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COMPUTER-AIDED DESIGN OF SPAR FOR ROTOR BLADE OF WIND-POWER PLANT

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Abstract— *The problem of size and the area of the upper and lower belts of specified spar of wind-power plant determination is considered. The optimization of the spar by weigh is realized.*

Index terms—Computer-aided design; wind power plant; rotor blade; weigh optimization.

I. STATEMENT OF THE PROBLEM AND THE BASIC DATA

The spar is the main load-bearing element of many engineering structures, located along the length of the structure. The main power factor perceived by spar is bending moment. In addition to this, spars are involved in the perception of the shearing force. Structurally the spar can be made monolithic or composite. Composite spar has upper and lower zones and the wall. In case of the box section it has two walls. Belts are connected to the wall by riveting, bolting, electric spot welding or gluing. Belts work on tension-compression of the bending moment. They make up most of the cross-sectional area of the spar.

Formulation of the problem:

1. Determine the size and the area of the upper and lower belts of specified spar.
2. Determine the wall thickness and spar counters step.
3. Calculate riveted joint fastening the upper and lower belts of the spar to its wall.
4. Calculate the junction zone of the spar.

The main inputs:

Number of spars, the distance from the end of the blade to the first spar $\overline{X}_1$ (% of the blade chord), the distance between the spars $\overline{X}_{12}$ (% of the chord), profile of the blade, the distance between the calculated cross sections of the blade [2]. Pressures in the design section of the blade and the material of construction (Figs 1, 2).

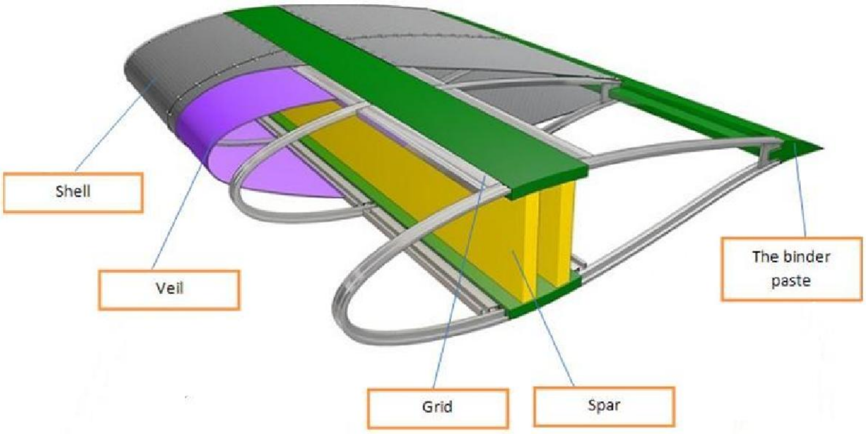

Fig. 1 Structure of the blade

II. CALCULATION OF SPAR TWO-PIECE BLADE SPAR

A Features of the calculation of one-piece blade

Significant part of the one-piece blade bending moment is perceived by powerful upper and lower blade panels [1].

Let h be the part of bending moment which is perceived by two spars blade. Then

$$h = \frac{M^{i}_{bend.b}}{M^{i}_{bend}},$$

where $M^{i}_{bend.b}$ is the bending moment in the ith blade section, perceived only by spars; M^{i}_{bend} is the total bending moment in the ith section of the blade.

Let us assume that:

– blade section is schematized as a rectangular with working height H = 0.95 of average overall caisson height;

– warping oppression of the root portion of the blade does not affect the elements of settlement sections;

– M^{i}_{bend} is only perceived by blade panels (upper and lower) and spars' belts, and Q (lateral or shear force) – only by spars' webs.

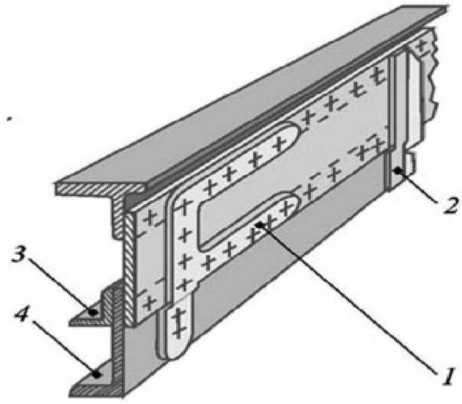

Fig. 2. Structure of the spar: *1* is the pad; *2* is the front; *3* is the additional spar belt; 4 is the lower spar belt

B Design and calculation of the blade spar

To determine the linear dimensions of the cross sections of the blade let us define the reduction factor depending on the size of the known data: half blade length (l / 2), the distance from the rotor axis to the first section (k_1e), the distance between the cross sections (e).

$$a_1 = \frac{1}{2} - ek_1 \sin\sigma;$$

$$a_2 = \frac{1}{2} - ek_{1-e} \sin\sigma,$$

then on the basis of triangles similarity we have

$$\frac{a_1}{a_2} = \frac{\frac{1}{2} - ek_1 \sin\sigma}{\frac{1}{2} - ek_{1-e} \sin\sigma}.$$

Let us denote ratio $\frac{a_1}{a_2}$ by $k_{0\,ef}$

$$k_{0\,ef} = \frac{\frac{1}{2} - ek_1}{\frac{1}{2} - ek_{1-e}},$$

where e is the distance between the sections; k_1 is the given section; k_{1-e} is the previous section.

Then, taking into account the coefficient of similarity we obtain the following cross-sectional dimensions of the spar 1-1 by the formula:

$$a_i = \frac{a_{i-1}}{k_{0\,ef}}.$$

Linear dimensions of the blade cross section are shown in Fig. 3.

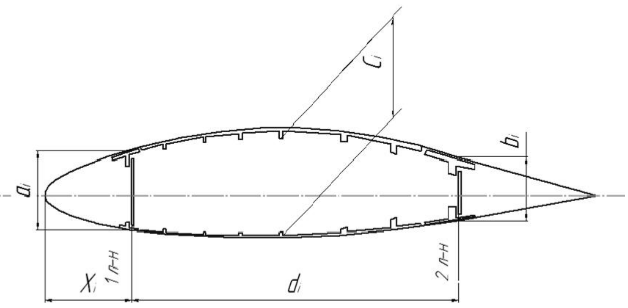

Fig. 3. Linear dimensions of the cross section

The reduced area of the top panel with the upper belts of two spars at the i th section:

$$F^{i}_{red.up} = \frac{M^{i}_{bend}}{H^{i} y_{crit\,zone}},$$

where $y_{crit\,zone}$ is the critical belt stress, which is considered to be equal to critical local buckling stress; H^{i} is the working height blade in the i th section.

For double-spar blade

$$H^{i} = 0.95\frac{a_i + b_i + c_i}{3}.$$

At $T = \frac{b}{d} < 9$ total profile buckling is difficult, in this case, we can accept

$$y_{crit\,zone} = y_{crit},$$

where y_{crit} is the critical local buckling stress.

In order to find critical stress we will ask value of T for the D16T material and take $T = 6{,}5$; by graph of $y_{crit} = f(T)$, we find $y_{crit} = 33{,}50$ kg/mm^2. Let us calculate H^{i} and $F^{1}_{red.up}$ for the first section:

$$H^{1} = 0.95\frac{a_1 + b_1 + c_1}{3},$$

$$F^{1}_{red.up} = \frac{M^{1}_{bend}}{H^{1} y_{crit\,zone}}.$$

Calculation of the total area of the upper zone of the two spars at the i th section:

$$F^{1}_{top} = h\,F^{1}_{red.up},$$

for double-spar blades:

$$F^{i}_{top} = F^{i}_{top1} F^{i}_{top2},$$

where F^{i}_{top1} is the area of the upper zone of the spar 1 in the i th section; F^{i}_{top2} is the area of the upper zone of the spar 2 in i th section.

Areas of the upper belts of the spar are approximately distributed in proportion to the height of these spars:

$$\frac{F^i_{top}}{a_i+b_i}=\frac{F^i_{top1}}{a_i};\quad F^i_{top1}=F^i_{top}\frac{a_i}{a_i+b_i};\quad \frac{F^i_{top}}{a_i+b_i}=\frac{F^i_{top1}}{b_i};$$

$$F^i_{top2}=F^i_{top}\frac{b_i}{a_i+b_i};\qquad F^i_{top1}=F^i_{top}\frac{a_i}{a_i+b_i}.$$

There are similar calculations for the remaining sections.

According to the selected values of T and F^i_{top1} we determine the size of spar belts. Wherein

$$d^i=k\sqrt{F^i_{top1}},$$

where $k=0{,}2–0{,}25$, let us select $k=0{,}23$.

$$b^i_n=Td^i,$$

$$B^i=\frac{F^i_{top1}-b^i_n d^i}{d^i_1},\qquad H^i_n=b^i_n-d^i_1,$$

where $d^i_1=(1{,}3...1{,}5)\ d^i$, $d^i_1=1{,}5\ d^i$.

Calculations for the remaining sections are performed similarly (Fig. 4).

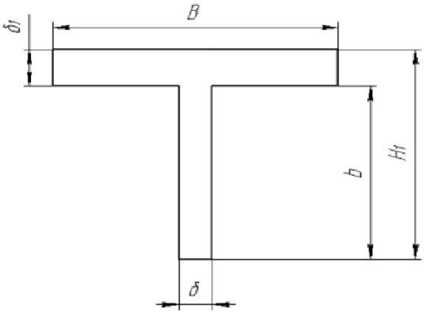

Fig. 4. Dimensions of spar belts

To reduce the tension at the junction of the spar shelf and casing, modifying linear dimensions of the zones of the spar without changing calculated squares is recommended [3]. Then, the recommended cross section will look like in Fig. 5, where B is the estimated width of the horizontal shelf of the spar belt. Reduction of d^i at the place of blade casing attachment and a corresponding increase in the middle of the spar belt with the invariance of the area of the original size found namely $Bd_1=B(d_2+d_3)$.

Then let us perform calculations for the drawing construction, namely obtain new dimensions of top shelf of the spar. From the condition d_2 = 3 mm to obtain any section

$$d_3=d_1-d_2.$$

From the condition of belt area invariance, i. e. S = const for any values of B and d_1, let us choose B_2 and B_3 that would satisfy the equality:

$$Bd_1=2B_2d_2+B_3d_3,$$

B_3 taken with the fixing bolts of hull plates of 10 mm diameter in sections 1-1, 2-2 and 3-3. The bolt in sections 4-4 and 5-5 is 6 mm diameter.

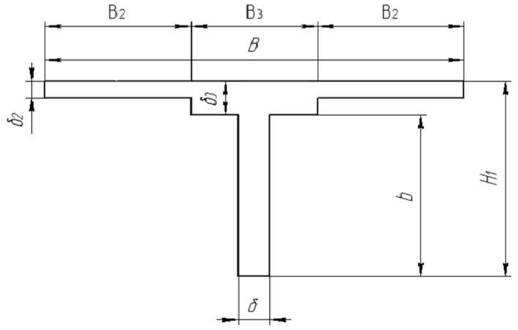

Fig. 5. The recommended cross section

Reduced area of the bottom panel with the lower belts of the two spars at the i th section of the blade is given by

$$F^i_{red.bot}=\frac{M^i_{bend}}{H^iK\,y_v},$$

where H^i is the working height schematized monoblock blades in the i th section; K = 0,9 – attenuation coefficient of bottom panel; y_v is the tensile strength of D16T (y_v = 40 kg/mm^2).

Let us tabulate the rounded data of (H^i, $F^i_{red.bot}$).

Calculation of the total bottom spar chord area in the i th blade section F^i_{bot}.

$$F^i_{bot}=h\,F^i_{red.bot},$$

for double-spar blade

$$F^i_{bot}=F^i_{bot1}+F^i_{bot2},$$

where F^i_{bot1} is the upper belt area of the spar 1 in the i th section; F^i_{bot2} is the upper belt area of the spar 2 in i th section.

Areas of lower belts of the spars are distributed proportional to the height of the spar:

$$\frac{F^i_{bot}}{a_i+b_i}=\frac{F^i_{bot1}}{a_i},\qquad F^i_{bot1}=F^i_{bot}\frac{a_i}{a_i+b_i},$$

$$\frac{F^i_{bot}}{a_i+b_i}=\frac{F^i_{bot2}}{b_i},\qquad F^i_{bot2}=F^i_{bot}\frac{b_i}{a_i+b_i}.$$

The bottom panel and spars' belts are stretched during flight. Therefore, the value T for the lower belt are taken from 8...12. According to the selected value of $T = 10$ and the values of F^i_{bot1} we determine the lower spar belts dimensions wherein:

$$d_i = k\sqrt{F^i_{bot1}},$$

where $k = 0.2...0.25$, in this case we choose $k = 0.23$

$$b^i_n = Td^i, \qquad B^i = \frac{F^i_{bot1} - b^i_n d_i}{d^i_1},$$

$$H^i_n = b^i_n + d_i, \qquad d^i_1 = (1.3...1.5)d^i,$$

we choose $d^i_1 - 1.45d^i$.

Calculations for the lower shelf are performed similarly as for the top one.

B_3 is taken with the fixing bolts of hull plates of 10 mm diameter in sections 1-1,2-2 and 3-3. In the sections 4-4 and 5-5 bolt diameter is 6 mm.

Determination of the wall thickness and the pitch racks of the first spar (Fig. 5).

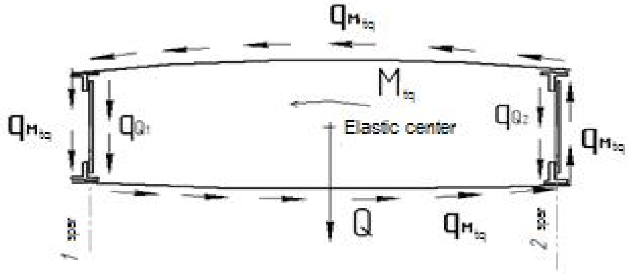

Fig. 5. Linear tangential forces acting on the wall of the 1st (q^i_{Q1}) spar in the i th section

The reduced shear force in the i th section Q^i_{red} (considering spar taper):

$$Q^i_{red} = Q^i - \frac{M^i_{bend}}{H^i}\sigma,$$

where Q^i is the shear force in the i th section; M^i_{bend} is the total bending moment in the i th section; σ is the taper angle of blade in radians.

Shear force accounted for the wall of the 1st (Q^i_1) spar in the i th section:

$$Q^i_1 = Q^i_{red}\frac{a_i^2}{a_i^2 + b_i^2}.$$

Linear tangential forces from shear force $Q^i\left(q^i_Q\right)$ for 1st spar:

$$q^i_{Q1} = \frac{Q^i_1}{H^i_{1p}},$$

where $H^i_{1p} = 0.95a_i$ is the estimated height of 1st spar in the i th section. Linear tangential forces from M^i_{tq} action can be determined by the following formula:

$$q^i_{M_{td}} = \frac{M^i_{td}}{2F_{cont}}, \qquad F_{cont} = \frac{a_i + b_i + c_i}{3}d_i.$$

Total linear tangential forces acting on the wall of the 1st (q^i_{wall1}) spar in the i th section:

$$q^i_{wall1} = q^i_{Q1} + q^i_{M_{td}}.$$

Thickness of the front spar wall in the i th section:

$$d^i_{wall1} = \frac{q^i_{wall1}}{\phi_k}.$$

The resulting thickness is rounded up to the standard one.

Spar pitch racks in the i th section

$$t^i_{wall} = d^i_{wall}\sqrt{\frac{5.04E}{\phi_p - 3.4E\left(\frac{d^i_{wall}}{H^i_p}\right)^2}},$$

where H^i_p is the estimated height of the spar in the i th section.

$$\phi_p = \phi_k = 0.3d_b.$$

In the cross section 5-5 for reasons of easing construction and manufacturing techniques blade pitch racks assumed to be 100 mm.

Calculation of rivet joint attachment of the spar wall to the belts.

The force acting on a rivet fastening wall of the spar to the belt in the i th section:

$$T^i_r = \frac{q^i_{wall}t_r}{n^i},$$

where t_r is the rivets step; $t_r = 24\ldots40$ mm depending on the rivets diameter and the number of rows; n^i is the number of rows of rivets in the i th section.

III. OPTIMIZATION OF THE SPAR BY WEIGHT

The main objective of optimizing the spar by weight of is the definition of an optimal pitch racks and material costs of spar racks, which in this case will satisfy the conditions of the spar durability.

The structural embodiment of the blade spars wall consists of the actual walls and the supporting struts.

Let us find the distance between the centers of mass of the spar belts:

$$h_{ef} = H - \frac{d_p + \delta_c}{2},$$

where d_p is the thickness of the upper belt; δ_c is the thickness of the lower belt; H is the height of the blade.

Let us define the parameters of loading on the beam:

$$\frac{\sqrt{Q}}{h_{ef}},$$

where Q is the limit load.

Let us determine the ratio of $\frac{h_{ef}}{\delta_{fact}}$, to determine the minimum needed wall thickness.

We find the ratio of $\frac{t}{h_{ef}}$ and using it the optimal pitch racks (t is the step of fasteners in a row).

We determine the optimum value of the relative material costs of the rack to the wall $\alpha = \frac{F_{wall}}{t\delta_c}$ and using it the minimum needed cross-sectional area racks

$$F_{wall} = \alpha t \delta_c .$$

The number of casing layers in each section of the spar is calculated by dividing the thickness of the case to the thickness of one layer of unidirectional fiberglass and rounding up to the nearest integer.

In the same way calculations are performed for the shear ribs, but it needs to be rounded up to the nearest even number to make it symmetrical. Given that the compressive strength of the unidirectional fiberglass is less than the tensile strength, the number of layers in the compressed case will be higher by almost twice [4], [5].

$n_{com} = \frac{d_{com}}{d_{ply\ cap1}}$ is the number of layers in the compressed spar case,

$n_{ten} = \frac{d_{ten}}{d_{ply\ cap2}}$ is the number of layers in the tensioned spar case,

$n_s = \frac{y_t}{d_{ply\ web}}$ is the number of layers in the shearing edge,

where $d_{ply\ cap1}$ is the compressed thickness of the spar hull; $d_{ply\ cap2}$ is the thickness of the hull and spar tie; $d_{ply\ web}$ is the thickness of the shear edge.

CONCLUSIONS

The software of computer-aided design of load-bearing elements of rotor blade for wind power plant is proposed. It is shown that the optimization of the spar by weigh improve the quality of design.

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В. М. Синеглазов, В. М. Бойко. Автоматизоване проектування лонжерона лопаті ротора вітроенергетичної установки

Розглянуто проблему визначення розміру та площі лонжерона лопаті вітроенергетичної установки. Реалізовано оптимізацію ваги лонжерона.

Ключові слова: автоматизоване проектування; вітроенергетична установка; лопать; оптимізація лонжерона.

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Рассмотрена проблема определения размера и площади лонжерона лопасти ветроэнергетической установки. Реализована оптимизация веса лонжерона.

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