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INSPECTIONS OF AIRCRAFT COMPOSITE COMPONENTS

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Inspections and intervals between inspections are often controlled by various parameters in the aviation industry. One of them is the method related to the p-set function, which determines the probability of crack formation and its impact on the service life of a component. It especially concerns polymer matrix composite components. Consequently, a deeper look into the basic principles and analysis of economics is needed, which will develop the theory and broaden the perspective from different angles.

Keywords: **fatigue, fracture, threshold, composites, strategy, analysis, economics**

INTRODUCTION

The evaluation of program development is usually based on the results of long-term tests of composites not only with a polymer matrix. On the other hand, estimating the mechanical or tensile strength properties of polymer [1] or metal matrix composite components or materials requires manufacturing quality (e.g. composite molding technology). Generally, the interval between inspections of components is used to estimate the distribution parameters so that the reliability indicators can be improved. Reliability and the probability of reliability are usually very difficult to determine. It especially concerns polymer matrix composite components, which are treated as brittle materials.

If some part of the reliability data and the system of its changes are used and no conditions are met, then there is a possibility that with minimal changes the ratability indicators independent of the unknown probability of confidence can be determined.

Over the past few years, a great deal of research has been conducted on the use of mobile expert systems and the estimation of critical failure rates for a component or information management technology in the area of non-intermodal transport. However, the practical literature poorly analyses the process of monitoring cargo conditions, cargo information security and other important issues [2-7].

MODEL FOR ESTIMATING REPAIR COSTS OF STRUCTURAL ELEMENTS OR COMPONENTS

A definition of *p-set* functions is developed, which is applied to prevent the development of problems and to control a certain inspection program [8]. This time, it is assumed that a structurally significant element whose failure is acceptable, that the entire system under consideration is characterized by a randomness vector (T_d, T_c), where T_c is assumed to be the critical failure index for the component, T_d is the service time when something failed, for example, a crack is applied to the material. A certain time interval is assumed and in that interval a check is made, during which a structurally significant failure will be eliminated. It is also assumed that the required operating time of the system is limited by the so-called specific lifetime, t_{SL}, when the system failed.

It is assumed that Z and X are randomly chosen vectors with m and n dimensions and that the class $\{P\Theta, \Theta \in \Omega\}$ on which the probability distribution of random vector $W = (Z, X)$ is known. Nevertheless, in relation to θ, as the distribution is labeled, all that is known is that it is in a certain set Ω, with a set of parameters.

$$S_z(x) = \bigcup_i S\, z_i(x) \tag{1}$$

In such cases, the values of the sets of dysfunctions of z values are determined as a function of x, then the statistically assumed function $S\_z\ (x)$ is a p-set function for a randomly assumed vector. Z is based on the model $(x = x_i\ \dots\dots, x_n)$.

$$\underset{\theta}{SUP}\ \sum_i P(Z \in S_{Z,i}(X)) \le p, \tag{2}$$

Here, vector $Z = (T_d, T_c)$ is interpreted as a random vector quantity for some of the systems of structural quantities. Observation vector X will be used to confirm the test result. It is assumed that $\breve{\theta} = \breve{\theta}x$ from parameter Θ, will not be considered in the calculations.

Nonetheless, part of $S_z(x) = \bigcup_i S\,z_i(x)$, is the sequence of intervals after which checks should be made. This sequence determines the test program under consideration. In the program of technological parameters, it is assumed that the size of the determined fatigue crack a_d is fixed [9].

Next, let us consider a minimal approach to verify the inspection program. Here it is necessary to solve the problem related to vector function $t(\breve{\theta})$, where $t = t_1, t_2, \dots, t_n)$, and where t_i is the moment of time for the inspection, while i = 1, 2,…n is the number of inspection. In the case of t_{n+1} = $\mathrm{t_{SL}}$, the probability of damage to a structurally significant element can be considered according to [9].

$t_{n+1} = t_{SL}$ does not reach a small size $\underset{\theta}{SUP}\; p_f(\theta, t) \le \varepsilon$, T_1 ... T_2, where those elements are taken as randomly selected inspections, or randomly selected vectors:

$$(T_1 \dots, T_n) = t\breve{\theta};\ T_0 = 0;\ T_{n+1} = t_{SL}, \tag{3}$$

This means that vector $\mathrm{t}\breve{\Theta}$ actually defines the p-set function for vectors (T_d, T_c), when $p = \varepsilon$. For this reason, the order in structure selection $t = (t_1, t_2, \dots, t_n)$ is a special problem. In this case, two existing problems are usually examined. This time the problem when t parameter Θ is unknown is considered, but the time when there may be a failure is known. The proposed mini-max approach can be applied to any structure of sequence t. In real practice, the following sequence is usually used:

$$t_i = t_1 + d(i-1),\ d = \frac{t_{SL} - t_i}{n},\ i = 1,2,\dots,n;$$

in this case we only need to choose t_1 and n. To simplify this equation, $t_1 = d$ in a simple case, which can be chosen without parameter p in relation to T_c, or as an a value corresponding to the minimum for the expected value of n at a fixed required confidence level, etc. Now the probability will be a function of Θ and n and denoted as $p_f(\theta, n)$. It is assumed that $p_f(\theta, n)$ will now be $\lim_{n\to\propto} p_f(\theta, n) = 0$, where all θ and for each small value of ε there will be a minimum number of inspection times $n(\theta\,,\varepsilon)$, as $p_f(\theta, n) \le n(\theta, \varepsilon)$ if $p_f(\theta, n) \le \varepsilon\varepsilon$, but all $n\ \ge n(\theta, \varepsilon)$. The real outcome of Θ is unknown. Then it must be assumed that $\acute{n} = n(\breve{\theta}, \varepsilon)$ and $\acute{p_f} = p_f(\breve{\theta}, \acute{n})$ are random variables. It is expected that commercial production and operations will commence only when certain requirements are met [9].

As an example, the following conditions can be considered: 1) $\acute{n} \le n_R$, 2) $\acute{t_c} \le t_R$…., where n_R, t_R, …., are constants defined in specific documents t_c, quantity T_c is expected.

If these conditions are met, then $\acute{\theta}\ \in\ \Theta$ where $\Theta_0 \in \Theta$ and becomes a part of the parameter. It is assumed that $\left(\breve{\Theta} \notin \Theta_0\right)$ will approximate the required number of checks for some fixed ε, for which the threshold n_R, is exceeded or the expected values of T_c, $\acute{t_c}$ are too small compared to t_R, then a redesign of the uses of the structural components is needed so that the probability of failure after this redesign is zero.

Let us define

$$\acute{p}_{f0} = \{\,\acute{p_f}(\theta, \acute{n}) \text{ if } \acute{\theta} \notin\ \Theta_0 \text{ and } 0 \text{ if } \acute{\theta} \notin\ \Theta_0\} \tag{4}$$

For the strategy type, the average fatigue failure probability $w(\theta, \varepsilon) = E_\theta \acute{p}_{f0}$ is a function of Θ and ε. If a limited t_{SL} has its maximum regardless of ε, then to reach its maximum size $\varepsilon = \varepsilon^*$ at which $w^* = \max w\ (\theta, \varepsilon^*) \le 1 - R$, the strategy that determines the checks number $n = n(\acute{\theta}, \varepsilon^*)$ can be obtained.

A strategy that has the required reliability R can be obtained with the following approximations, which are usually used for the fatigue crack propagation function:

$$\begin{aligned}&\alpha(t) = \alpha(0)/(1 - \mu(a(0))^\mu Qt1)^{1/\mu} = \\ &\alpha \exp(-(\log(\,1 - \mu\omega Qt))/\mu), ja\ \ \mu \ne 0,\end{aligned} \tag{5}$$

or $a(t) = \alpha \exp(Qt)$, if $\mu = 0$ where $a(t)$ is the fatigue crack size at time t (the number of flights); $\alpha = a\ (0)$, μ, Q are parameters of the fatigue crack growth model $\omega = \alpha^\mu$, parameter α is the so-called equivalent initial flow size; μ depends on the material properties, technology and structure, while Q depends on the mode [10].

Generally, it is assumed that all structurally significant elements have the same stress level. This assumption allows these fatigue cracks to be considered as observations of the same random process and a corresponding vector parameter of the fatigue for crack estimates ($\acute{\alpha}$, Q') which enables observation of the random vector with the same control defect fatigue. This fatigue crack should be known to model the fatigue crack test result. It is very difficult to form for a three-dimensional vector (α, μ, Q). Therefore, it will only be considered as the case of an exponential fatigue crack, where $\mu = 0$, as follows:

$$\log(a(t)) = \log(a) + Q(t) \text{ or } y = y_0 + y_1 x \tag{6}$$

$$y = \log\,(a(t)), y\_0 = \log\,(\alpha), y\_1 = Q, x = t \tag{7}$$

The parameter estimates Y_0, Y_1 can be easily obtained using regression analysis as well as from the results of the fatigue tests of specimens with the fixed initial flow size $\log(a(t)/a) = Qt$, or $y = Y_1 x$, where $y = \log(a(t)/a)$, $Y_1 = Q, x = t$. The estimated Q can again be easily obtained using regression analysis. Finally, the equation gives us a quite understandable result in the range of observations $\{T_d, T_c\}$, where T_d is the time when the crack can be detected, and T_c is the time period when the crack reaches its critical threshold value. Then with this function, the following can be determined:

$$T_d = (\log a_d - \log \alpha)/\, Q = C_d/Q \tag{8}$$

$$T_c = (\log a_c - \log \alpha)/\, Q = C_c/Q,$$

where a_d is the critical size if the probability of its detection is equal to unity. a_c is the crack size corresponding to the minimum residual strength of the aircraft component allowed by the special design regulations [11].

If these conditions are not met, time and money will be lost due to late identification of the defect.

SWOT ANALYSES FOR COST ESTIMATION

In the next step, the cost of lining the rail flanges will be considered for the case of a crack occurring and the parts needing replacement. The strengths and weaknesses of the flange cladding will be investigated with SWOT analysis, which is often used in economics. First, let us consider the SWOT analysis for the moving part of the rail flange structure, including the construction and logistics functions.

Strengths:

- Ease of identifying failure related to the operational process of the structure
- Parts are made from available materials
- The procurement process can be performed in a fast time frame
- AMM (Aircraft Maintenance Manual) and FIM (Fault Isolation Manual) work assignments do not allow a long period of time.

Weaknesses:

- Influence of external conditions on the mechanism in case of failure (wear and tear)
- Dependence on the operating parameters recommended by the manufacturer and the duration of the work
- In case of no contract with the component manufacturer or supplier, delivery may take longer.

Opportunities:

- Before the time of failure, get the parts from the warehouse, so they can be replaced right away
- Predict the frequency and time frame of replacements from the technical side of the engineers
- Keep track of changes in the market segment and reduce delivery costs
- Successfully use testing opportunities.

Threats:

- As a result of the development of failure mechanisms, no more new materials are produced
- The element may have more failures than in previous periods of the duty cycle
- Changes in the global situation affect the market, which increase supply and component costs.

REPAIR COST ESTIMATION

When considering the repair strategy, the economic justification of the cost of the component needs to be taken into account. Looking at the above-mentioned influencing factors and mathematical calculations, an incorrect distribution of work and inspections makes the operation more expensive and over time creates additional costs for the company (related to the SWOT analysis factors).

In order not to incur unnecessary costs and ensure that the total investment costs are minimal, (which are directly or conditionally related to the availability of material and the provision of logistics services), the total costs associated with the operating materials and services depending on the availability of components need to be determined.

The total investment cost, C_Σ, includes operating costs, material supply and logistics costs as well as the invested capital. C_1 is the cost of purchasing the and repairing the component. Operating expenses, in connection with the replacement of mechanism components are denoted as C_2. Next, C_3 represents the costs for repair of the composite shell cladding, while C_4 is the logistics delivery costs (linked with the need to receive the necessary parts) and other unexpected additional costs are C_5 [12].

First, let us consider C_1, i.e. the cost of purchasing the parts and repairing the component, which is calculated as:

$$C_1 = \frac{C_m \sum_{i=1}^{n_j} t_s}{3600 m_p} + \frac{100 C_{val} \sum_{i-1}^{n_j} t_s}{365 T_m * a_{fre} * 3600 m_p} * E_n \tag{9}$$

where: C_m – cost of a given component, in monetary units, t_s – average working time for the component, duration of the i-th work cycle h; E_n – regulatory coefficient of the efficiency of capital investment. C_{val} – value of component, a_{fre} – component frequency coefficient, T_m – work in hours (h), which must be done to replace the part, m_p – ratio of the number of parts needing replacement to the total number of parts replaced during a replacement task, n_j – quantity required for the construction.

The operating expenses and capital investment are tied to the number of hours spent on component replacements and inspection costs:

$$C_2 = \frac{l_m}{m_p * n_{del}} \left(C_m + \frac{C_{p.k.}}{v_t}\right) + \frac{C_{p.k} * t_s}{m_p * n_{ie}} \tag{10}$$

where: l_m – component replacement time [h]; v_t – component operation time in cycles [h]; C_m – variable costs; $n_{del} = \frac{q^* * \gamma_q}{m_p + * n_j}$ average value of material delivery speed average value; q^* – material delivery time; γ_q – material utilization factor.

$$C_{p.k.} = C_p + \frac{100 C_a * E_N}{365 \alpha * T_N} \tag{11}$$

where: $C_{p.k.}$ – independent costs and capital investment; C_p – fixed costs; C_p – value of component, α – component replacement intensity value; T_N – average time required for component replacement, repair in h; $t = n_j * t_s$ – idle time while the part is being replaced and the aircraft does not fly, h.

The costs for repairs of composite shell cladding C_3 are as follows:

$$C_3 = \frac{100A_k * \lambda_K * n_j * t_{gl}(C_{one} + E_N * C_{one})}{365m_p}, \tag{12}$$

where: A_k – cost size of the carbon fiber component in Euro; λ_K – coefficient that determines the frequency between replacements; t_{gl} – component storage time between replacements; n_j – component repair costs per time unit; C_{one} – one-time payment if the entire component is replaced; E_N is 0.15 (adopted for capital investment [12]).

The logistics costs associated with the on-time delivery of parts and their capital investment are:

$$C_4 = \frac{l_p}{q * \gamma_{st} * \beta}\left(C_m + \frac{C_{p.k.}}{v_t}\right) + \frac{C_{p.k} * t_s}{q * y_{st}} \tag{13}$$

where: l_p – cost for delivery of one part; q – quantity of parts delivered at one time; γ_{st} – statistical coefficient; β – supply utilization factor; C_m – variable costs in Euro; $C_{p.k.}$– independent costs and capital investment; t_i – idle time, h.

$$C_5 = \frac{100n_j * C_{Kj} * (E_N + 0.01\, H_{amor})t_{av}}{365m_p * \alpha_k} \tag{14}$$

where: C_{Kj} – component j-type value in Euro; H_{amor} – amortization or depreciation costs expressed as % of the value of the component; t_{av} – average type of material circulation.

The most efficient way that ensures the lowest costs is chosen. This means, that if the technical costs of one part are known, it is possible to determine the rational structure, which will be $C_\Sigma = f(m_p)$. The required quantity of components is given below:

$$Z_a = \frac{N_a^g * T_{ap}^a * k_a}{T_v * m * n_a * k_n} \tag{15}$$

where: N_a^g – the required volume that is replaced at one time, T_{ap}^a – duration from the moment of sending the part to receiving it:

$$T_{ap}^a = \frac{L_p}{v_a} + t_{ds} \tag{16}$$

where: L_p – total time to deliver the part; average time to make a delivery; t_{ds} – idle time; T_v – time required for repairs to be carried out; m – number of hours needed for replacement [h]; k_n – coefficient that determines depreciation; k_a – coefficient if additional unforeseen repair conditions are detected. This means that if unforeseen circumstances occur, the total cost values will increase. Ensuring the required number of component replacements gives:

$$n_k = \frac{(1 + k_r)Q_g * t_{del}}{365q_k} \tag{17}$$

where: Q_g – component replacement frequency, h; q_k – component average replacement frequency; t_{del} – time required to deliver parts (from order to delivery); k_r – part number.

In the SWOT analysis, the threats can be considered and some of them are directly related to the costs of the repair of the damaged composite shell cladding C_3[12].

$$C_3 = \frac{A_{kj} * \lambda_K * n_j * t_{gl}(C_{k.p.} + E_N * C_{one})}{365m_p} \tag{18}$$

where: A_{kj} – cost of the carbon fiber component in Euro; λ_K– coefficient that determines the frequency between replacements; t_{gl} – component storage time between replacements; C_{one} – one-time payment if complete replacement of the cladding is made [12].

RAIL FLANGE REPAIR COST ESTIMATION BASED ON SWOT ANALYSIS

The SWOT analysis of composite materials is based on an undetermined state of material failure prediction, which includes an increase in all costs. The rail flange component weaknesses and strengths are as follows:

Strengths:

- Carbon fiber reinforced polymer shell lasts a long time
- Replacement does not take long if the cover is in stock

Weaknesses:

- The effect of carbon fiber reinforced polymer external conditions on the shell can be critical
- The occurrence of a crack in a carbon fiber reinforced polymer shell may be detected in time
- Component or carbon fiber reinforced shell may take a long time to find and deliver
- Repairs to a carbon fiber reinforced polymer shell can be very expensive
- The types of testing recommended by the manufacturer may require a great deal of work
- Shell repair can take a long time, up to 6-12 months

Opportunities:

- From an engineering point of view, predict the frequency and speed of crack development for carbon fiber reinforced polymer
- Listen to information from other operators
- Keep track of changes in the market and reduce delivery/repair costs
- Develop technological investigations

Threats:

- As a result of crack development, there may be a shortage of manufacturers that supply the materials

- Cracks can occur when they collide with other bodies, which causes a long inspection phase
- Replacement covers may not be available on the market
- The time for maintenance checks specified by the manufacturers takes a long time
- Changes in the global situation affect the transportation and materials market, costs increase.

Regarding the previous information, according to the SWOT analyses, more information is available about the component weakness and strength characteristics as well as mathematical and physical data about the material. In the next steps, rail flange repair cost summarizing is done. Please note that all the prices and working hours are considered in approximate terms, as per the following examples:

$$C_1 = \frac{43000*5*10}{3600*10} + \frac{100*38000*5*10}{365*4*3*3600*10} * 5 =$$

$$= 5972 + 1204 = 60924 \quad \text{(Euro)} \qquad (19)$$

The capital investment is linked with the number of hours spent on component replacements and inspection costs:

$$C_2 = \frac{4}{10*0.3}\left(1000 + \frac{6000}{100}\right) + \frac{1000*20}{10*0.3} =$$

$$= 1.33 * 1060 + 6666 = 80764 \text{ (Euro)} \qquad (20)$$

The costs for repairs of composite shell cladding C_3 are as follows:

$$C_3 = \frac{100*4000*0.3*5*5000*(10000+0.15*600)}{365*10} =$$

$$= 739726 \text{ (Euro)} \qquad (21)$$

The logistics costs associated with on-time delivery of the part, C_4 are:

$$C_4 = \frac{8000}{5*0.4*0.8} * \left(1000 + \frac{6000}{100}\right) + \frac{1000*72}{5*0.4} =$$

$$= 5000 * 1060 + 3600 = 5303600 \text{ (Euro)} \qquad (22)$$

Capital investment C_5:

$$C_5 = \frac{100*5*10000*(0.15+0.01*35)*3000}{365*10*100} =$$

$$= 2136.96 \text{ (Euro)} \qquad (23)$$

Calculation of the costs of material delivery and all the related costs is possible. The calculation costs can be determined when the materials and components are not used or an aircraft is on the ground.

CONCLUSIONS

The repair costs and delivery times can affect the costs of aircraft operation. All the composite material deliveries cost more than the system-related components. Once a change of components is needed when the aircraft is on the ground, the cost can double, and so can delivery costs. Taking into account the nature of composite materials and the difficulties in delivering them, it is necessary to consider that the calculated delivery time and cost can double. To avoid delays, as mentioned above, the cost of repairs can be calculated using p-set functions, which help reduce the costs of the items. At the same time, the time period can be calculated when cracks are noticed in the material, and also by using SWOT analysis, information can be collected about the economic aspect of changing parts.

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