STRENGTH CALCULATION OF COMPOSITE FLANGES FOR THE COMPOSITE CASING PARTS OF AIRCRAFT ENGINE

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Abstract. Some light composite casing parts are currently scheduled for adoption in the new aircraft engine. These parts are made from glass/epoxy and carbon/epoxy laminate by hand laying-up epoxy prepregs with different orientation. The casing part flanges are also made from the plastics to obtained the maximum of mass reduction. These flanges are the most load-carrying elements of the composite casing parts. So the prediction of carrying capacity and design life of the flanges is very important in the design of composite casing parts. The mathematical model was developed to predict of the carrying capacity of various composite flanges at exploitation loads. This model allowed calculation to be made for various flanges to find a more appropriated ones design. The results of the stress-strain state and strength analysis for some composite flanges are shown. So the considered composite flanges and corresponded casing parts have reasonable safety factors. These composite structures can be recommended to use in case of aircraft engine.

One of the lines of the new aircraft engine parameters improving is the adopting of composite structural components [1]. There are some reasons to choose composites over traditional materials. First of all is the reduction in part weight, which reduces fuel consumption. Then the composite cases ensure more effective of noise protection. At last the composites can reduce the cost production of some aircraft engine structural components. The most preference components for the composite materials adopting are the aircraft engine case details.

So some light composite casing parts were designed for a new turbofan aircraft engine. These casing parts were maid from glass/epoxy and carbon/epoxy laminate. Fig. 1 shows typical composite casing parts for example. These casing parts are the parts of the outside case of aircraft engine.

All casing parts consist of the inside and outside laminates and the internal hollow segments for noise protection. The parts have flanges to fastening. At designing it was found that the using of traditional metal flanges for thin and light composite case details is ineffective. The weight of the metal flanges is almost equal weight of the composite segments. And also we have a problem of adhesion violation on the metal-plastic contact zones. So light composite flanges must be designed for all these composite casing parts.

There were designed about ten variants of composite flanges. Fig. 2 shows the laminated structures of some composite flanges. Most of flanges were formed from the woven-fabric glass/epoxy laminates. The warp fibers of layers were oriented along generator directional of casing parts and along tangential direction. The circumferential winding

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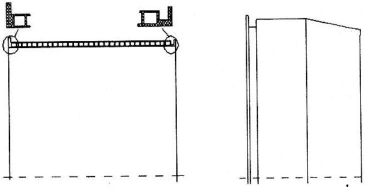
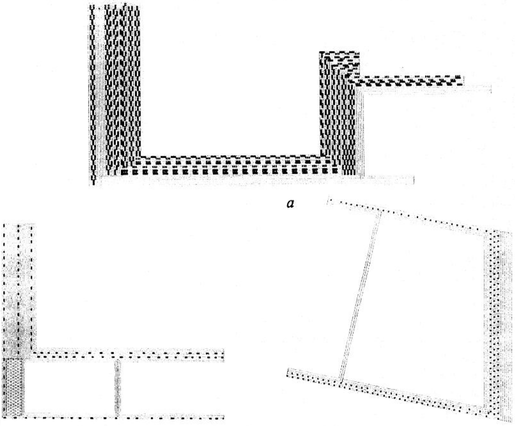
of unidirectional glass/epoxy prepregs reinforced some flanges (for example fig. 2, b). And then there were flanges reinforced by unidirectional carbon/epoxy prepregs oriented with fibers along generator and tangential direction (fig. 2, a).



a *b*

Fig. 1. Typical composite casing parts of aircraft engine: the outside back suspension case (*a*), the nozzle case (*b*),



b *c*

Fig. 2. The composite flanges of the power case (*a*), suspension case (*b*) and the cone segment of the nozzle case (*c*):

– the layer of epoxy impregnated glass-fabric with warp along the generator direction;

– the layer of epoxy impregnated glass-fabric with warp along the tangential direction;

– the layer of unidirectional carbon/epoxy prepregs with fibers laid along the tangential direction;

– the layer of unidirectional carbon/epoxy prepregs with fibers laid along the generator direction;

– the layer of circumferential winding of unidirectional glass/epoxy prepregs

The main stages of the composite flange forming for the cylinder segment of the nozzle case of aircraft engine are illustrated on Fig. 3. After flanges have been formed the composite details were seated in autoclave for solidification.

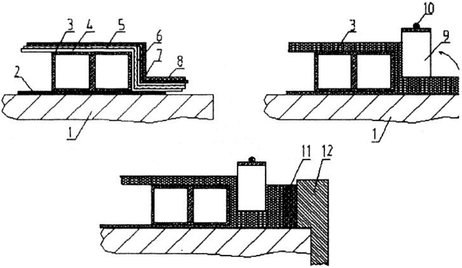


Fig. 3. **Forming of the composite flange for the nozzle case cylinder segment of aircraft engine: *1* - arbor, *2* - inside laminates, *3* - noise proof paneles, *4* - six layers, *5* - one layer, *6* - five layers, *7*- fourteen layers, *8* - one layer, *9* - rubber tape, *10* - clamp, *11* - twelve layers, *12* - block ring.**

The flanges are the most loaded elements of the composite casing parts. The mathematical model was developed to predict of the carrying capacity of various composite flanges at exploitation loads. This model allowed calculation to be made for various flanges to find a more appropriated ones design.

There are two main external forces having action on every casing part. The first is the force of inertia of the mass G, which applied in the center of the mass of the casing parts at a distance l from flange. The bending moment M of this force is calculated as

$$M = nGl, \tag{1}$$

where n is the overload coefficient for take off and landing aircraft engine condition ($n \approx 5,3$). The second main force is the axial force of the jet of aircraft engine gas - T, which applied on internal cone surface of nozzle. These forces are cyclic with frequency are up 5 to 200 Hz, but at first we calculated the carrying capacity of the composite details at maximum static loads corresponding amplitude cyclic loads.

The equivalent force P_{eq} applied on the flange was calculated using these main external forces by the following equation [2]

$$p_{eq} = k_1 \frac{M}{D} + T, \tag{2}$$

where k_1 is the coefficient of flange rigidity ($k = 2,674$), D is a diameter of middle surface of a casing part. For the composite polymer flanges we took the coefficient $k_1 = 4$.

Then the equivalent force P_{eq} was considered as load p^{eq} distributed on the cross section of every flange. On the surface of the bolted joint we took moving hinge support condition. Fig. 4 shows boundary conditions for the four investigated flanges.

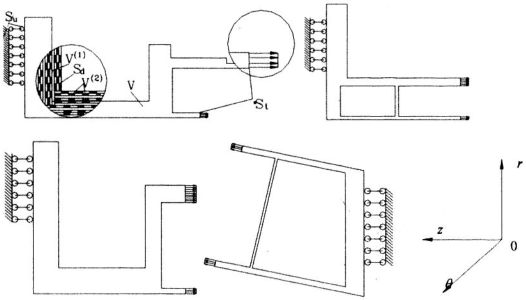


Fig. 4. **Boundary conditions for the problem of the stress-strain calculation of the composite flanges**

At the first we calculated the stress-strain state of the flanges. For various flanges the force of inertia of the mass G was from 1000 N up to 2000 N; axial force of the jet of aircraft engine gas T was 77000 N. The diameters of middle surface of casing parts D was about 1900 mm. So the equivalent loads ^{eq} distributed on the cross sections of considered flanges were from 3,68 MPa up to 7,8 MPa.

The mathematical statement of the axially symmetric boundary-value problem of the theory of elasticity for composite laminar flanges includes following equation. Lagrange's functional is

$$\delta J_u = \int_V \epsilon_{ij} C_{ijkl} \delta\epsilon_{kl} dV - \int_{s_t} p^{eq} i \delta u_i dS. \tag{3}$$

Cauchy's equations are

$$\epsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}). \tag{4}$$

Boundary conditions are

$$u_z = 0\,|_{S_i}. \quad \sigma_{ij}.N_j = p^{eq} i|\, S_t. \tag{5}$$

Conditions for the interlaminar boundary S_d are

$$u_i^{(1)} = u_i^{(2)} \Big|_{S_d}, \sigma_{ij}^{(1)}.N_j = \sigma_{ij}^{(2)}.n_j \Big|_{S_d}. \tag{6}$$

Each layer was considered as ortotropic or transversally isotropic material. Fig. 5 shows the possible orientation of these layers in the composite structures. The equations

$$X_{i'j'k'l'} = C_{ijkl}\alpha_{i'i}\alpha_{j'j}\alpha_{k'k}\alpha_{l'l} \tag{7}$$

allows to calculate of elastic modulus tensor components in structure global coordinate system $C_{i'j'k'l'}$ from the components of this tensor in local coordinate system of layer C_{ijkl}.

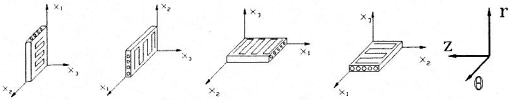


Fig. 5. **Orientation of layers in composite flanges with respect to the global coordinate system Orzθ**

The components of the matrix of axis rotation $\alpha_{ij}^{(n)}$ for composite layers are

$$\alpha_{ij}^{(1)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}; \quad \alpha_{ij}^{(2)} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix},$$

$$\alpha_{ij}^{(3)} = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}, \quad \alpha_{ij}^{(4)} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \tag{8}$$

where the up index $n = 1 - 4$ is the number of lamina orientation as shown on Fig. 5. The components of the elastic modulus tensor C_{ijkl} for ortotropic materials are calculated from the Young's modula (E_{11}, E_{22}, E_{33}), Poisson's ratios $(\nu_{12}, \nu_{31}, \nu_{23})$ and shear modula (G_{12}, G_{13}, G_{23}) by the following equation [3]

$$C_{1111} = \frac{1}{E_{22}A}\left(\frac{1}{E_{33}} - \frac{\nu_{23}^2}{E_{22}}\right), \quad C_{2222} = \frac{1}{E_{33}A}\left(\frac{1}{E_{11}} - \frac{\nu_{31}^2}{E_{33}}\right),$$

$$C_{3333} = \frac{1}{E_{11}A}\left(\frac{1}{E_{22}} - \frac{\nu_{12}^2}{E_{11}}\right), \quad C_{1122} = \frac{1}{E_{33}A}\left(\frac{\nu_{31}\nu_{23}}{E_{22}} + \frac{\nu_{12}}{E_{11}}\right),$$

$$C_{1133} = \frac{1}{E_{33}A}\left(\frac{\nu_{12}\nu_{23}}{E_{11}} + \frac{\nu_{31}^2}{E_{33}}\right), \quad C_{2233} = \frac{1}{E_{11}A}\left(\frac{\nu_{12}\nu_{31}}{E_{33}} + \frac{\nu_{32}}{E_{22}}\right),$$

$$C_{2323} = G_{23}, \quad C_{1313} = G_{13}, \quad C_{1212} = G_{12},$$

$$A = \frac{1}{E_{11}E_{22}E_{33}}\left(1 - 2\nu_{12}\nu_{23}\nu_{31} - \frac{E_{11}}{E_{33}}\nu_{31}^2 - \frac{E_{22}}{E_{11}}\nu_{12}^2 - \frac{E_{33}}{E_{22}}\nu_{23}^2\right). \tag{9}$$

To estimate the static strength of the flanges and to determine their safety factor we utilized the criteria of maximum stress and the modified criterion of Misses-Hill. The criterion of maximum stress for the orthotropic layers is defined as number of nonequality

$$\begin{aligned} &S_{11}^{c-} \le \sigma_{11} \le S_{11}^{c+} \\ &S_{22}^{c-} \le \sigma_{22} \le S_{22}^{c+} \\ &S_{33}^{c-} \le \sigma_{33} \le S_{33}^{c+} \\ &S_{13}^{c} \le \sigma_{13}, \qquad S_{12}^{c} \le \sigma_{12}^{c}, \qquad S_{23} \le \sigma_{23}, \end{aligned} \tag{10}$$

where S_{ij}^c is the static strength of the layer material. Safety coefficients for the components of stress tensor (σ_{ij}) and the layer materials (p) are calculated by the equation

$$n_{ij}^{(p)} = \min_{\mathbf{r}\in \mathbf{V}^{(p)}} \left(\frac{S_{ij}^{c(p)}}{\sigma_{ij}^{(p)}(r)} \right). \tag{11}$$

Safety coefficient for a composite structure as a whole is calculated by equation

$$n = \min_{i,j,p} \binom{(p)}{ij}.$$

The modified criterion of Misses-Hill is defined as

$$\begin{aligned} &\Phi_\sigma = C_1(\sigma_{11} - \sigma_{22}) + C_2(\sigma_{22} - \sigma_{33}) + C_3(\sigma_{33} - \sigma_{11}) + C_4\sigma_{12}^2 + C_5\sigma_{23}^2 + C_6\sigma_{13}^2 - 1 < 0 \\ &C_1 = \frac{1}{2}\left(\frac{1}{S_{11}^{c2}} + \frac{1}{S_{22}^{c2}} - \frac{1}{S_{33}^{c2}}\right) \qquad C_2 = \frac{1}{2}\left(-\frac{1}{S_{11}^{c2}} + \frac{1}{S_{22}^{c2}} + \frac{1}{S_{33}^{c2}}\right), \\ &C_3 = \frac{1}{2}\left(\frac{1}{S_{11}^{c2}} - \frac{1}{S_{22}^{c2}} + \frac{1}{S_{33}^{c2}}\right). \qquad C_4 = \frac{1}{S_{12}^{c2}}, \quad C_5 = \frac{1}{S_{23}^{c2}}, \quad C_6 = \frac{1}{S_{13}^{c2}}. \end{aligned} \tag{12}$$

And then we preliminary estimate the strength of the composite flanges subjected cyclic loading. In this case the load was presumed to be symmetrical cyclic with an amplitude is equal to the maximum static load p^{eq}. The fatigue criteria were obtained from the static criteria eq. (8) and eq. (10) where endurance limits S_{ij}^b had been substituted for the static strength S_{ij}^c.

The relationship between the endurance limits S_{ij}^b and number of cycles to failure N_b was taken as exponential function [4].

$$S_{ij}^b = A_{ij} N_b^{B_{ij}}, \tag{13}$$

where A_{ij}, B_{ij} are the material constants tensors.

The elasticity modulas and Poisson's ratios for various composite layers are given in Table 1. The material constants of the static strength were taken from various experiments and the endurance limits were taken as estimation from the literature date, these constants are given in Table 2. The constants A_{ij}, B_{ij} in equation (13) for the considered composite are calculated from the static strength S_{ij}^c. and the endurance limits S_{ij}^b b on base of $N_b = 10^8$ cycles (Table 2).

Table 1. The elasticity modulas and Poisson's ratios of the composite layers

Composite	E_{11},	E_{22},	E_{33},	G_{12},	G_{13},	G_{23},	ν_{21}	ν_{13}	ν_{32}
	10^9 Pa								
woven glass-fabric/epoxy laminate	24	18	6	4	3	3	0,15	0,42	0,18
unidirectional carbon/epoxy composite	125	7	7	5,4	5,4	3	0,018	0,32	0,3
unidirectional carbon/epoxy composite	59,2	13,4	13,4	3,9	3,9	2,5	0,059	0,26	0,272

Table 2. The static strength (I) and the endurance limits (II) on base of Nb $=10^8$ cycles of the composite layers (MPa)

Strength constant	woven glass-fabric/epoxy laminate		unidirectional carbon/epoxy composite		unidirectional carbon/epoxy composite	
	I	II	I	II	I	II
S11	$\frac{410}{320}$	84	$\frac{1047}{724}$	186	$\frac{1400}{724}$	186
S22	$\frac{230}{120}$	48	$\frac{44}{128}$	10	$\frac{35}{100}$	10
S33	$\frac{44}{128}$	8	$\frac{44}{128}$	8	$\frac{35}{100}$	10
S12	150	40	74	18	65	18
S13	70	18	74	18	65	18
S23	70	18	50	11	35	11

* the numerator of a fraction is tension strength, the denominator of a fraction is compression strength

The boundary-value problem for every flange was solved by FEM. The special program complex for personal computers was developed for this calculation.

The results of the stress-strain state analysis for the flanges are shown on Fig. 6. These stress diagrams illustrate the most loading zones in flanges and the most critical points in accordance two criteria (eq. (10) and eq. (12)).

For example the safety coefficients calculated for the power case composite flange are given bellow. For the woven glass-fabric/epoxy layers the safety coefficient of the stress in warp direction is $n_{11} = 16.0$; of the stress in weft direction is $n_{22} = 31.0$; of the stress in transversal direction is $n_{33} = 4.7$; of the shear stress is $n_1 3 = 9.4$. For the unidirectional carbon/epoxy layers the safety coefficient of the stress in fiber direction is $n_{11} = 9.8$; of the stress in transversal direction is $n_{22} = 4.7$, of the shear stress is n23 =6.7. So the safety coefficient for the flange at whole is $n = 4.7$, due to stress in transversal direction n33 in woven glass-fabric/epoxy laminate. The criteria Misses-Hill (12) have a maximum value max $\Phi_\sigma = -0.936$ for the point F in Fig. 6. The number of cycles of loading to failure in laminate beginning calculated by eq. (11) and (10) was $N = 3.9110^7$.

For all of the considered composite flanges the safety factors for woven glass-fabric/epoxy layers in warp and welt direction were in limits from 7 to 30, and so for the shear stress. The minimum safety factors were for the transversal stress in layers. These safety factors were in the limits from 1.8 (for the flanges of the nozzle case) to 4.7 (for the flanges of the power case).

The numbers of cycles of loading to failure beginning in the most loading layers were about 109 for the first and second flanges (Fig. 2, a, b) and about 210^3 for the flanges of the nozzle casing (Fig. 2, c).

The experiment to fracture at static loading of one really composite casing part with composite flange verified the calculated estimation of carrying capacity and suggested zone of fracture.

So the considered composite flanges and corresponded casing parts have reasonable safety factors. These composite structures can be recommended to use in case of aircraft engine. The further research of the composite flanges and casing parts with some damage are interested. The calculation shows that the typical suggested damage mode for these laminated composite structures is the delamination due to interlaminar shear or transversal tension. But the laminated composite structures with delamination can enough carrying capacity for further service. The modeling of damage accumulation in composite structures will allow more accurate estimating ones carrying capacity and behavior under cycling loading.

References

1. *Handbook of composites* / Ed. G. Lubin. - Van Nostrand Reinhold Company Inc., 1982
2. Lizin V.T., Pjatkin V.A., *Design of thin wall structures* (rus.), Moscow. Mashinostroenie, 1985, - 344 p.
3. Fudzii T., Dzako M, *Fracture mechanics of composite materials* (rus.), Moscow. Mir, 1982, 232 p.
4. Bolotin V.V, *Life prediction of machines and structures* (rus.), Moskva. Mashinostroenie, 1984, 312 p.