VERIFICATION OF CFRP COMPONENTS FATIGUE EVALUATION PROCEDURE UNDER IRREGULAR CYCLING LOADING

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Abstract

The procedure is proposed to evaluate the CFRP components fatigue under irregular loading in compression zone. A number of aspects of current CFRP damage under cyclic loading are considered. The proposed procedure of evaluating the fatigue under combined loading in compression zone is verified. The verification has demonstrated the procedure applicability. The recommendations are issued based on the procedure parameters values.

1 Introduction

The experience of CFRP materials application has already a rather long history. The early aircraft structural components made of CFRP materials started emerging in the 70-th of the last century. But during the recent decade only the CFRP materials were used for manufacturing the most loaded and critical components, a wing included. This has caused the challenge to understand profoundly the nature of fatigue damageability of such structures as the analysis and computation concepts applied previously do not allow constructing the optimal structure that implements the major benefits of current CFRP.

The principle difference between the CFRP and the conventionally used metallic alloys is that the CFRP fatigue properties depend on significantly more number of parameters, including laminate stacking sequence, orientation and loading type, stress ratio as well as the presence of several different damage types and their interaction. Therefore in spite of the great number of papers that cover the CFRP components fatigue (see references of papers [1, 2 and 3]) the completed researches that consider the combined irregular loading impact on fatigue are practically not available. If the knowledge of this impact and the fatigue evaluation procedure are not available it is not possible to develop the effective procedure that determines the CFRP components loading programs equivalent.

The degree of difference among the fatigue damages which the structural component under consideration has obtained in the course of experimental tests and under the standard flight conditions is considered to be an equivalent in the given case. The problem of defining the equivalents is of a particular importance for the metal-composite structures due to different mechanisms of damages initiation, their accumulation rate and the scattering parameters of the metal and the CFRP. The fatigue calculated definition complexity has resulted into the fact that the damage no-growth approach [4] has become the basic one to provide the aircraft structures integrity conditioned by damage tolerance. Following this approach the stresses that affect the structure are necessary to be limited by the stress level that provides, at least in the service life of structure, the absence of fatigue damages which lead to structural component failure. In the majority of cases the CFRP high fatigue properties and the application of not-high levels of allowable stresses that are selected with taking into account all possible operational factors including the impact, the thermal and moisture effect and the characteristics scattering lead to automatic realization of damage no-growth approach and the fatigue estimation procedure is needed only to evaluate if the physical structures and sub-components loading program would enable the validation of the CFRP components fatigue characteristics required. Therefore the procedure must be relatively simple, not predict too optimistically estimations and not require the high scope of experimental studies in order not to extend the tests program which is already extremely huge. The given paper proposes the procedure to evaluate the CFRP structural components fatigue and its verification based on the number of experimental data sets for samples, which are strips with open hole in compression zone.

2 General

In order to evaluate the CFRP component fatigue it is necessary to develop and give proof of possibility to apply the procedures as follows:

- The S-N curve approximation in fatigue range up to 10^7 cycles;
- The constant life diagrams;
- The fatigue damage accumulation models.

2.1 Fatigue Curve Approximation

When evaluating the fatigue, two zero-to-tension and zero-to-compression S-N curves have been used which are being obtained by experimental values approximation by the power dependence:

Compression zone: $$N=\left(\frac{\sigma_{c-}}{\sigma_{min}}\right)^{m_{-\infty}},\quad(1)$$

Tension zone: $$N=\left(\frac{\sigma_{c+}}{\sigma_{\max}}\right)^{m_0},\quad(2)$$

N – is a number of cycles before the failure;

m_R – is an S-N curve exponent with R asymmetry coefficient ($m_{-\infty}$ and m_0 – under compression and tension, correspondently);

σ_{c-} and σ_{c+} – are experimental constants which in examples hereunder coincided with the ultimate strength under compression and tension correspondently;

$R=\dfrac{\sigma_{\min}}{\sigma_{\max}}$ – is a stress ratio;

$\sigma_{\min}$ and $\sigma_{\max}$ – are minimal and maximal cycle stresses values.

The relationships (1) and (2) are selected from two relationships (exponential and logarithmic) currently mostly used for the S-N curve approximation, owing to the fact that the use of the logarithmic relationship, when calculating the standard aircraft spectrum, results into paradox in terms of the dominant lowest loads effect upon the damageability and the slight high loads effect including the "ground-air-ground" cycles. The latter does not agree with the existing experience of CFRP structural components application.

2.2 Constant Life Diagrams

The cycles with the R arbitrary values are reduced to zero-to-compression and zero-to-tension values with usage of formulae as follows:

Compression zone: $$\sigma^*_{R=-\infty}=-\frac{2\sigma_a}{\left(1-\dfrac{1}{R}\right)^{\kappa}},\quad(3)$$

Tension zone: $$\sigma^*_{R=-\infty}=\frac{2\sigma_a}{(1-R)^{\kappa}},\quad(4)$$

$\sigma_a=\dfrac{\sigma_{\max}-\sigma_{\min}}{2}$ – is a cycle stresses amplitude;

κ – is a constant that depends on the material and the state of stress at the point under consideration.

The relationship (4) known as Oding formula is widely used when calculating the airplane metal alloys structures because it describes comprehensively the fatigue behavior of materials and structural components in R range that is standard for airplane engineering under $\sigma_m\geq 0$, where $\sigma_m=\dfrac{\sigma_{\max}+\sigma_{\min}}{2}$ is an mean value of loading cycle. For the compression area the relationship (4) was modified appropriately into expression (3) in order to be in the best way in line with the

CFRP components behavior. The ease of (3) and (4) formulae usage consists in possibility to determine explicitly the equivalent stresses as well as in relationship simplicity, i.e. to make a calculation it is necessary to know the κ parameter magnitude, the value which of, as the experience has shown, is in 0.5-1.0 range for the existing CFRP. At this in case of the experimental data absence the 0.5 value is possible be used as the conservative estimate.

In the process of qualification of material for airplane structure as a rule, the S-N curves are obtained for the asymmetries: R = –∞, -1, 0, correspondently; the S-N curves for R = –∞, 0 may be used as basic ones for the tension and the compression (1) and (2), and with R = -1 – may be used to estimate the κ parameter magnitude. Thus, the data only being obtained in the process of qualification are sufficient to realize the procedure under consideration and no additional experimental studies are needed excepting Miner's sum what about will be given hereunder. Seven parameters are to be altogether obtained for each tested concentrator: $\sigma_{в+}$, σ_{c+}, $\sigma_{в-}$, σ_{c-}, $m_{-\infty}$, m_0 and m_{-1} ($\sigma_{в+}$ and $\sigma_{в-}$ – are the component ultimate strength under tension and compression correspondently) or only five parameters are to be obtained if the experimental data allow plotting the S-N curve through the ($\sigma_{c+} = \sigma_{в+}$ and $\sigma_{c-} = \sigma_{в-}$) ultimate strength magnitude. It is to pay attention that all the values both of the static strength and the fatigue one are to be obtained under comparable loading rates.

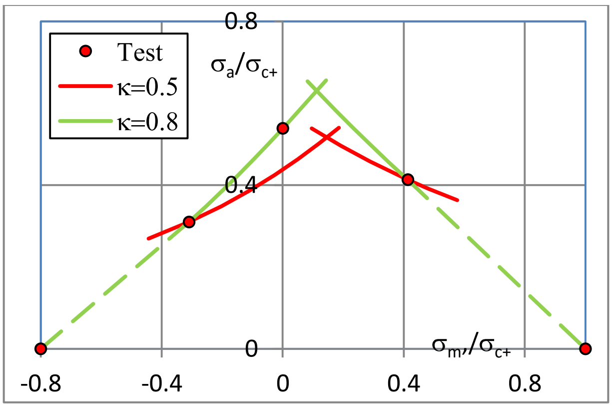

Fig.1

At presence of all constants the constant life diagrams take the form as presented in the Fig.1. In $1 \le R \le \infty$ and $0 \le R \le 1$ ranges the graph is approximated by the linear relationship. The graph in the Fig.1 shows that the application of the $\kappa = 0.5$ gives the most pessimistic results. Thus, the use of the procedure proposed requires no extension of the test program on account of tests under other stress ratio except those ones marked in the Fig.1 as based on the data, which we have, the relationships (3) and (4) make it possible to justify reliably the life characteristics in $-\infty \le R \le 0$ range and the loads in $0 \le R \le \infty$ range damage insignificantly the aerostructures, although the measure of this effect must be determined later on.

2.3 Fatigue Damage Accumulation Model

In order to evaluate the damage of loading cycles with different parameters under irregular loading impact two approaches were used: the linear damage accumulation rule (LDAR) and the strength degradation model.

Accordingly to the linear damage accumulation rule the failure occurs when the D_i total fatigue damages reaches the A critical value:

$$\sum_i D_i = \sum_i \frac{n_i}{N_i} \ge A\,, \qquad (5)$$

n_i – is a number of cycles at the i loading step;

N_i – is a number of cycles to failure at the regular loading level of i-step;

A – is a test parameter that was called a Miner's sum and that depended on the material, concentrator type and loading program parameters.

The strength degradation model [5, 6] describes the residual strength behavior as:

$$\sigma_{u,i} = \sigma_{c-} - \sum_i (\sigma_{c-} - \sigma_i) \cdot \left(\frac{n^*_{i-1} + n_i}{N_i} \right)^{\nu}, \qquad (6)$$

σ_u – is a residual strength;

σ_i – is stress at the i-th step;

ν – is an empirical constant that in general case depends on σ_i loading level. Under $\nu = 1.0$ the relationship (4) is transformed into the linear strength degradation model on the number of cycles [7]:

$$\sigma_{u,i} = \sigma_{c-} - \sum_i (\sigma_{c-} - \sigma_i) \cdot \left(\frac{n_i}{N_i} \right), \qquad (7)$$

n^*_{i-1} – is a number of cycles that corresponds to the $\sigma_{u,i-1}$ residual strength level at the $(i-1)$-th level under effect of the σ_i stresses of i–th level by the relationship as follows:

$$n^*_{i-1} = N_i \left(\frac{\sigma_{c-} - \sigma_{u,i-1}}{\sigma_{c-} - \sigma_i} \right)^{\frac{1}{\nu}};$$

The failure takes place when the $\sigma_u \le \sigma_i$.

3 Fatigue evaluation procedure verification

To verify the fatigue evaluation procedure the experimental studies results are used that are given in FAA reports [8 ÷ 11] that contain the description of the completed cycle of works devoted to the CFRP components fatigue resistance (strip with hole and impact damage) under irregular loading. Among the parameters under consideration there were the load type, the load level and the sequence of different levels loads as well as the loading spectrum modification effect. Sufficiently vast amount of work has been carried out to determine the behavior of two abovementioned concentrators under regular loading and irregular one. At this the authors faced one of the main problems that occur when determining the current CFRP components fatigue resistance parameters. It is conditioned by the significant difference of strength characteristics of the matrix and the reinforcement. This difference is caused by the carbon fibers strength enhancement during the last twenty years. Therefore if previously the primary matrix failure in form of its local transversal and longitudinal cracking resulted into the rapid fibers degradation and consequently to the total specimen failure by the mode that corresponds to the loading type (eg. for the specimen with hole under tension-to-fracture along the hole cross-section) then nowadays the fibers do not lose integrity right up to the total matrix failure in the specimen material large volume (eg. the total failure of matrix in 90 layers under tension). It is such a failure of matrix but not of the reinforcement that now must be a criterion for specimen failure. At this the specimen visual failure signs are practically absent right up to specimen's utmost condition. Correspondingly, if previously during the fatigue tests the number of cycles up to specimen total failure or up to the change of its definite stiffness limit was recorded and the S-N curves were plotted based in these data, then nowadays the simple quantitative criteria of specimens matrix failure (delamination) under fatigue loading are absent as the existing NDT methods (ultrasonic and X-ray inspection tomography and so on) do not allow providing the contiguous control of the specimen condition.

The paper [11] has given the data of testing two groups of specimens of 9 items (strip with open hole) per each under loading by modified TWIST with/without reduction. The reduction consisted in exclusion of two steps with minimal load from loading. Table 1 demonstrates the initial data and the results of calculated fatigue estimation of the specimen with open hole for the not-reduced program. The analysis of data obtained under regular loading showed that $\kappa = 0.66$, but taking into consideration the small amount of experimental data all the calculations were carried out when using two κ values that were 0.5 and 0.8. The initial data on loading that are given in Table 1 from paper [11] were used for the ($\sigma_{m\ fl}$) averaged flight stress that corresponded to 32.5% from the ultimate strength under compression. The S-N curve parameters values are as follows: $m_{-\infty}$ =26.4 under κ = 0.5 and $m_{-\infty}$ =29.2 under κ = 0.8. The “% vs total” table columns show the single step damage percentage vs the total of block; k_{mII} – is the coefficient by which the $\sigma_{m\ fl}$ value is multiplied for the i-th loading step. D_i – is a damage of the i-th loading step. Based on the results of calculation the main part of block damage (about 60%) is formed by the single maximal cycle with amplitude of $1.6\sigma_{m\ fl}$, and the first two loading steps that are composed of three cycles contribute more than 90% of total block damage. At this six bottom steps of loading that

Table 1

# step, i	k_{mll}	n_i	σ_{ai}	$\sigma_{\min i}$	$\sigma_{\max i}$	R_i	Damage of step			
							κ =0.5		κ =0.8	
							D_i	% vs total	D_i	% vs total
1	1.6	1	183	-297	68.4	-4.3	0.182	63%	0.0245	60%
2	1.5	2	171	-285	57.0	-5.0	0.0926	32%	0.01345	33%
3	1.3	5	148	-262	34.2	-7.7	0.0117	4.0%	0.00207	5.1%
4	1.15	18	131	-245	17.1	-14.3	0.00343	1.2%	0.00075	1.8%
5	0.99	52	113	-227	-1.14	199	0.00049	0.17%	0.00015	0.36%
6	0.84	152	95.8	-210	-18.3	11.5	0.00006	0.020%	0.00003	0.07%
7	0.68	800	77.6	-192	-36.5	5.3	0.00001	0.002%	0.00000	0.012%
8	0.53	4 170	60.5	-175	-53.6	3.3	0.00000	0.000%	0.00000	0.002%
9	0.37	34 800	42.2	-156	-71.9	2.2	0.00000	0.000%	0.00000	0.000%
10	0.22	358 665	25.1	-139	-89.0	1.6	0.00000	0.000%	0.00000	0.000%
Fatigue, blocks							3.4		24.4	

represent 398 639 of 398 665 block cycles contribute less than 1% of damage and may be excluded from the loading program without spoiling the test accuracy.

Based on the data (Table 1), the calculation in accordance with the algorithm proposed shows that the average fatigue of the samples under consideration is from 3.4 up to 24.4 blocks in dependence on κ parameter value. The average fatigue that is obtained experimentally with taking into account the censored sampling is 7.41 blocks under $S_{\lg N}$ = 0.264. Thus, the average value of the experimental fatigue lies in rated values scatter band and taking into consideration the S-N curve power exponent high values the agreement between the calculated data and the experimental ones may be regarded as good (A evaluation is within the 0.3 ÷ 2.1 range). Additionally, the fatigue scattering under regular loading had been obtained, which turned out to be higher than under the more complex one. The supplementary experimental studies only can answer the question whether this is regularity for CFRP or not.

Currently the experimental and calculation activities start devoted to development and verification of the procedure that provides the life characteristics of the airframe primary CFRP components. Hereunder the first research results are given as the investigation program is far away from completion. The fatigue tests were carried out of specimens with open hole under regular loading with three stress ratio: R = 20, -6, -1. The tests were performed under the same loading rate.

Fig.2 shows the experimental data (dots) for all three ratio and the S-N curves (lines) that approximate them in form as " $\sigma_{\min}/\sigma_{c-}$ – cycles" relationship. Fig. 3 shows the same data and the design S-N curve (red line) but in the reference, where the equivalent stresses by dependence (3) are placed on the ordinate axis. The summarized S-N curve was plotted by least-squares method by dependence (1); at this the κ parameter was determined by the maximum of the R^2 determinacy coefficient of this dependence and was found out to be equal to κ=0.927.

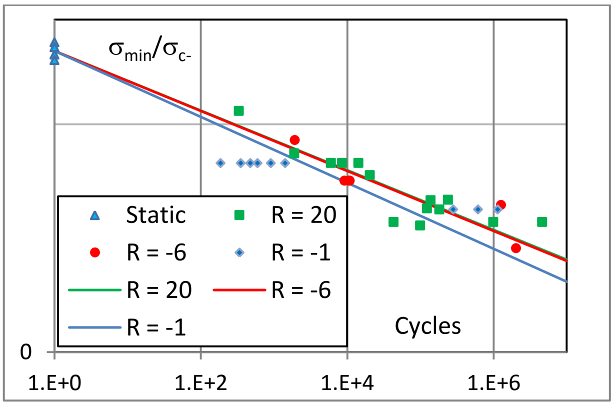

Fig. 2. Experimental data for three asymmetries and the S-N curves that approximate them

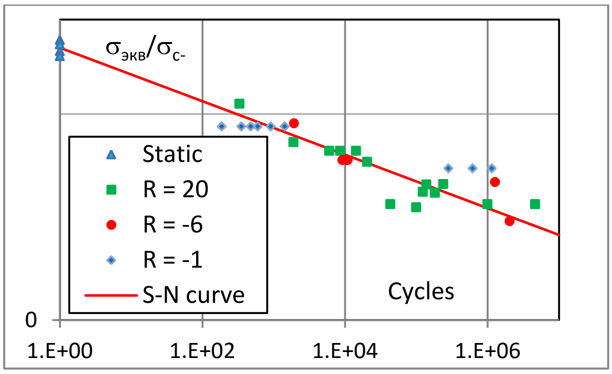

Fig. 3. Design S-N curve and experimental data

Based on data (Fig.2 and Fig.3) it is possible to conclude that the use of Oding formula leads to the approximation of points with different ratio The obtained κ parameter value that is near 1 indicates the low influence of cycle mean value that follows from (3) as under $\kappa \to 1$ the value of $\sigma^*_{R=-\infty} \to abs\left(\sigma_{\min}\right)$. It's true at least for the material been tested in $-\infty \le R \le -1$ ratio range.

The investigation of loading irregularity effect was carried out using the loading program which was generated based on the civil airplane wing stress loading that is predicted for the standard flight. In major part of cases the program for ascending sequence of cycle's amplitudes was used. The low but numerous cycles are carried out at first, and then the more damaging not-numerous cycles follow. The selection of such a sequence was conditioned by the ease to register the tested loading block damage when the specimen failure, i.e. by the recoding of the number of the last cycle as when using the random sequence it would be necessary to register all the tested loading cycles. The loading was carried out by blocks per 60 000 cycles. The tests were performed with a few scaling factors by which all the extremums of program of loading were multiplied and that were chosen by the getting of experimental values into the range of $5\cdot10^4 \div 10^6$ cycles or of $5 \div 10$ blocks.

Fig.4 shows the design S-N curve and the tests results of irregular loads program under different scaling factors. The stress loading of specimens under irregular loading and with k_σ scaling factor was converted into the equivalent stresses by the relationship as follows:

$$\sigma^*_{k_\sigma} = k_\sigma \cdot \left(\frac{\sum \frac{n_i}{N_i}}{60\,000} \right)^{\frac{1}{m}} \cdot \sigma_{co-}, \qquad (7)$$

m and σ_{co-} – are design S-N curve parameters.

Fig 4 introduces the following notations:
"Regular" – are the experimental data under regular loading that are marked by symbols;
"Acs." – are experimental data under irregular loading (IRL) with ascending sequence of cycles;
"Desc." – are experimental data under irregular loading. The loading block was carried out in reverse order. The features of the loading program (the sequential order of cycles values) and the selected scaling factor level resulted into the fact that at this step all the specimens were destroyed after the first block testing under high loads of the second package and are shown in plot for information purpose.
The arrow shows the specimen without failure.

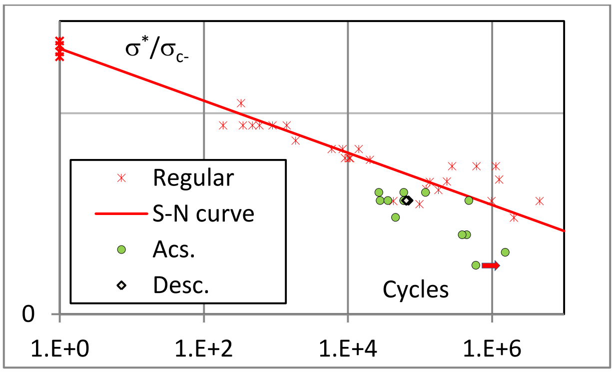

Fig. 4. Design S-N curve and test results under regular and irregular loading

Based on Fig.4 the mean value of A sum for the specimens been adopted as valid was 0.132 that is of good agreement with the recommendation [3, 5, 12] that for spectrum loading, a A of 0.1 was considered 'to be safe for the most cases. It is of interest that if to draw a straight line by the points of minimal fatigue at each level i.e. by the left boundary of experimental sampling it will be practically parallel with the design S-N curve. It means that, at least, the design S-N curve slope value under regular loading may be used for the effective slope of design `S-N curve by the minimal values. The effective slope of deemed

S-N curve is deemed to be an S-N curve slope been plotted by the tests results under irregular loading.

The similar calculation but using the (X.2) logarithmic relationship for the design S-N curve has brought to $A = 0.151$ somewhat higher value of Miner's sum. But this difference may be regarded as not essential and until the additional experimental data obtained it is possible to use the procedure to calculate the fatigue under irregular loading in compression area. This procedure comprises the use of relative linear damage accumulation rule (5) with $A = 0.1$, the Oding generalized formula (3) and the power approximation of the S-N curve (1).

The discrepancy between the test results under irregular loading and the LDAR calculation results is defined mainly by the fact that LDAR implies the independency of fatigue damage that is contributed by cycles with different levels of loading on this level and the lack of loading history effect on the damage. As a result LDAR does not describe the influence of different levels stresses effect sequence and presumes the damages accumulation rate under loading of some specified stress level to be identical independently of the previous loading history. The experimental data show that the stresses application order factually plays a significant role and that the damages accumulation rate under the specified stress level may depend on the loading history. The problem to understand the essence of these factors effect emerged for the first time when attempting to explain the behavior of metal structural components. The problem was successfully solved when including into consideration the residual stresses that emerged due the effect of the previous cycles that led to the significant reduction of experimental values scattering for fatigue sum A. The similar determining factor for CFRP is not still found out; therefore the different empirical relations are mainly used to solve the problem of evaluating the fatigue under irregular loading. Fig. 5 shows the tests results that are given in Fig.4 and the rated relations obtained by a number of approaches. Fig. 5 uses the same notations as Fig. 4 and the next ones:

"A=1" – is a calculation by linear damage accumulation rule with use of the $A = 1$;

"A=0.1" – is a calculation by linear damage accumulation rule with use of A=0.1 recommended (lower boundary);

"Asc.,l"– is an estimation of fatigue for the program with ascending sequence of loading cycles by use of relationship (7);

"Desc.,l" – is an estimation of fatigue for the program with descending sequence of loading cycles by use of relationship (7);

" Asc.,n"– is an estimation of fatigue for the program with ascending sequence of loading cycles by use of relationship (6) at $\nu = 0.3$;

" Desc.,n"– is an estimation of fatigue for the program with descending sequence of loading cycles by use of relationship (6) at $\nu = 0.3$.

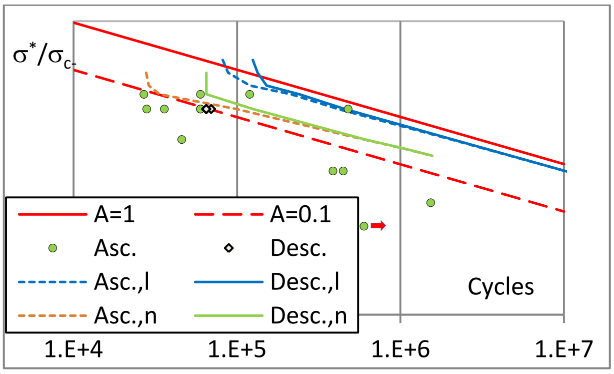

Fig. 5. Comparison of calculation results for different approaches of damages summation

The data (Fig.5) show that the use of the strength degradation model resulted into better agreement between experimental data and the computed ones especially when using the non-linear relationship (6) with $\nu = 0.3$ coefficient. At this, beyond the magnitude of ν the loading program with "ascending" sequence of loads is of lower fatigue that the "descending" one. This difference becomes more evident only on the basis of up to $1 \div 2$ flight blocks ($60\,000 \div 120\,000$ cycles) and is mainly explained by the ordered structure of the loading block. Due to this, e.g. when under "descending" sequence influence if the failure has not happened at the first cycle, the block as a whole will be tested without failure as the working stresses are descending in parallel to the residual strength decrease. When number of blocks is more than ten, the damaging effect of programs with different stresses interchange order becomes inessential and the curves for relationship (6) are transformed into curves which are practically parallel to the relationship being obtained by LDAR .

Summary

The analysis is carried out of fatigue tests results under regular and irregular loading of the CFRP specimens in form of strip with open hole. The analysis resulted into:

1 Based on performed researches outputs the preliminary conclusion is made up on the possibility to apply the approach that uses the approximation of S-N curve by the power dependence, the Oding generalized formula and the LDAR of $A = 0.1$ on order to evaluate the fatigue of CFRP structural components with concentrators in form of open hole. To make a final decision it is necessary to fulfill the planned amount of works devoted to define experimentally the fatigue characteristics of wing materials, which are manufactured by infusion technology and for all standard concentrators which specify the lifetime characteristics of the structure.

2 The application of the strength degradation model allows better describing the specimens' behavior under irregular loading as compared with the LDAR at $A = 1.0$, but in order to use it the specially planned experimental studies using sufficient amount of specimens are necessary to be performed.

3 The experiment-calculated activities performed have demonstrated that to proof the fatigue and the damage tolerance of CFRP airframe structure it is sufficient to apply the peak loads (e.g. ground-air-ground cycles only). The tests are recommended to be performed using the program of quasirandom GAG cycles loading which should be representative of the anticipated service usage.

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