INVESTIGATION OF OPERATIONAL FAILSAFE CHARACTERISTICS OF THE SAILPLANE LAK-12 "LIETUVA"

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Presented at the XXI OSTIV Congress, Wiener-Neustadt, Austria (1989)

SUMMARY

The paper presents operational survivability characteristic investigation methods adopted for parts made of composite materials in the certification of the LAK-12 "Lietuva" sailplane. Rated conditions, quality control and maintainability characteristics have been determined. The paper includes the full-scale sailplane component survivability test results. Operational survivability characteristics of the CM parts determined by way of theoretical and experimental investigation provide the specified in-service safety level of the LAK-12 "Lietuva" sailplane during its service life.

INTRODUCTION

The main criterion for providing safe life of the sailplane parts made of composite materials (CM) is "an operational survivability" which is predicted in the stage of technical proposal by calculation, is achieved in the project stage by design/technological means, and substantiated in the certification stage by calculation and experimental analysis and is maintained in use by periodical integrity checking and restoration of the strength by suitable repairs.

The work related to analysis and providing of operational survivability characteristics for the CM parts, required in all stages of the sailplane development is carried out in the certification stage in line with the following interconnected trends:

—forming rated conditions of operational survivability;

—determination and providing specified characteristics of the controllable CM parts taking into consideration check methods in a wide-scale production and intended use;

—determination and providing of the specified maintainability characteristics of the CM parts taking into consideration efficiency and labor content of the durability recovery methods;

—rated experimental determination and providing of required residual strength characteristics of the damaged CM parts;

—determination and providing of specified characteristics of the CM parts safe use in terms of failure probability.

The values of the operational survivability characteristic obtained are compared with design criteria, such as admissible failure probability in service life $ß_{\Sigma}^{adm}$ allowed level of specific labor consumption or maintenance, minimum mass of the structure.

We chose for investigation the most critical and highly loaded parts made of CM — such as the wing, comprising two panels (Figure 1) and stabilizer (Figure 2), the integrity of which substantially determines safe life of the sailplane. The wing panel and stabilizer enclosures represent three-layer structures covered by skins of glass plastic on glass cloth fabric TCU-8/3-BM-78 and epoxy resin ED-20. The PB-I-65 plastic foam is used as a filler. The spar located inside the wing torsion box has a H- shape in section. The spar booms are made of unidirectional carbon plastic on a base of carbon tape LUP-0,2 or ELUP-P and epoxy binding 5-211B.

1. RATED CONDITIONS

The design conditions in the certification stage determine the amount and type of the load applied, also the climatic spectrum influences properties of the CM parts and needs to be taken into account when carrying out tests of the full-scale structures for failure of those parts. The tests are planned on the basis of the technical requirements according to the wide-scale production data and analogue constructions service, and also sample test data. The design conditions include:

1.1 Rated conditions related to climatic spectrum influence upon crack resistance of the CM parts.

Substantial strength and safe-life reduction of the CM parts on polymer base under the influence of climatic factors is not only one of the properties distinguishing them from metal parts behavior, but also presents a serious problem, the solution of which requires more complete and accurate description of service conditions. The rated conditions related to climatic factors are formed with reference to basing regional data and flight mission in intended service and comprise:

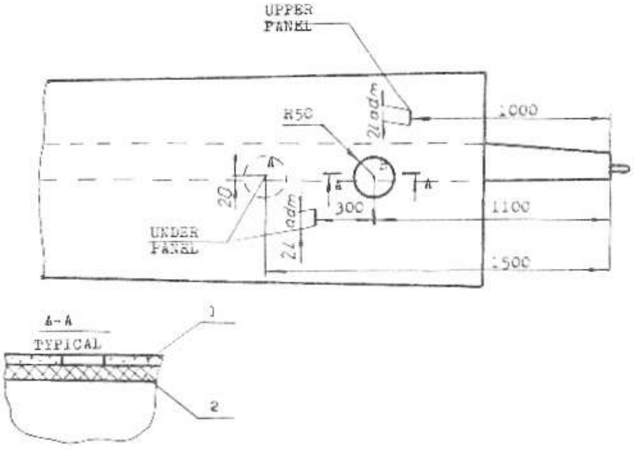

Figure 1. Wing panel disagram indicating dimension and location of damage. Blows of = are applied in points A,B.

a) climatic factors variation between extreme values:
—ambient temperature t_{min}=-10°C; t_{max}=54°C;
—ambient air humidity p_{min}=20%; p_{max}=98%;
—atmospheric pressure p = 760 Hg;

b) heating and moisture content of the CM parts corresponding to these extreme climatic conditions.Taking into account good thermo-insulating properties of the foam plastic used as a filler in the enclosures of the wing panels and the stabilizer, also likely carriageof water ballast in the wing torsion boxes one may conclude that only external glass plastic skin of the wing panel and the stabilizer enclosure will be subjected to intense heating due to sun radiation. At the specified maximum ambient temperature value we assume tp = 104 degrees C as rated heating temperature. For the remaining parts of the wing and for the stabilizer made of CM including carbon plastic materials, we assume tp = 22 degrees C as rated heating temperature value. Equilibrium moisture content level in glass and carbon plastics on the base of epoxy matrices we assume to be equal to ΔG=0,84% in service, which corresponds to a wide range of climatic factors.

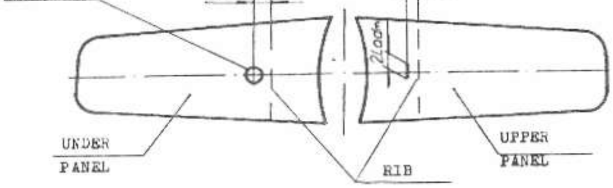

Figure 2. Stabilizer diagram indicating dimension and location of damage.

c) lightning and hail characteristics in the region. Hailstone impacts and lightning discharge strokes are among the main reasons of the CM parts damage. Taking into consideration specific service of the sporting sailplanes, probable damage due to lightning strokes or hailstone impacts in flight is neglected.

1.2 Rated conditions related to damage-ability.

The design conditions related to damageability in the certification stage include:

—dimensions and recommendations on model building of theoretical technological faults, appearing in all the stages of component manufacturing, which exist as the moment of going into service and would not be revealed during its life;

—dimensions and recommendations for model building on in-service damage due to middle and low speed impacts on the parts.

As a rated dimension of the technological fault, we assume $2L_{adm}$, beginning from which it can be reliably detected in the production process by instrumental checking, also by means of such nondestructive tests such as acoustic, x-ray, impedance. All intermediate products (elements, parts) are subjected to postoperational inspection. It is assumed that defects of $2L \geq 2L_{adm}$ dimension are eliminated by repair or rejection. The $2L_{adm}$ value has been set on the base of the data, characterizing efficiency of the test methods used in wide-scale production, also the production faults list of the LAK-12 gliders, made according to results of technical inspections during manufacture, inspection of the glider requiring repair, and comments from the clubs received in the period 1983-1986.

For typical CM parts as a rated dimension of the production fault we assume:

—three-layer enclosures of the wing skins and stabilizers $2L_{adm}=150$ mm for dents, stratifications, glue failure in a regular zone of the enclosure (beyond the glueing area with hinge assembly, the structure and carbon plastic spars);

—$2L_{adm}=80$ mm for glue failure, stratification in the enclosure adhesion area with hinge assembly, rib structure, also carbon plastic spars.

The above defects in the tests of the full-scale designs are simulated on the bottom surface of the wing skin and stabilizer enclosures in the areas of maximum faults in the form of slits, regularly oriented to the longitudinal axis of the part (Figures 1 and 2).

—wing spar: the carbon plastic spar booms are the major wing parts, the destruction of which cause wing break up. The most dangerous of the defects is edge stratification, resulting from low-speed impacts. Faults resulting in a full-scale production with a low automation accuracy of the wing spar equipment transportation and assembly are mainly related to infringement of technological operations. As a rated dimension for edge stratification in the carbon plastic spar booms we assume the dimension of damage resulting at impact applied by a steel ball of 1.5 kg mass 62 mm in diameter having energy. The above impact is applied by allowing the ball to fall from 1 m height on lateral edges of the upper and lower carbon plastic spar booms in the maximum loaded areas (Figures 1 and 2).

The analysis of the operational faults list, made subsequent to inspection of the CM parts in the LAK-12 sailplanes in the clubs in the period of 1985-1986, shows that their main reason is high wing and stabilizer loading at the moment of touch down in case of heavy landings (so called "compasses"). Due to the fact that the wing panels and stabilizer are of integral construction, operational damage on the spars and ribs may not be disclosed during repair. Therefore, we assume as a rated dimension the following:

a) wing spar:

$2L_{adm}^{a}=15$ mm, for an edge crack in the carbon plastic booms

b) wing rib:

$2L_{adm}^{a}=30$ mm, for a crack in a rib wall

$2L_{adm}^{a}=60$ mm, for stratification in the rib wall;

c) stabilizer rib:

In the event of rib wall damage, it is not subjected to repair but the stabilizer is removed from service;

d) three-layer enclosures of the wing panel and the stabilizer:

After repair the rated dimensions for operational damage in the three-layer enclosures we assume for corresponding type zones as equal to $2L_{adm}^{a}=2L_{adm}$.

Impact applied during the "compasses" landing is considered to be an acidental event which may take place at the very beginning of the glider service. It means that the above dimensions $2L_{adm}^{a}$ correspond to theoretical (design) case of damage the CM part defect not being revealed during its entire life.

The operational damage is simulated by the defect in the form of a slit in the maximum load areas of the corresponding CM parts.

1.3 Safety factors related to residual strength of the CM parts.

With reference to the methods given in (1) the required safety level of the CM parts according to "operational survivability" conditions is provided by applying safety factors related to the residual strength f_{pc}. In the certification process of full-scale constructions life-time and residual strength of the CM parts should be confirmed for the main cases of loading:

a) No design technological defects $2L_{adm}$ and operational damage revealed during its life-time. For this case the recommended value in (1) is $f_{pc}^{a}=1,5$. Consequently, the full-scale structures of the wing panels and stabilizer with the above damage after fatigue tests corresponding to its life-time, taking into consideration the specified safety factors, should maintain the allowed residual strength

$$(p_c^{adm})^a=1.5 \cdot p_c^{max} \cdot (f_{cl}/k_T \cdot k_h) \qquad (1)$$

were p_o^{max}=maximum operational load:

f_{cl}= factor evaluating the reduction of crack resistance characteristic of the CM parts, due to the influence of climatic factors during the entire service life;

k_T, k_h=factors taking account short-term reduction of crack resistance characteristic due to the influence of temperature and humidity;

b) Operational damage of the CM parts obvious after general inspection, when noticed by the glider pilot. According to recommendation given in (1) for this case of the CM part damage f_{pc}=0,67. Included under the heading is the damage caused by bird encounters. Tests of the full-scale construction, particularly with wing panels and stabilizer nose damage of $2L_{adm}^{o}$=100 mm have shown that allowed residual strength:

$$(p_c^{adm})^o=0{,}67\cdot p_c^{max}\cdot(f_{cl}/k_T\cdot k_h) \qquad (2)$$

is sufficient.

If, during the influence of climatic factors is to be simulated, then $f_{cl}=k_T=k_h=1$.

If climatic factors are not simulated, we assume for compressed zones of the construction $f_{cl}^{c}=1.00$; $k_T^{c}=1.00$; $k_h^{c}=0{,}83$, and for extended zones of the construction $f_{cl}^{e}=1.00$; $k_T^{e}=1.00$; $k_h^{e}=1.00$. After applying the above values into equations (1,2) we obtain, for compressed construction zones:

$$(p_c^{adm})^a=1{,}8\cdot p_c^{max}=120\%p^p;$$
$$(p_c^{adm})^o=0{,}8\cdot p_c^{max}=53\%\ p^p;$$

and for extended structures:

$$(p_c^{adm})^a=1.5p_o^{max}=100\%\ p^p;$$
$$(p_c^{adm})^o=0.67\ p_o^{max}=44\%\ p^p.$$

where p^p, rated load.

2. SPECIFIED CHARACTERISTICS OF QUALITY CONTROL

Generally, the interval between inspections of the CM parts is determined by consideration of intensity of operational damage appearance, inspection reliability, in-service stresses, and crack resistance. Taking into consideration the sailplane service conditions (wide dispersion of the clubs, lack of these instruments and skilled staff for carrying inspections) dimensions of rated technological and in-service damage are chosen so that relatively great damage of the CM parts does not result in a reduction of safety level in comparison with the specified value.

Figure 3 shows requirements for quality control of wing panel and stabilizer structure sections and areas in terms of detection probability dependance Po (2L) against damage dimension at instrumental test and visual inspection.

The repaired CM parts after fatigue test made at a time corresponding to service life, and taking into account the specified reliability factors related to longevity, should maintain admissible residual strength $(p_c^{adm})^a$, determined from equation 1. This condition sets requirements for efficiency of the damaged CM parts repair methods.

3. THEORETICAL AND EXPERIMENTAL DETERMINATION OF THE RESIDUAL STRENGTH CHARACTERISTICS FOR DAMAGED CM PARTS

Two wing panels and one stabilizer of the LAK-12 sailplane have been subjected to test.

The wing test program included loading in sinusoidal cycle of variable amplitude by applying force simulating varying load factor of +5.3 and -3.0 in flight.

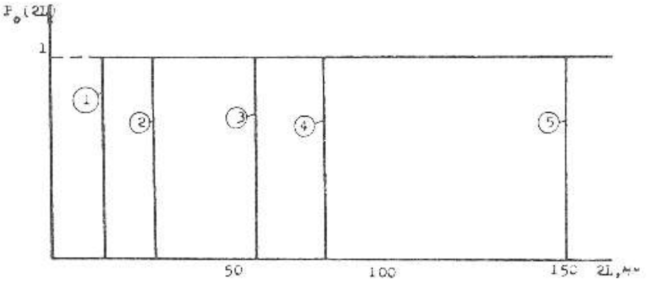

Figure 3. Requirements for quality control of the CM parts,

1 — special instrumental checking of the wing spar booms (crack and stratification detection).

2 — special visual inspection of wing ribs (crack detection).

3 — special visual inspection of the wing ribs (stratification detection).

4 — general complex (visual and instrumental inspection) of the three-layer wing and stabilizer enclosures in junction area.

5 — general complex inspection of the three-layer wing and stabilizer enclosures in regular area.

Rated technological faults $2L_{adm}$ and in-service damage $2L_{adm}^{a}$ were applied acording to Figure 1. After running the specified number of loading cycles both wing panels withstood 125% of rated static load without obvious residual damage or strain. After simulating "obvious" operational damage one panel withstood 121% p^p (after 10,590 cycles of operation) while other panel endured 80% p^p (after 15,000 cycles of operation). Rupture took place in the extended spar boom at the location of a slit.

The stabilizer test program included loading by applying force, simulating varying load factor of +5.0 and -3.0 in flight. The test comprised two stages. In the first stage the stabilizer withstood 8950 loading cycles without damage. Later defects of $2L_{adm}$ and $2L_{adm}^{a}$ dimensions were applied (Figure 2). After 17,000 loading cycles and stabilizer withstood 130% p^p load without residual damage or strain. At "obvious" in-service damage the residual static strength of the stabilizer is equal to 155% p^p. Rupture took the form of enclosure stability loss at the point of impact application.

The tests have shown that artificially applied damage in highly loaded parts of the structure did not get extended during the loading process. Rigidity and acting stress variation was within measurement dispersion.

4. DETERMINATION OF IN-SERVICE SAFETY CHARACTERISTICS OF THE CM PARTS

The in-service safety characteristics of the CM part is defined as the failure probability value during its life β_Σ. To determine β_Σ, we use a failure probability model of the CM parts taking into consideration their damage ability, suggested in (1) and based on the methods of reliability theory. According to the above probability model, using the method of "dismembering" of a complex accidental event, which represents failure of the damaged part, into simple ones, we obtain the relation between β_Σ and all rated cases in the form of independent components

$$\beta_\Sigma=\beta^a+\beta^o, \qquad (3)$$

where

β^a - failure probability of the part with technological defect $2L_{adm}$ and operational damage $2L_{adm}^a$ during the entire service life; and

β^o - failure probability of the part having damage $2L_{adm}^o$ in flight.

Assuming that the occurrence and influence of technological faults and operational damage upon the CM part are independent, the strength equation (3) may be expressed as follows:

$$\beta_\Sigma=\beta_f^a \bullet H_t(2L^a) \bullet T_c+\beta_f^o \bullet H_t(2L^o) \qquad (4)$$

where

T_c = 1000 flying hours — service life of the glider;
$H_t(2L^a)$; $H_t(2L^o)$-intensity of $2L_{adm}^a$ and $2L_{adm}^o$, damage occurrence per flight hour.

In calculating failure probability during the lifetime, we assume in equation 4, $H_t(2L^a) \bullet T_c=1$; $H_t(2L^o)=1$, where

β_f^a - failure probability of the part having technological defect $2L_{adm}$ or operational damage $2L_{adm}^a$ per flight hour;

β_f^o - failure probability of the part having operational damage $2L_{adm}^o$ per flight hour.

In order to take into account residual strength dissipation of the parts and maximum operational load while determining β_f^a values we use results of paper /2/. Figure 4 shows failure probability per flight hour versus residual strength variation factor pc- $_c$ and safety factor $f_{pc}=p_c/p_o^{max}$, where p_c- residual strength average value obtained from survivability test results of the CM parts. For maximum operational load we assume normal distribution of probabilities of accidental values with variation factor =8%, which corresponds to the case when most of the loading is due to the monoevring load. It follows from the above results of the full-scale structure test for residual strength that for the wing panels $f_{pc}=1.51$, $_c=28,8\%$ and for the stabilizer $f_{pc}=2.21$, $_c=8\%$. The excessive $_c$ value for the wing panels is explained by the fact that a slit in the spar booms was made at the same place at which the impact of a steel ball was applied. It leads either to damage interaction (condition of independent damage influence upon the strength of the part is not fulfilled) or to some combination of their dimensions, resulting in substantially different damage conditions for two panels. Taking into consideration the above circumstances, we assume the design value $_c$ corresponding to strength variation factor, obtained from the static strength test of undamaged wing spars which had not been subjected to preliminary fatigue tests. Owing to the fact that the CM parts during the residual strength tests simultaneously had damages of 2L, $2L_{adm}^a$, $2L_{adm}^o$ dimension we assume $\beta_f^a=\beta_f^o$.

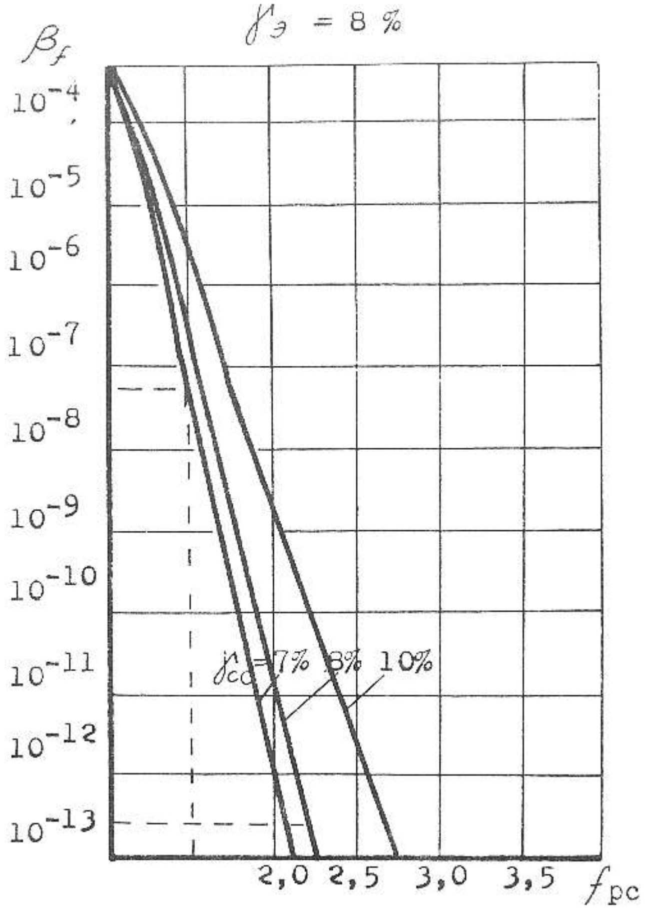

Figure 4. Failure probability versus safety and residual strength variation factors.

Having determined β_f^a values from Figure 4 and inserted them into equation 4, we obtain $\beta_\Sigma^w \approx 6.2 \bullet 10^{-5}$ for the wing panel and $\beta_\Sigma^{st} \approx 3 \bullet 10^{-10}$ for the stabilizer. The total value for the most critical and highly loaded sailplane parts, $\beta_\Sigma^{sp}=2 \bullet \beta_\Sigma^w=\beta_\Sigma^{st} \approx 1.24 \bullet 10^{-4}$, corresponds to the permissible failure probability value during life time $\beta_\Sigma^{adm}=10^{-3}+10^{-4}$, accepted as a project oritcrion.

REFERENCES

(1) Selikhov, A.F. Ushakov, A.E. 1988 — The probability failure model of damaged composite structures. Presented at International Conference on Composite Materials and Structures. FRP Research Center, Indian Institute Technol., Madras, India.

(2) Stewart, A.B. 1977 — Methods of safety factor determination for structures with time varying bearing capacity. Transactions of Central Aerohydrodynamics Institute, Publ. 1876, Moscow, U.S.S.R.