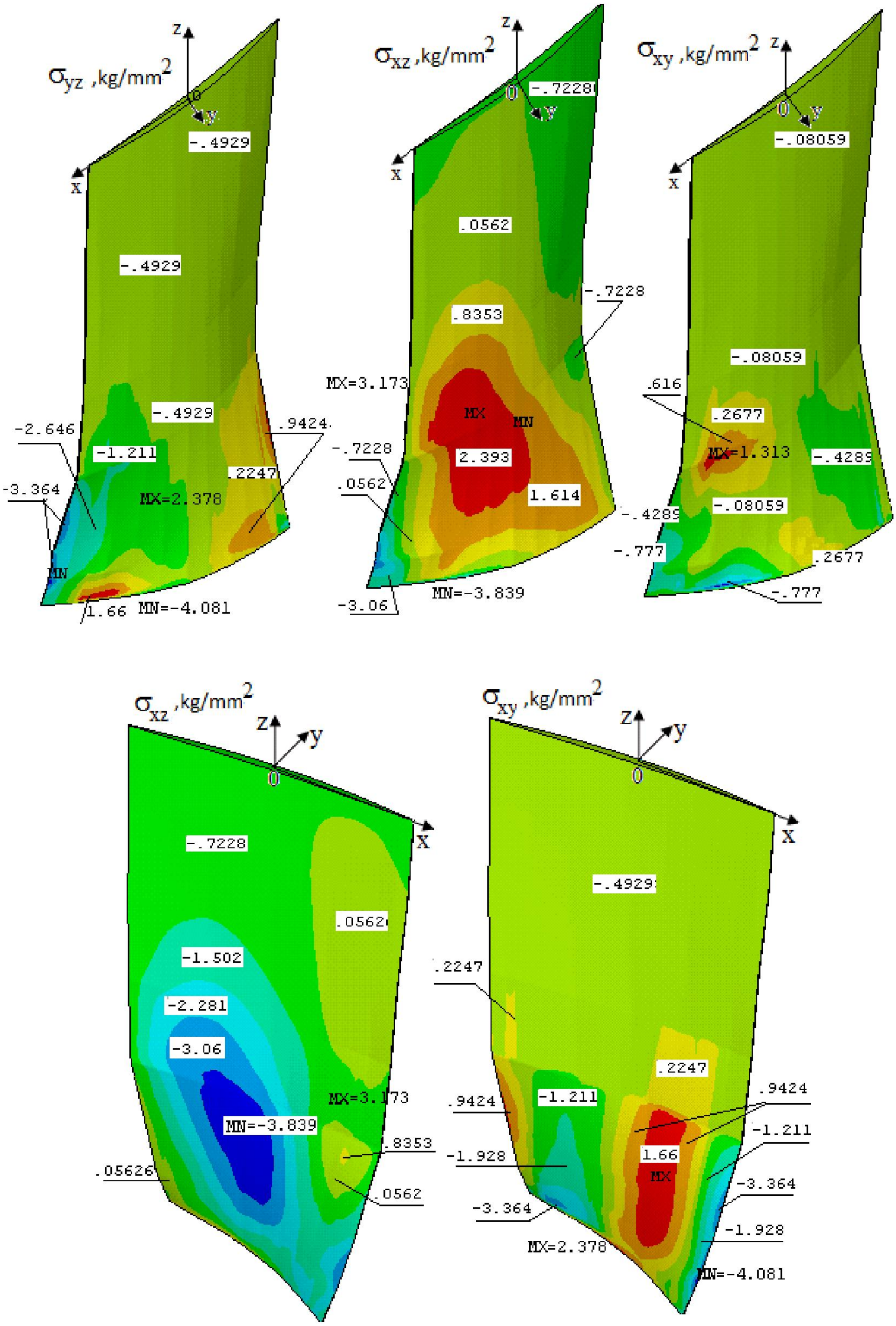

Figure 8 – Distribution of the tangential stresses σ_{xz}, σ_{yz}, σ_{xy} on the back and backet by the boron aluminum blade length

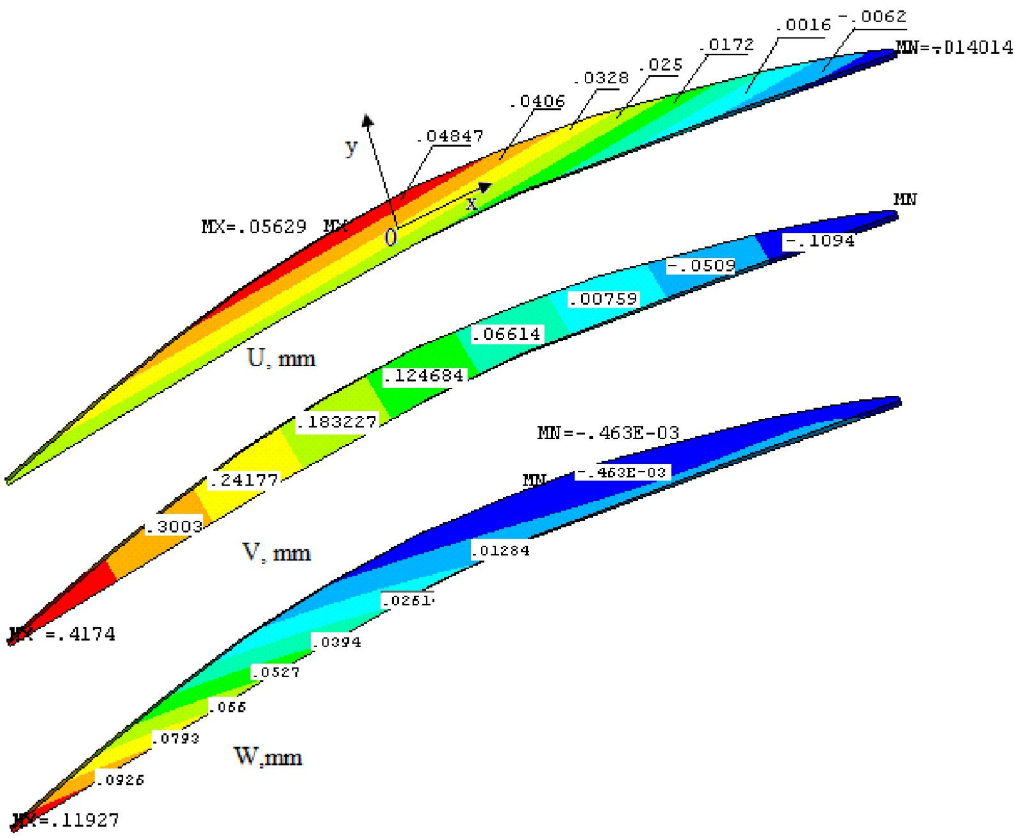

Figure 9 – U, V, W displacement patterns on the fourth boron aluminum blade section

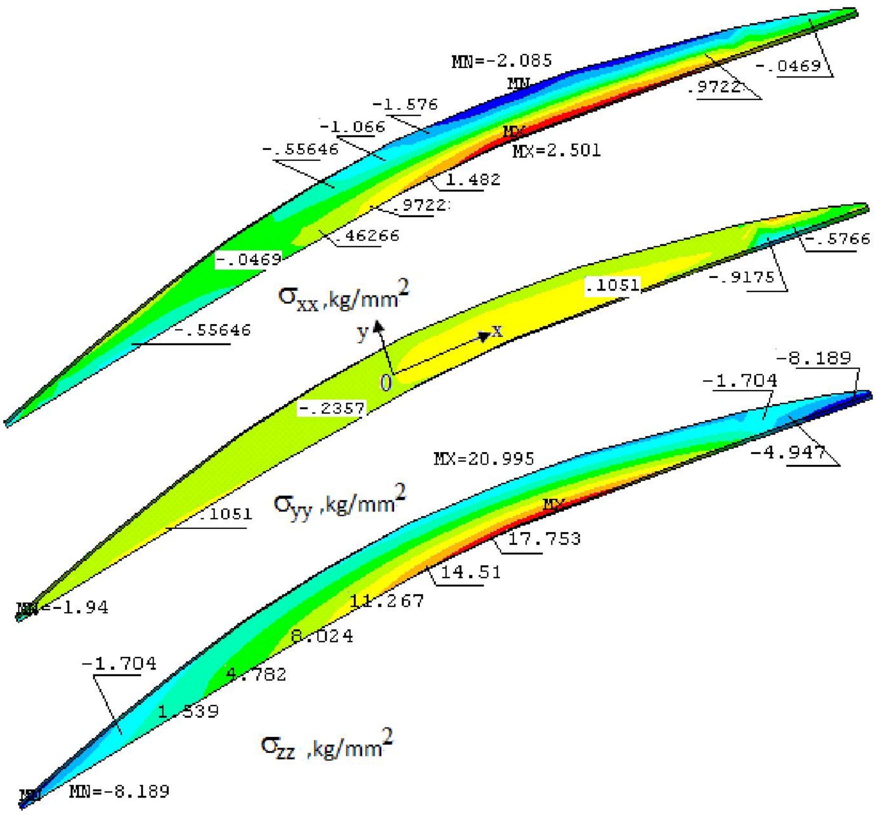

Figure 10 – Distributions of the stresses σ_{xx}, σ_{yy}, σ_{zz} on the fourth boron aluminum blade section

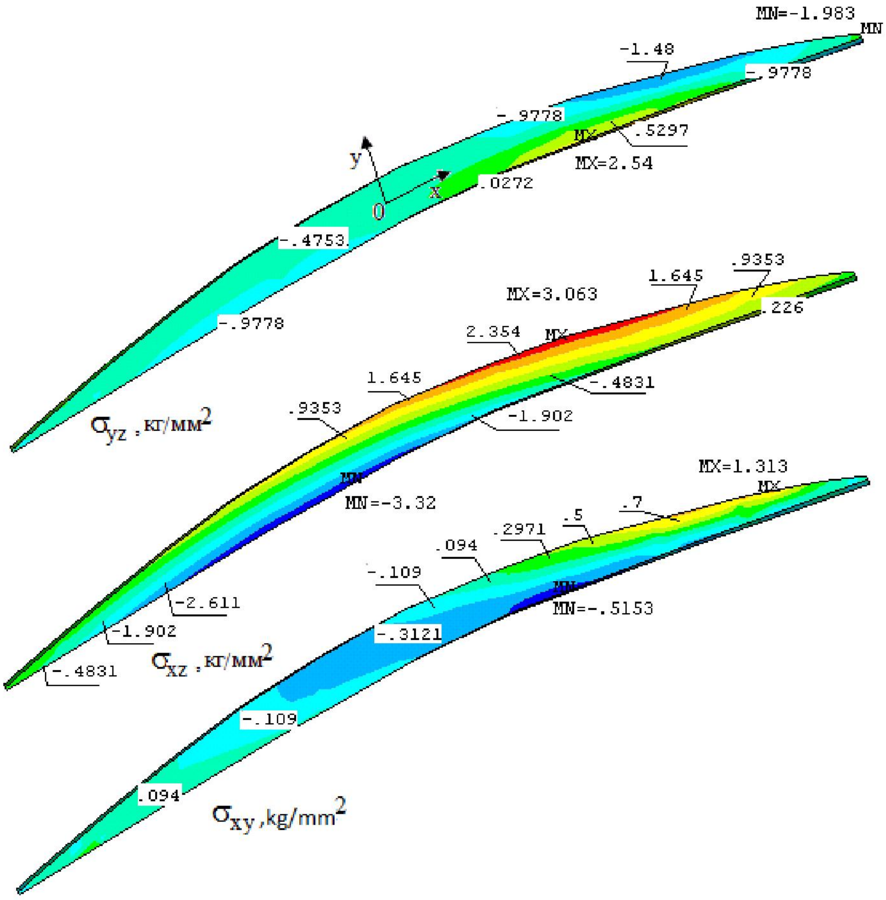

Figure 11 – Distributions of the stresses σ_{yx}, σ_{xz}, σ_{xy} on the fourth boron aluminum blade section

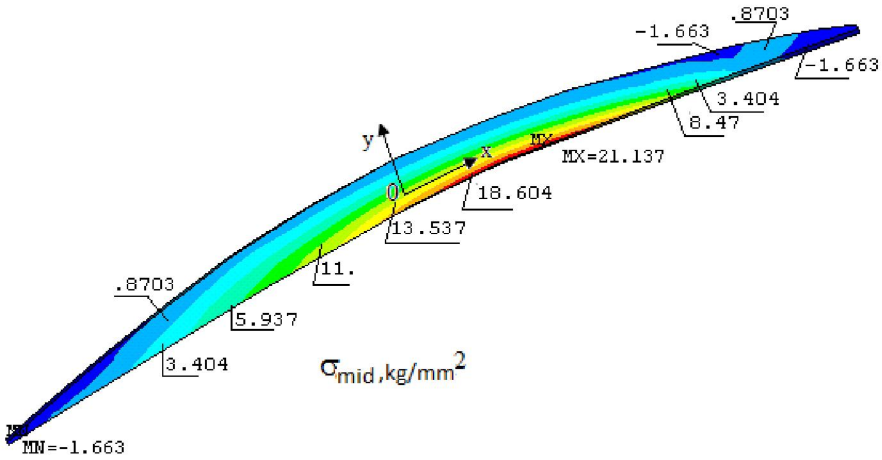

Figure 12 – Distributions of the stress σ_{avg} on the fourth boron aluminum blade section

In the same manner, distributions of the tangential stress σ_{xy} (figure 11) on the fourth blade section show that the tangential stress σ_{xy} concentration area is lower by its value on 200%-300% from the normal stress σ_{zz}. The highest tangential stress $\boldsymbol{\sigma_{xy}}$ occur in the backet layers neighboring to the gravitational center. In the feathered layers (4th section) of the entry and tailing blade edge, the compression tangential stresses are equally distributed. Values of the tangential stress σ_{xy} in the concentration areas are comparable with values of the stresses σ_{yz}, σ_{xz}. Therefore, materials in the layers, neighboring to the gravitational center should have higher tensile and compression-resisting properties.

The tangential stress σ_{yz} distribution isograms on the fourth blade section show that the tangential stress σ_{yz} distribution area is lower by its value on 15-20 times from the normal stress σ_{zz}. The highest tensile tangential stress σ_{yz} is distributed in the layers of the entry blade edge and is insignificant by its value.

The tangential stress σ_{xz} distribution isograms on the fourth blade section show that the tangential stress σ_{xz} distribution area is lower by its value on 5-7 times from the normal stress σ_{zz}. The highest tensile tangential stress σ_{xz} is distributed in the layers in the middle back part, and the compression tangential stress – on the backet. In the feathered layers (4th section) of the tailing blade edge, the compression tangential stresses are equally distributed and insignificant by their value. The highest tangential stress σ_{xz} by its value is higher on 4-6 times in comparison with values of the tangential stress σ_{yz} and from value of the normal stress is lower on 5-7 times. Therefore, it is necessary to consider influence of the tangential stress σ_{xz} for the layered thin rods.

Conclusions. Thus, the studied examples show that selecting material for the separate layers or reinforcing in them, it is possible over a wide range regulate the level of stress and deformation in the same physical rotor cycles. There is no such wide regulation opportunity for the isotropic material blades.

Thus, in the given geometrical blade form, selected from aerodynamic considerations, by two-way reinforcement of its layers, the level of stress σ_{zz} may be reduced, at the same time avoiding high compression stresses on the profile edges and achieving their more uniform distribution (σ_{zz}) by the section.

The carried out calculations of the blades of specific types showed that the peripheral blade section unwinding angle may be reduced both by increasing the torsional stiffness by the layers' two-way reinforcement and using the stiff material layers in the package of materials. When increasing the layers' rigidity curve ratio level (the layers' curve ratio (elastic modulus, shearing modulus, etc.), difference of the normal stresses in the cross section and value of the tangential stresses between the layers increase. The high tangential stresses between the layers occur due to the different rigidity of the contacting layers. Continuous transition of the material properties from layer to layer is required.

The multilayer composite materials' operation analysis in conditions close to the working conditions of the blades allowed determine a series of the stress distribution features in reinforced materials. It is found that increase in the normal stresses on 2-4 times in comparison with their average values occurs when stretching the blades from the composite materials in the centrifugal force field in external layers.

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КӨПҚАБАТТЫ КОМПОЗИТТІК ҚАЛАҚШАЛАРДЫҢ ОРТАЛЫҚ ТЕБУ КҮШТЕРДІҢ ӘСЕРІНЕН КЕРНЕУ ДЕФОРМАЦИЯЛАНҒАН КҮЙІН САНДЫҚ АНЫҚТАУ

Аннотация. Композиттік материалдардың (КМ) механикасының негізгі мәселелерінің бірі, оның құрамдас бөліктерінің физика-механикалық қасиеттеріне және олардың материал көлеміндегі таралу заңдылығына сүйене отырып КМ тиімді серпімділік сипаттамаларын есептеу. Көп қабатты КМ қабатының қасиеттерінің ықтимал шашырауы құрылымдық біркелкі емес орталар үлгілерін құру кезінде және олардың тиімді сипаттамаларын есептеу кезінде ескерілмейді. Сондықтан қабат қасиеттерінің материалдың тиімді сипаттамаларына, сондай-ақ тұтастай құрылымның сенімділігіне әсерін бағалау қажет.

Жұмыста, кез келген қимадағы композиттік қабатталған дене бұралуының техникалық теориясын пайдалана отырып, орталықтан тепкіш күштердің әсеріндегі қабатты композиттік қалақшаның кернеу деформацияланған күйін сандық анықтауға мүмкіндік беретін бағдарлама құрастырылды.

Табиғи бұралған көпқабатты композитті қалақша созылғыш күштердің, иілу және бұралудың біріктірілген әрекеті сәттерінде немесе орталықтан тебу күштердің әсерінде қарастырылады. Бағдарламада, қалақша осіне параллель орналасқан жазықтықта, қалақшаны қабаттардың жапырақшаларына пішудің технологиялық мәселесі шешілді (бұл қалақшаның ұзындығы бойымен әртүрлі қималары болғандықтан

қалақшаның ұзындығы бойынша жапырақтары пайда болады). Бұл жұмыста зерттелген қалақша сегіз қимадан тұрады.

Түйін сөздер: қалақша, бұру, созу, майыстыру, деформация, кернеу, бороалюминий, қима.

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ЧИСЛЕННОЕ РЕШЕНИЕ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ МНОГОСЛОЙНЫХ КОМПОЗИЦИОННЫХ ЛОПАТОК В ПОЛЕ ЦЕНТРОБЕЖНЫХ СИЛ

Аннотация. Одной из основных задач механики композиционных материалов (КМ) является вычисление эффективных характеристик упругости КМ на основе информации о физико-механических свойствах их компонент и законах распределения компонент по объему материала. Возможное рассеяние свойств слоя многослойного КМ не учитывается при построении моделей структурно-неоднородных сред и при вычислении их эффективных характеристик. Поэтому необходима оценка влияния свойств слоя на эффективные характеристики материала, а также на надежность конструкции в целом.

В работе, используя полученную техническую теорию кручения композиционного слоистого стержня произвольного сечения, составлена программа, позволяющая численно определить напряжено-деформированное состояние (НДС) слоистой композиционной лопатки, находящейся в поле центробежных сил. Естественно-закрученная слоистая композиционная лопатка находится под объединенным действием растягивающих сил, изгибающих и скручивающих моментов или под влиянием центробежных сил. В программе решена технологическая проблема раскроя лопатки на лепестки (эти лепестки по длине лопатки появляются в результате переменного сечения по длине лопатки) в плоскостях, параллельных оси стержня. Лопатка, исследованная в данной работе, представлена восемью сечениями.

Ключевые слова: лопасть, кручение, растяжение, изгиб, деформация, напряжение, бороалюминий, сечение.

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