Polskie Towarzystwo Materiałów Kompozytowych
Polish Society of Composite Materials

26: 1 (2026) 1–10

COMPOSITES
THEORY AND
PRACTICE

ISSN (online): 2299-128X

Anwar Zabirov[1], Vladimir Shestakov[1], Rafał Chatys[2], Zariw Zabirov[1]

[1] *Riga Technical University, Aviation Transport, Riga LV-, Latvia*
[2] *Kielce University of Technology, 25-314, Kielce, Poland*
Correspondence: anvarzabirov@yahoo.com, shestakov@inbox.lv, chatys@tu.kielce.pl

Received (Otrzymano) 6.10.2025
Published on-line (Opublikowano) 31.03.2026

NUMERICAL MODEL OF AIRCRAFT TECHNICAL MAINTENANCE OPERATION PROCESS ESTIMATING IMPACT OF REPAIRING COMPOSITE STRUCTURES ON AIRPORT DEPARTURE DELAYS

https://doi.org/10.62753/ctp.2026.05.1.1

This article presents the results of analyses of aircraft emergency state changes during flight (S1 ... S4 in section 1.1), which will help refine the models of aircraft technical operation processes at airports within a given airline network to enable continued flight. Therefore, in-flight aircraft state changes are eliminated because equipment failures (i.e. aircraft state changes) occur at each stage of the aircraft's flight, requiring fault resolution. Hence, the aircraft's transition through the states during a single flight is presented in the form of a graph. The operational management circuit of the airline's aircraft fleet is represented as a sequence of flights, each consisting of a series of segments between airports within the airline's network within the calendar timeframe of the aircraft's presence in that circuit. The model allows assessment of the aircraft's ability to recover, if necessary, at airports within the airline's network, utilizing the probabilistic and temporal characteristics of the recovery processes employed by airports, which pose a risk of flight delays. Recovery time must be considered to assess the probability and duration of flight delays.

Keywords: aircraft, composite structures, operational management, polymer matrix components, technical operation

INTRODUCTION

The issue of aircraft safety is of crucial importance. Due to the widespread use of composites for the production and repair of airplanes, those materials play a crucial role in ensuring their safe operation. Rośkowicz and Smal [1] experimentally analyzed the durability of composites used to expedient the repair of damaged aircraft components. The authors applied numerical calculation as well experimental tests and proved that the failure of aircraft components is linked with local loss of stability in the case of the aircraft's skin, and stiffness in the case of girders and beams. Recently, Li et al. [2] presented a new approach to quantitatively evaluate the repair tolerance of composites in civil aircraft using the Bayesian updating method. It was reported that this method, proposed in conjunction with extensive simulations as well as full utilization of field damage inspection data, may efficiently simulate unexpected impact damage situations which can happen during civil aircraft service. It can also evaluate the economic feasibility and reliability of the repairs. Equally recently, Liao et al. [3] developed a method based on image visual recognition technology with the aim to detect defects in aircraft fuselages produced from composite materials. The authors integrated a drone and a thermovision camera for real-time image transmission to ground stations. Moreover, MATLAB image analysis software was utilized to analyze thermovision images and detect structural defects. The authors claim that it offers rapid detection and addresses blind spots in aircraft inspections.

Moreover, the use of various models for aircraft maintenance, operation and rotation is widespread in aviation. It also contributes to improving aircraft safety. Yousefi et al. [4] proposed a three-step methodology for risk assessment considering probability, location, in addition to the consequences of accidents by means of advanced statistical methods. The authors proposed novel models for the implementation of these three steps in a selected airport. Li et al. [5] presented a new dynamic runway overrun risk assessment model based on data collected from the quick access recorder (a device which monitors and records flight parameters). The model was evaluated against real data from a Chinese airline. In [6] a dataset of almost three hundred accident/incident investigation data was used as training samples, which was later applied to develop a data-driven Bayesian network model by means of machine learning for dependency intensity assessment and inference analysis. Chen et al. [7] presented a corrected SHELLO model employed to classify the causes of civil aviation accidents in China. The authors also presented an improved entropy gray correlation algorithm and applied it to identify and rank the key causative factors of flight accidents. On the other hand, a simulation model was developed in [8]. Its aim was to simulate aircraft rotation in a multiple airport environment. The obtained simulation results were compared with actual data in order to validate the effectiveness of the model. Very recently, Aljaly et al. [9] developed an integrated five-step framework that combined a failure mode as well as effects analysis with the "Define–Measure–Analysis–Improve–Control" method to systematically address and reduce a selected issue of aircraft maintenance.

Failure states in flight refer to the condition of the aircraft and its crew in the event of an abnormal situation resulting from the failure of an aircraft component. A failure situation is characterized by changes in the flight characteristics of the aircraft and the state of the crew. Each of these states has its own level of danger in terms of completing the flight without aviation incidents. The degree of danger of a failure state will quantitatively depend on the degree of danger of the failure itself.

The current paper presents a model for the change of aircraft state during one of the flights of the route. The model takes into account peculiarities regarding the composites' structures in such a sense that aircraft is mainly composed of composite materials.

METHODOLOGY

General information

The technical operation of an aircraft encompasses ground maintenance of the aircraft, and airborne technical operation during flight [10]. Each of these aspects is characterized by its own set of states, represented as graphs with specific nodes and transitions [11, 12]. The nodes of the graph correspond to tasks, and the edges represent relationships between tasks. Graphical models allow the identification of quantitative relationships between the nodes to enhance the processes of aircraft technical operation using statistical research methods. States occurring during the ground maintenance of the aircraft are not considered here as they are fully addressed in [12, 13]. Let us delve further into the states of the aircraft during flight [14, 15].

The "state of the aircraft in flight" denotes a situation that arises when the aircraft, operating in normal flight mode (denoted as S0), is subjected to one or more adverse factors that lead to a reduction in flight safety such as damage to the composite structure of the aircraft. The problem of failure accumulation in the composite (in the structure) is related to the occurrence of defects (microcracks) in the neighborhood of the main crack, interaction of the developed crack or the multiplication of microcracks in the damaged area.

The analyses in this area were based on a continuum approach of a uniform material (through the stiffness theory [16]) and the specific location of the microcrack.

The method of determining these damages and the process of their summation is most often related to the course of changes in the properties of the tested polymer-based components or composites during the fatigue process by damage function D, which depends on the level of applied stress [17, 18]:

$$D = F(\sigma, n, T, w, \ldots) \tag{1}$$

where:

σ – applied level of stress (usually σmax) or another controlling quantity

n – number of fatigue cycles completed

T – temperature

w – humidity.

One method for estimating damage accumulation, or summing up fatigue damage in materials [19, 20], is finite chains and Markov processes [21, 22]. The term “chains” refers to the case of a discrete time parameter, and the term “process” refers to the case of a continuous parameter. Structural failure occurs after the destruction of a critical microvolume composed of longitudinal fibers or fiber bundles (operating in the elastic range) and a brittle matrix in which plastic deformations accumulate during cyclic loading (i.e. the matrix and other layers with an alignment angle different from that of the fibers operating along the fiber axis).

As a result of cyclic loading, the number of elements operating in the elastic range capable of absorbing stress is reduced by a certain value r_R, causing damage to the elements operating along the fiber axis, until the entire structure slowly fails.

The states are defined by the number of damaged elements along the axis (case A) and the yield stress number r_Y (case B). The probability transformation matrix can be represented as a set of (r_Y+1) blocks of (r_R+1) internal states for each block. Indices *i* and *j* represent the input and output states, by indices i_Y, i_R, j_Y, and j_R, using the formula:

$$i = (r_R + 1)\,(i_Y - 1) + i_R\,;$$
$$j = (r_R + 1)\,(j_Y - 1) + j_R\,, \tag{2}$$

The above events correspond to transition states recorded using a Markov chain. The symbolic matrix filling for the case ≥ 2 is shown in Table 1. It needs to be emphasized that maintenance states occurring during aircraft ground maintenance are performed through specific flight cycles (i.e. cyclic interactions: such as temperature or structural fatigue). The proposed model, in the form of a probability matrix (Table 1), is one example of such an estimation of fatigue of an aircraft component or subassembly through the accumulation of damage in a composite structure, which affects flight safety.

TABLE 1. **Example of structure of probability transformation matrix [19, 21]**

		j_Y	*1*			*2*			*3*		
		j_R	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
i_Y	**i_R**	**i \ j**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	*1*	**1**	$p_{R0}p_{Y0}$	$p_{R1}p_{Y0}$	$p_{R2}p_{Y0}$	$p_{R0}p_{Y1}$	$p_{R1}p_{Y1}$	$p_{R2}p_{Y1}$	$p_{R0}p_{Y2}$	$p_{R1}p_{Y2}$	$p_{R2}p_{Y2}$
	2	**2**	0	$p_{R0}p_{Y0}$	$p_{R1}p_{Y0}$	0	$p_{R0}p_{Y1}$	$p_{R1}p_{Y1}$	0	$p_{R0}p_{Y2}$	$p_{R1}p_{Y2}$
	3	**3**	0	0	1	0	0	0	0	0	0
2	*1*	**4**	0	0	0	$p_{R0}p_{Y0}$	$p_{R1}p_{Y0}$	$p_{R2}p_{Y0}$	$p_{R0}p_{Y1}$	$p_{R1}p_{Y1}$	$p_{R2}p_{Y1}$
	2	**5**	0	0	0	0	$p_{R0}p_{Y0}$	$p_{R1}p_{Y0}$	0	$p_{R0}p_{Y1}$	$p_{R1}p_{Y1}$
	3	**6**	0	0	0	0	0	1	0	0	0
3	*1*	**7**	0	0	0	0	0	0	1	0	0
	2	**8**	0	0	0	0	0	0	0	1	0
	3	**9**	0	0	0	0	0	0	0	0	1

The symbols pR0 and pR1 denote the probability of failure corresponding to the number of elements operating in the elastic (rigid) state, and pY0 and pY1 denote the probability of failure of the corresponding numbers in case B, whose elements operate in the plastic (yielding) state. The authors of [19-21] assumed that the number of elements operating in the elastic state destroyed after a single step has a binomial distribution, while the number of elements operating in the plastic state has a log-normal distribution.

In the following discussion, unfavorable factors are treated exclusively as aircraft equipment failures that result in aircraft failures in flight [22, 23].

Failure states in flight are classified based on the degree of danger of their consequences as shown in Table 2.

TABLE 2. **Overview of failure states [22]**

State	Characteristics
1	Failure states that do not affect flight safety, i.e. they do not have an adverse impact on the operational capabilities of the aircraft or increase the workload on the crew [24, 25] – failure states without complicating flight conditions (S_{NR}).
2	Failure states that slightly decrease the safety of the aircraft in flight and require actions from the crew that are within their capabilities. These states are characterized by a minor reduction in safety margins or functional capabilities, a slight increase in crew workload, or some physical discomfort for passengers – failure states with complicating flight conditions (S_1).
3	Failure states that significantly reduce the aircraft's capability or the crew's ability to cope with adverse operating conditions. These states involve a noticeable decrease in safety margins or operational capabilities, a significant increase in crew workload, deterioration of conditions for passengers or flight attendants, possibly causing injuries – complex states (S_2).
4	Failure states that diminish the aircraft's capabilities or the crew's ability to handle adverse conditions to such an extent that it leads to: - deterioration of working conditions or excessive workload to the point where it cannot be ensured that the flight crew will fulfill their tasks accurately and completely - serious or fatal injuries to a relatively small number of non-flight crew members on board – emergency states (S_3).

Failure states leading to disasters with numerous casualties usual result in the loss of the aircraft. In the event of such a situation, preventing a catastrophe becomes a practically improbable event, requiring exceptional skill and selflessness from the crew. Let us try to determine the above-mentioned catastrophic states that a structure made of various polymer-based components (e.g. composites, honeycomb sandwich cores, etc.) may encounter during operation.

We know that the use of composite materials depends largely on their strength, stiffness, and integrity under specific operating conditions throughout their service life. Based on the failure states presented above (Table 2), Table 3 identifies defects (in the structure or components) that can contribute to critical situations during flight.

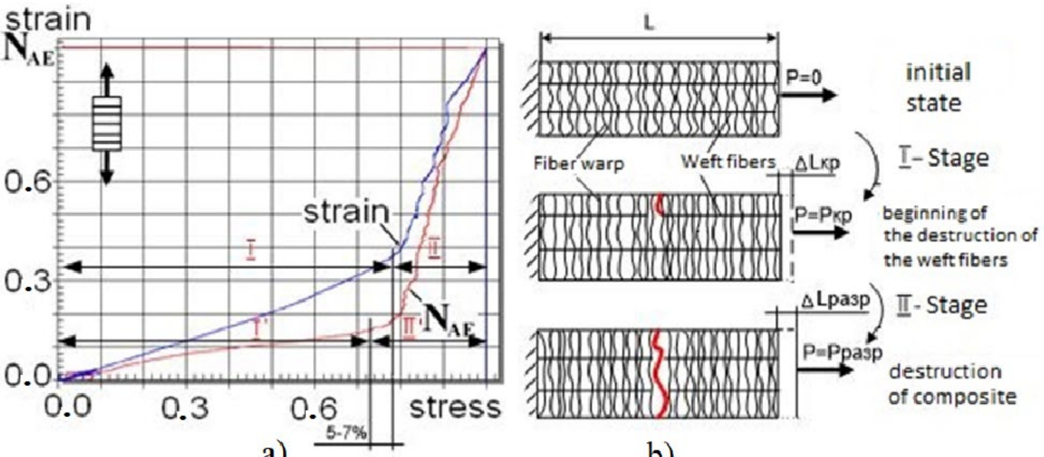
TABLE 3. **Defects in polymer matrix components according to the European Aviation Safety Agency guidelines for composite aircraft structures [26]**

State	Defect characteristics
1	Defects that are not relevant to flight safety include: surface inaccuracies (structure of structural elements) such as laminate surface ripples or slight resin bubbles in non-structural zones.
2	Defects of limited significance to flight safety that may locally affect properties (but without the risk of failure) include: small resin losses in the laminate structure without damaging the supporting fibers (e.g. in the structure of an aircraft wing), or local delaminations (e.g. aerodynamic fairings up to 10 mm).
3	Defects such as the delamination of layers in the laminate (in lightly loaded areas – parts of the tail, covering, etc.), or small cracks in the sandwich core (around mounting holes), or inclusions of foreign bodies (e.g. air bubbles), which can be eliminated by the application of a patch with gluing.
4	Defects that reduce load-bearing capacity and fatigue life pose a threat to flight safety. These include: extensive laminate delamination in stressed areas; crushing or loss of adhesion of the honeycomb core in a sandwich structure beneath the skin surface and to the skin, respectively – e.g. in a wing or stabilizer; cracking or destruction of load-bearing fibers; and puncture of the laminated skin due to bird strike, ice shard, or tool impact.

Before being used in aircraft technology, components made from these materials (as well as metal-matrix components) are subjected to inspection processes. Experimental methods such as photoelasticity, strain gauges, Moiré methods, and holography [27] play a significant role in monitoring the fracture process of composites or laminates. Unfortunately, they do not solve problems related to micro-level damage.

It seems that a more accurate determination of fracture mechanisms and deformation to determine the strength of composites is provided by the acoustic emission method, highly sensitive to fracture mechanisms at the micro level [28], which is very important, especially in the case of civil and military flying objects such as UAVs, aircraft, rockets or guided missiles.

During the testing of glass fiber laminate samples [29], with a transverse fiber arrangement and the presence of both warp and weft fibers, a two-stage nature of deformation (up to tensile strength – Fig. 1) was revealed for both the deformation parameters (sections I and II) and the total acoustic emission parameters (sections I’ and II’). The stage of proportional change of these parameters with stress (sections I and I’) and the stage of their intensive increase characterize the beginning of the process of irreversible destruction of the composite (sections II and II^1).



a) b)

Fig. 1. (a) Graphical representation of changes in total acoustic emission and strains as a function of stress with marked process stages, (b) proposed mechanism of composite failure in cross-section of base fibers relative to tensile force at main stages [29]

Thus, the presence of weft fibers, along which the loading process takes place, leads to load regrouping (load redistribution) on the weft fibers themselves or on the matrix. In Fig. 1, the process of irreversible deformation (the second stage of composite fracture) begins at approximately 0.8 and 0.75 times the critical (breaking) stress in the deformation parameter (the boundary of sections I and II) and in the total acoustic emission parameter (the boundary of sections I1 and II1), respectively, which corresponds to 40% of the breaking load.

The presence of a list of failures permissible for flight (not only in relation to the materials) enables the classification of acceptable states of the aircraft in flight concerning the arising need for aircraft recovery at airports within the airline network [22, 25]:

S0 – The aircraft has no detected failures.

S1 – The aircraft has at least one detected failure that causes minor complicating flight conditions but does not threaten flight safety. Such a defect could be a growing crack in the structure of the elevator (or rudder or aileron) made of a polymer matrix composite, which results in a loss of controllability of the aircraft. If the above defect does not significantly degrade the strength properties of the component, we assume condition S2.

S2 – The aircraft has at least one detected failure that complicates flight conditions but allows the aircraft to be used until the next line maintenance. However, when the above defect significantly deteriorates the strength properties of a given component, we assume the S3 condition.

S3 – The aircraft has at least one detected failure potentially threatening flight safety but allows the aircraft to be used until reaching the base airport.

S4 – The aircraft has at least one detected failure for which the flight of the aircraft is not permitted. Such a failure may be a breach of the composite sandwich structure in the aircraft wing structure. Locating damage in the honeycomb core [30, 31] in the form of a warp crack, fiber breakage, or delamination was one of the causes of the 2005 crash of the Grumman G-73T Turbo Mallard (N2969) seaplane operated by Chalk's Ocean Airways [32]. The accident commission identified a fatigue crack in the lower spar as the main cause of the crash, which had been previously hidden under a layer of sealant (in the S2 version), resulting in separation of the wing.

Flight structure of the airline

Each flight of the airline's aircraft, considering intermediate stops between the base (origin) and final destination airports, consists of N individual (discrete) n flights [33]. Parameter n represents the flight number in the given route, taking values from the sequence of integers, $n \in \{1, \dots ,N\}$. The flights in a route are conducted between airports of different types. In this study, all the airports included in a route are divided into three categories based on the aircraft recovery possibilities in case of need:

- ***B*** – Base airport. It serves as the origin and destination airport in any flight
- ***T*** – Transit airport
- ***TB*** – Transit base.

The overall duration of aircraft recovery is described by the recovery time distribution function, $F_{(t)}$, for the corresponding airport type. If spare parts are not available, they are delivered through available channels. The delivery time is determined by distribution function $G_{(t)}$ for the corresponding airport type. Individual flights between airports are separated by turnaround time intervals, T_S. At any stage of the airline network aircraft's flight, equipment failures (changes in the aircraft's condition regarding the strength, stiffness and integrity of its composite materials in certain working conditions throughout the operation time or time of repairs and maintenance) are possible, requiring the elimination of failures (aircraft recovery) to allow it to continue the flight. Thus, a change in the aircraft's state in flight requires aircraft recovery at the airline's network airports, posing a risk of flight delay. The recovery time must be considered to assess the probability and duration of flight delays. The article presents a mathematical model of the aircraft state changes during a flight, including the assessment of recovery possibilities at the airline's network airports in case of need [34].

Probability indicators used in qualitative and quantitative analysis of failure states in flight

In the case of quantitative analysis, probability indicators are expressed as acceptable ranges of average probability per hour of flight or per flight. These probabilities are used in the design of aircraft with more than one engine, considering the expected operating conditions of the aircraft and the crew's actions according to the flight operations manual. Normative documents utilize the following classification [22, 25]:

1. Common failure states, S_{NR}, that do not affect flight safety, i.e. they do not have an adverse impact on the operational capabilities of the aircraft and do not increase the workload on the crew. Their probability of occurrence is the magnitude of $P_{NR} \leq 10^{-3}$ per hour of flight (one flight).
2. Probable failure states (Probable) S_1, whose occurrence is expected one or more times during the total service life of a specific aircraft. The probability of occurrence does not exceed the magnitude of $P_1 < 10^{-4}$ per hour of flight (one flight).
3. Remote failure states (Remote) S_2, whose occurrence on each aircraft is hardly possible throughout its entire service life, but which can occur several times over the total service life of a specific fleet of aircraft of the same type. The average probability of occurrence is on the order of $P_2 < 10^{-5}$ per hour of flight (one flight – increasing cracking of the composite structure).
4. Extremely remote failure states (Extremely remote) S_3, whose occurrence is not anticipated on each aircraft during its entire service life but may occur a small number of times when considering the total service life of all aircraft of the same type. The average probability of occurrence is $P_3 < 10^{-6}$ per hour of flight (one flight).
5. Practically improbable failure states (Extremely improbable) S_4, whose occurrence is not anticipated during the entire service life of all aircraft of the same type. The average probability of occurrence is $P_4 < 10^{-7}$ per hour of flight (one flight – it should be mentioned that the structural components made of laminates or polymer matrix components, e.g. wings, meet the given condition).

It should be noted that the absence of an approved list of failures leads only to states S_0, S_1, S_2, and S_{NR}. In summary, we will use the established upper limits for the probability of failure states per flight as [23, 24]:

- For catastrophic failure states – $P_4 < 10^{-7}$
- For hazardous failure states – $P_3 < 10^{-6}$
- For complex failure states – $P_2 < 10^{-5}$
- For failure states with complicating flight conditions – $P_1 < 10^{-4}$
- For failure states without complicating flight conditions – $P_{NR} < 10^{-3}$

Thus, the possible transitions of the aircraft through states S within one flight can be represented in the form of a graph under the following conditions, as shown in Fig. 2:

- In-flight, the aircraft state does not improve.
- Departure for a flight (i.e. from a type ***B*** airport) is allowed only in states S_0, S_1 and S_2.
- Departure for a flight from type ***T*** and ***TB*** airports is allowed in states S_0, S_1, S_2, and S_3.

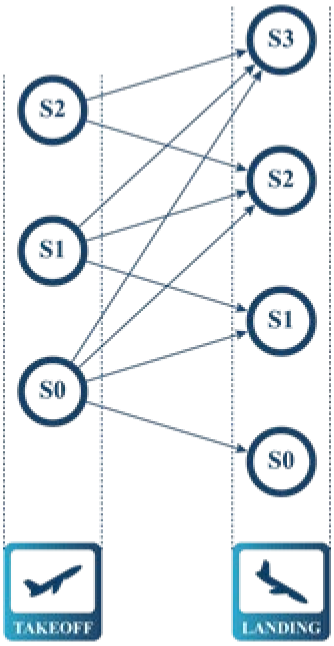


Fig. 2. Transition of aircraft stages at takeoff and landing

*State S_{NR} is not included in the graph as it does not affect flight safety, and the aircraft can perform flights in this state until the engineering and technical service makes the necessary decision.

In order to assess the probability of departure delays at the airports within the airline network, it is necessary, based on the approaches outlined above, to develop mathematical models for the change of the aircraft's state over the time it stays within the operational management contour during a flight:

- Model of aircraft state changes in one of the flights of the route
- Model of aircraft state changes during a flight
- Model of aircraft state changes within the sequence of flights during the time spent in the operational management contour of the technical operation process of the aircraft.

Due to the limited scope of the article, a model for the change of aircraft state during one of the flights of the route is proposed. It needs to be added that other types of coatings (apart from composite layers) could also be considered as part of the aircraft elements [35, 36].

Model of aircraft state changes

Each flight consists of a sequence of $\boldsymbol{N}$ individual flights, separated by layover intervals at type $\boldsymbol{T}$ airports [28, 34]. Let $\boldsymbol{\eta}$ denote the state of the aircraft at the beginning of the flight. The possible values of $\boldsymbol{\eta}$ (Figure 2) will be states $\{\boldsymbol{S_0}, \boldsymbol{S_1}, \boldsymbol{S_2}\}$. Let $\boldsymbol{q_0}, \boldsymbol{q_1}, \boldsymbol{q_2}$ represent the probabilities that the aircraft at the beginning of the flight is in states $\boldsymbol{S_0}, \boldsymbol{S_1}, \boldsymbol{S_2}$, respectively. This can be expressed as:

$$P\{\eta = S_j\} = q_j; \textstyle\sum_j q_j = 1; j = 0,1,2 \tag{3}$$

The state of the aircraft at the beginning of the flight is, thus, a random variable with a set of states $\{\boldsymbol{S_0}, \boldsymbol{S_1}, \boldsymbol{S_2}\}$ and a probability distribution (3). Let ξ denote the state of the aircraft at the end of the flight. The possible values of ξ (Figure 2) will be states $\{\boldsymbol{S_0}, \boldsymbol{S_1}, \boldsymbol{S_2}, \boldsymbol{S_3}\}$.

Let $\boldsymbol{p_0}, \boldsymbol{p_1}, \boldsymbol{p_2}, \boldsymbol{p_3}$ denote the probabilities that the aircraft at the end of the flight is in states $\boldsymbol{S_0}, \boldsymbol{S_1}, \boldsymbol{S_2}, \boldsymbol{S_3}$ respectively. This is expressed as:

$$P\{\xi = S_j\} = p_j; \textstyle\sum_j p_j = 1; j = 0,1,2,3 \tag{4}$$

The state of the aircraft at the end of the flight is a random variable with four possible states $\boldsymbol{S_0}, \boldsymbol{S_1}, \boldsymbol{S_2}, \boldsymbol{S_3}$ and a probability distribution (4).

Let us denote as the conditional probability that the state of the aircraft at the end of the flight becomes $\boldsymbol{S_i}$, given that its state was $\boldsymbol{S_j}$ at the beginning of the flight. Such conditional probabilities $\boldsymbol{p_{ij}}$ possess the property [15,37].

$$\textstyle\sum_{i=0}^{3} p_{ij} = 1; j = 0,1,2 \tag{5}$$

Some of the values of $\boldsymbol{p_{ij}}$, according to the scheme in Figure 2, will be equal to zero.

All the mentioned elements $\boldsymbol{p_{ij}}$ are placed in a rectangular matrix $\boldsymbol{P}$ of size 4 x 3, which is called a transition matrix or a matrix of transition probabilities for changing the states of the aircraft from the beginning to the end of the flight.

$$P = \begin{pmatrix} 1 - p_{10} - p_{20} - p_{30} & 0 & 0 \\ p_{10} & 1 - p_{21} - p_{31} & 0 \\ p_{20} & p_{21} & 1 - p_{32} \\ p_{30} & p_{31} & p_{32} \end{pmatrix} \tag{6}$$

The probabilities of the initial states ($\boldsymbol{q_j}$) and final states ($\boldsymbol{p_j}$) are expressed in the form of probability state vectors:

$$p = \begin{pmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{pmatrix}, q = \begin{pmatrix} q_0 \\ q_1 \\ q_2 \end{pmatrix} \tag{7}$$

Then, the relationship between vectors $\boldsymbol{p}$ and $\boldsymbol{q}$ is given by the formula, which can be succinctly expressed in matrix form as:

$$p = Pq \tag{8}$$

Conditional probabilities $\boldsymbol{p_{ij}}$ are considered given and are associated with the reliability level of the operated fleet of aircraft, as well as the justification of the list of permissible aircraft failures before reaching the type $\boldsymbol{B}$ airport and/or the next periodic maintenance of the aircraft. Thus, probabilities $\boldsymbol{(1 - p_{00}) = p_{10} + p_{20} + p_{30}}$, $\boldsymbol{(1 - p_{11}) = p_{21} + p_{31}}$, $\boldsymbol{(1 - p_{22}) = p_{32}}$ represent the probabilities of failures occurring in flight under the condition of the aircraft taking off into flight in states $\boldsymbol{S_0}, \boldsymbol{S_1}, \boldsymbol{S_2}$, respectively. Probabilities $\boldsymbol{p_{00}}, \boldsymbol{p_{11}}, \boldsymbol{p_{22}}$ represent the non-occurrence of failures in flight under the condition of the aircraft taking off into flight in states $\boldsymbol{S_0}, \boldsymbol{S_1}, \boldsymbol{S_2}$, respectively.

Ratios $\boldsymbol{\frac{p_{32}}{p_{30}}}, \boldsymbol{\frac{p_{31}}{p_{30}}}, \boldsymbol{\frac{p_{21}}{p_{20}}}$, which are by definition greater than or equal to one, can be considered as characteristics of the justification of the list of permissible failures for states $\boldsymbol{S_2}$ and $\boldsymbol{S_1}$, respectively. The lists are considered justified if these ratios are equal to one.

Using known reliability theory indicators [37, 38, 39], the expressions for $\boldsymbol{p_{00}}$ can be written in the following form:

$$p_{00} = e^{-\omega T_{BP}} \tag{9}$$

where $\boldsymbol{T_{BP}}$ is the average duration of a non-stop flight of an aircraft in the airline network, and $\boldsymbol{\omega}$ is the parameter of the aircraft failure rate in flight, given takeoff into flight in state $\boldsymbol{S_0}$.

If at the end of one of the flights the aircraft is in state $\boldsymbol{S_3}$, it must undergo restoration directly in that airport. After such restoration, the flight continues. Nevertheless, there may be a delay in departure at the restoration airport. The developed model applies to one of the flights of the route.

SUMMARY AND CONCLUSIONS

The proposed approach, based on the use of graphs, contributes to the development of models to improve the process of the technical operation of aircraft within the framework of operational management, taking into account the accumulation of defects and damage in structures made of polymer matrix components. The developed models allow evaluation of the processes of aircraft recovery and the occurrence of departure delays at the airports within the airline network using statistical research methods. The necessity of aircraft recovery at the airports within the airline network is driven by the occurrence of aircraft states in-flight associated with technical failures, leading to flight delays.

The authors highlight two main mechanisms for the development of such delays. The first one is associated with the mechanism of delays for airports of all types regarding the probability of including the aircraft in the flight. If exclusion takes place, the departure time is determined by the probability of the availability of a reserve aircraft for the flight, P_{res}. If a reserve aircraft is unavailable, the recovery mechanism is implemented by using the necessary spare parts available at the airport. The other mechanism for airports of types "$\boldsymbol{T}$" and "$\boldsymbol{TB}$" implies that:

- the overall duration of aircraft recovery in this case is described by distribution function of recovery time $\boldsymbol{F(t)}$ for the corresponding type of airport.
- if spare parts are unavailable, their delivery is carried out through available channels. The delivery time is specified by distribution function $\boldsymbol{G(t)}$ for the corresponding type of airport. In this case, the overall duration of aircraft recovery is the sum of the durations of $\boldsymbol{F(t)}$ and $\boldsymbol{G(t)}$ for the corresponding type of airport.

If the total recovery duration does not exceed the aircraft's stand time **(**$\boldsymbol{T_{ST}}$**)** at the airport, no departure delay occurs. Otherwise, the delay duration is determined as the difference between the overall recovery duration of the aircraft and its stand time **(**$\boldsymbol{T_{ST}}$**)**.

REFERENCES

[1] Rośkowicz M., Smal T., Research on durability of composite materials used in repairing aircraft components, Eksploatacja i Niezawodnosc – Maintenance and Reliability 2013, 15(4), 349-355.

[2] Li X., Zuo H., Yang B., Repair tolerance assessment for aircraft composite structures using Bayesian updating, Chinese Journal of Aeronautics 2024, 37(6), 360-391, https://doi.org/10.1016/j.cja.2024.03.038

[3] Liao K.-C., Liou J.-L., Hidayat M., Wen H.-T., Wu H.-Y., Detection and Analysis of Aircraft Composite Material Structures Using UAV, Inventions 2024, 9, 47. https://doi.org/10.3390/inventions9030047

[4] Yousefi Y., Karballaeezadeh N., Moazami D., Sanaei Zahed A., Mohammadzadeh S.D., Mosavi A., Improving Aviation Safety through Modeling Accident Risk Assessment of Runway, Int. J. Environ. Res. Public Health, 2020, 17, 6085. https://doi.org/10.3390/ijerph17176085

[5] Li X., Zhang L., Shang J., Li X., Qian Y., Zheng L., A Runway Overrun Risk Assessment Model for Civil Aircraft Based on Quick Access Recorder Data, Appl. Sci. 2023, 13, 9828. https://doi.org/10.3390/app13179828

[6] Lu N., Meng B., Risk Analysis of Airplane Upsets in Flight: An Integrated System Framework and Analysis Methodology, Aerospace 2023, 10, 446. https://doi.org/10.3390/aerospace10050446

[7] Chen N., Sun Y., Wang Z., Peng C., Identification of flight accidents causative factors base on SHELLO and improved entropy gray correlation method, Heliyon 2023, 9(2), e13534. https://doi.org/10.1016/j.heliyon.2023.e13534.

[8] Wu C-L., Caves R.E., Modelling of aircraft rotation in a multiple airport environment, Transportation Research Part E: Logistics and Transportation Review, 2002, 38(3–4), 265-277. https://doi.org/10.1016/S1366-5545(02)00010-8.

[9] Aljaly K., Masmoudi F., Aljuaid A.M., Hachicha W., Addressing Aircraft Maintenance Delays Using a DMAIC-FMEA Framework: Insights from a Commercial Aviation Case Study, Appl. Sci. 2025, 15, 12164. https://doi.org/10.3390/app152212164

[10] Kinnison H.A., Siddiqui T., Aviaton maintenance management, Publisher McGraw-Hill Education (Second Edition), 2013. https://commons.erau.edu/publication/1538/

[11] Smirnov N., Chinyuchin Yu., Modern Problems of Technical Operation of Aircraft, Moscow, MGTU GA, 2007.

[12] Smironov N., Methodology for performing practical exercises on the discipline Fundamentals of the theory of technical operation of aircraft and aircraft engines, Moscow, 2003. http://storage.mstuca.ru/jspu/bitstream/123456789/4441/1/00700014950022009001792.pdf

[13] Ickovic A. A., Fajnburg I. A., Management of aircraft technical operation processes (Управление процессами технической эксплуатации летательных аппаратов). Moscov, MGTU GA, 2012.

[14] Vaivads A., Tereščenko J., Shestakov V. A., Model of Interconnection Between Aircraft Equipment Failures and Aircraft “States” in Flight. Transport and Aerospace Engineering, 2018, 6, 30-36. https://doi.org/10.2478/tae-2018-000

[15] Fleet Maintenance Seminars, Airline Maintenance Program Development – BOEING. Commercial Aviation Services, May 4–8, 2015 Seattle, Washington U.S.A.

[16] Htchinson J.W., Act Metall, 35, 1987, 1605-1619.

[17] Dobryniewski K., Wyznaczanie stałych materiałowych kompozytu warstwowego o różnych współczynnikach wypełnienia, Kompozyty 2004, 12, 439-443.

[18] Bełzowski A., Metoda oceny wytrzymałości długotrwałej kompozytów polimerowych, Kompozyty 2002, 2, 38-41.

[19] Paramonov Yu.M., Kleinhof M.A., Paramonova A.Yu., Markov Model of Connection Between the Distribution of Static Strength and Fatigue Life of a Fibrous Composite, Mech. Compos. Mater. 2006, 42(5), 615-630.

[20] Chatys R., Investigation of the Effect of Distribution of the Static Strength on the Fatigue Failure of a Layered Composite by Using the Markov Chains Theory, Journal Mechanics of Composite Materials 2012, 48(6), 911-922.

[21] Paramonov Yu., Chatys R, Andersons J., Kleinhofs M., Poisson process of defect initiation In fatigue of a composite material, Proc. of XI International Conference on “Reliability and Statistics in Transportation and Communication – RelStat`11”, 20-23.10.2011, Riga, Latvia, 1-10.

[22] Easy Access Rules for Generic Master Minimum Equipment List (CS-GEN-MMEL), Powered by EASA eRules Page 2 of 65| Feb 2018.

[23] Helmreich R., Klinect J., Models of threat, error, and CRM in flight operations, Proc. of the Tenth International Symposium on Aviation Psychology, The Ohio State University 2010. https://www.researchgate.net/publication/255628975_Models_of_threat_error_and_CRM_in_flight

[24] Bogdane R., Vaivads A., Dencic D., Evaluation of Management System Effectiveness in the Preparation of the Aircraft for Flight in Faulty Conditions, Transport and Aerospace Engineering 2015, 2, 1. https://doi.org/10.1515/tae-2015-0002

[25] Aviation Regulations Part 25 - Airworthiness Standards for Transport Category Airplanes, Interstate Aviation Committee, Edition 5 with Amendments 2015, 1–8. https://www.ecfr.gov/current/title-14/part-25

[26] EASA AMC 20-29 - Composite Aircraft.

[27] Urbahs, A., Banovs, M., Harbuz Y., Turko, V., Feshchuk, Y., Khodos, N., Investigation of Mechanical Properties of Composite Materials Using the Method of Acoustic Emission, Proc. of 16th International Conference Mechanika 2011, Lithuania, Kaunas, 7-8 April 2011, 306-310.

[28] Urbahs A., Banovs M., Harbuz Y., Turko V., Feščǔks J., Khodos N., Estimation of Mechanical Properties of the Anisotropic Reinforced Plastics with Application of the Method of Acoustic Emission, Abstracts of 2nd International Specialized Symposium “Space & Global Security of Humanity”, Latvia, Rīga, 5-9 July, 2010, 93.

[29] Nechval K., Chatys R., Petukhov I., Alexander Bain New Approach for an Inspections Program and use of C-Factor Model for Stress Analysis of Composite Component Structure, Composite Theory and Practice 2024, 24(3), 205-212. https://doi.org/10.62753/ctp.2024.07.3.3

[30] Zhang H., Wang X., Guo Z., Qian Y., Shang Y., Cai D., On impact damage and repair of composite honeycomb sandwich structures. Materials 2023, 16(23), 7374. https://doi.org/10.3390/ma16237374

[31] Liu J., Chen W., Hao H., Wang Z., Numerical study of low-speed impact response of sandwich panel with tube filled honeycomb core (Numeryczne badanie odpowiedzi na uderzenie przy niskiej prędkości płyty warstwowej z rdzeniem o strukturze plastra miodu wypełnionym rurką.), Compos. Struct. 2019, 220, 736-748.

[32] Aircraft Accident Report National Transportation Safety Board A Notation 7756D Adopted May 30, 2007 N 490 L’Enfant Plaza, S.W. Washington, D.C. 20594, In-flight Separation of Right Wing Flying Boat, Inc. (doing business as Chalk's Ocean Airways) Flight 101 R S A Grumman Turbo Mallard (G-73T), N2969 Port of Miami, Florida December 19, 2005, pp. 1-63.

[33] Sales M., Aviation Logistics 2016. https://www.amazon.com/Aviation-Logistics-Dynamic-Partnership-Freight/dp/0749472707

[34] Skuratov K., Directions of interaction between airports and airlines as participants in the aviation market, 2009. https://cyberleninka.ru/article/n/napravleniya-vzaimodeystviya-aeroportov-i-aviakompaniy-kak-uchastnikov-aviatsionnogo-rynka/viewer

[35] Piotrowski J.Zb., Orman Ł.J., Lucas X., Zender – Świercz E., Telejko M., Koruba D., Tests of thermal resistance of simulated walls with the reflective insulation, Proc. of Int. Conf. “Experimental Fluid Mechanics 2013”, Czech Republic, EPJ Web of Conferences 2014, 67, 02095. https://doi.org/10.1051/epjconf/20146702095

[36] Radek N., Konstanty J., Pietraszek J., Orman Ł.J., Szczepaniak M., Przestacki D., The Effect of Laser Beam Processing on the Properties of WC-Co Coatings Deposited on Steel, Materials 2021, 14, 538. https://doi.org/10.3390/ma14030538

[37] Rausand M., Barros A., Hoyland A., System Reliability Theory: Models, Statistical Methods, and Applications, 2020. https://doi.org/\10.1002/9781119373940

[38] Beck J., McLoughlin B., Maintenance Program Enhancements, Boeing – AeroMagazine 2006, 04, 24-27.

[39] Smironov N., Manual on performing practical classes in the discipline: Fundamentals of the theory of technical operation of aircraft and motorized vehicles, Moscow, MGTU GA-2003.