DEVELOPMENT OF STRUCTURAL HEALTH MONITORING METHODS THROUGH THE ANALYSIS OF KINETICS OF LOCAL STRESS-STRAIN STATE

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Abstract

The application of tensometry as one of the most promising ways to maintain airworthiness under the conditions of strength of modern passenger aircraft is considered. The results of the application of local stress-strain state control during full-scale fatigue tests of fuselage panels with joints are presented. The method of monitoring according to the data of strain measurement taking into account the requirements for the strength of the damaged structure under irregular operational loading is developed. The method of monitoring according to the data of strain measurement taking into account the requirements for the strength of the damaged structure under irregular operational loading is developed. The possibility of monitoring multi-point cracks that occur in the longitudinal joint and cannot be detected in a timely manner by visual inspection methods is considered.

1 Introduction

The difficulties of creating an optimal aircraft design are primarily due to the solution of a wide range of tasks, each of which cannot be considered separately from the whole set of problems solved at the stage of designing aircraft (A/C). One of the main contradictions that must be resolved by the aircraft developer is the creation of an aircraft structure with a minimum weight and ensuring damage tolerance that is, giving the structure the property to withstand non-critical damage, taking into account the required level of safety. At present, the safety of the resulting damage is ensured by periodic and special forms of control, the mandatory nature and composition of which is regulated by the basic regulations in force in the aviation industry [1].

Operational inspection is aimed at timely detection of damage in the most critical elements and involves a certain type of study of structural integrity, taking into account the probability of damage, as well as the growth rate of the characteristic defect. Visual inspection is the preferred method, but a significant part of the damages that are located in places where there is no direct access for external inspection cannot be detected by visual methods.

The problem of researching the integrity of these places can be solved by means of additional forms of control, which involve the use of special equipment and, in most cases, the dismantling of certain elements to investigate the places most vulnerable to corrosion and fatigue within the power structure. Even though the fact that the instrumental control implies long intervals between inspections, the use of special equipment, disassembly of external components and downtime of aircraft due to routine maintenance work associated with research and repair of structure, make up a significant item of expenditure in the operation of A/C [2].

Alternative method of implementing the requirements arising from a damage tolerance approach is condition-based maintenance. The basis of this method is the constant acquisition and analysis of information about the state of the structure, accumulated by the health

monitoring system (HMS). Prevention of dangerous damage should be based on the results of this analysis.
At the moment, in the operation and flight tests of modern transport aircraft, some mainly test HMS are used. The purpose of the application of these HMS lies in the solution of special problems, due either to the peculiarity of the tasks of the aircraft, which leads to the necessity of taking into account for in-flight damage using load monitoring, or design features of the aircraft, which requires the introduction of additional monitoring of individual places (table 1).

Table 1 Examples of HMS, introduced into operation of some aircraft

The name of the system (A/C)	Tasks of HMS
SMN-200 - System of Load Monitoring (Be-200ChS)	Collection of data needed for fatigue damage estimation; Checkout of load limits
LTMS – Life Time Monitoring System (A400)	Optimization of the service schedule using flight data
TSI – Tail Strike Inspection (A340-500/600)	Inspection the integrity of the tail part of the plane

2 The structure of the health monitoring system

Theoretically, the organization of the system should be a kind of human body, where sensors act as sense organs and the analyzing and predicting functions of the human brain performs a special computing device that accumulates and processes information.
The instruments used on board shall enable an objective assessment of the integrity of the structural elements and shall be part of the aircraft's standard equipment. Sensors and systems must have the following properties:

- high durability of system components;
- no negative impact on the integrity and strength of the structure;
- maintainability and/or duplication elements of the system;
- small volume and weight;
- safety for the health of passengers;
- possibility to expand the list of inspection places.

One of the most promising methods that have been tested both in full-scale tests, and in the service of the aircraft, is the monitoring the local stress-strain state using strain gauges (SG). At the moment, there is no technical possibility of implementing a uniformly distributed sensor location scheme that could meet the requirements considered. The most rational, according to the author, is the approach in which the locations of the sensors are determined based on the analysis of the places of stress concentration and loading of individual elements of the A/C. Taking into account these features allows to estimate the speed and critical size of damage in different places of the structure, which will ensure the timely detection of damage with a minimum number of sensors, that is, will help to form an optimal scheme of their placement.

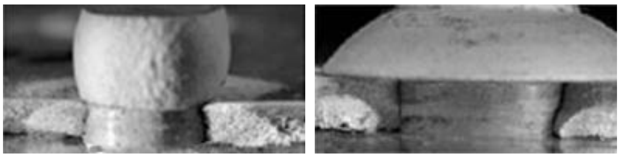
3 Determination of the parameters of the health monitoring system based on the analysis of tensometry

The control and analysis of the kinetics of the local stress-strain state can be carried out with the help of strain gauges placed on the structure: wire SG or fiber Bragg grating sensors [3]. The relative change of the SG readings obtained from the readings at the beginning and during the test or operation is used for the analysis:

$$\bar{\varepsilon} = \left|\Delta\varepsilon/\varepsilon_1\right| \cdot 100\% \leq \bar{\varepsilon}_{th} \qquad (1)$$

where $\bar{\varepsilon}_{th}$ – the threshold value of the local relative deformation, which is selected experimentally taking into account the error of determining the operating loads (according to the results of work [3] the value $\bar{\varepsilon}_{th}$ is taken not less than 15%); $\Delta\varepsilon$ – the difference between the readings of the SG at the first and last tensometry, $\Delta\varepsilon = \varepsilon_n - \varepsilon_1$ with the same loads, n – the number of measurements taken during the tests.
The prospect of using monitoring with help of monitoring stress-strain state was investigated during fatigue tests of longitudinal joints. Lap

joint of the sheets of the fuselage skin is one of the most important places of aviation design, fatigue of which limits the service life of modern A/C [4].



(a) (b)

Fig. 1 View of fatigue cracks located in the rivet area at the initial stage of growth

The most vulnerable fatigue site of the longitudinal fuselage joint is the last most remote from the edge of the bearing sheet a row of rivets. As a rule, the growth of fatigue cracks occurs in the plane perpendicular to the surface of the sheets, which passes in the space between the centers of the holes and the edges of the rivet heads in the fastening row. The shape of the fatigue crack at the initial stage of growth depends on the place of its origin. As a rule, the cracks formed on the edge of the hole have the form of a quarter of a circle or an ellipse (fig. 1 (a)), cracks growing closer to the edge of the rivet head have a semicircular shape (fig. 1 (b)). The main factor affecting the region of crack origin and hence its initial shape is the force that compresses these two sheets. The final shape of the cracks at destruction depends on the duration of the crack growth. Large fatigue cracks in the longitudinal joints may not appear on the outer visible surface of the joint until the final destruction. The presence of possible visually undetectable cracks makes it necessary to find additional ways to check the integrity of the longitudinal joints.

The feasibility of the use of checkout methods based on the analysis of the local stress-strain state is associated with the nature of changes in the deformation field, which are caused by cracks.

In practice, the irregularity arising near fatigue crack tips, occupy a larger relative area than the local change of the stress-strain state near the holes or fillets. Of particular interest is the study of the effects arising from the mutual influence of irregularities of the stress-strain state near multiple site fatigue cracks, the analysis of the development of which in the general case cannot be accomplished within the widely used on practice of the methods of linear fracture mechanics.

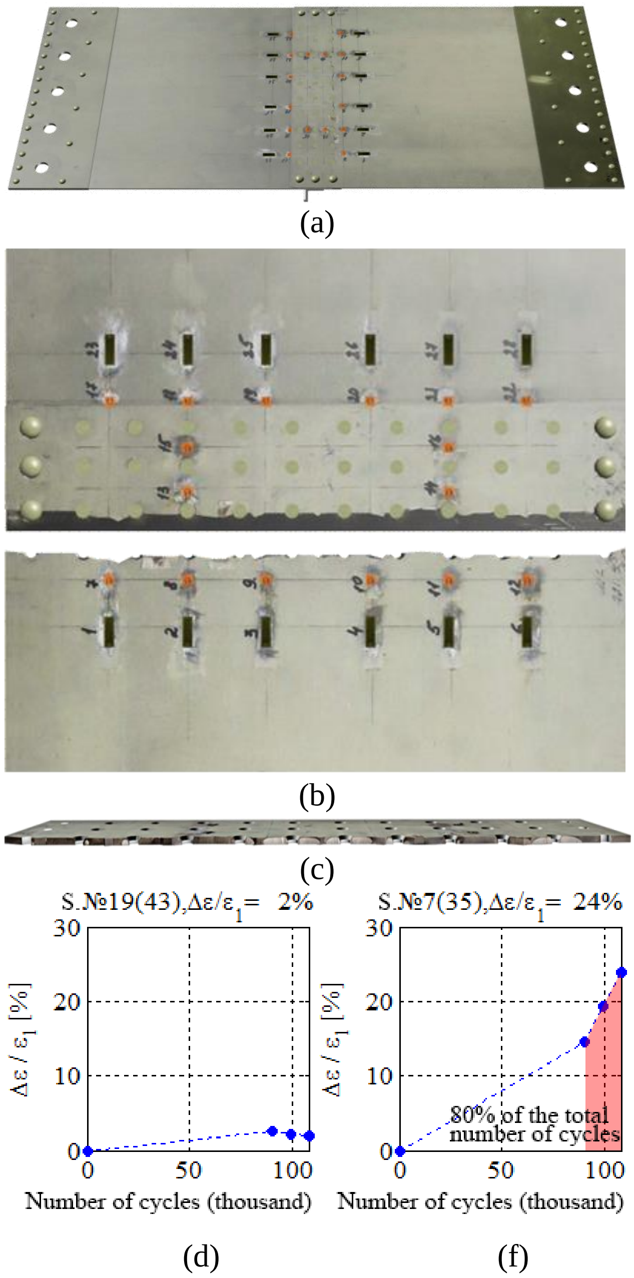
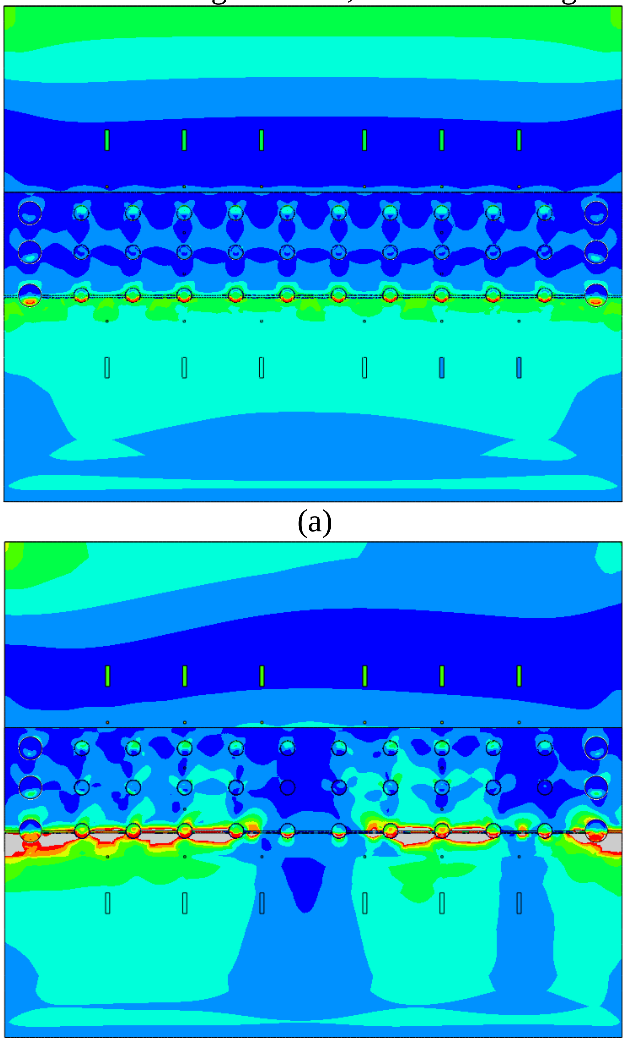


Fig. 2 View of sample of longitudinal joint- (a); Characteristic destruction of the outer bearing sheet on the last row - (b); Image of the fracture of the specimen with fatigue cracks - (c) Changes of SG readings in undamaged sheet - (d); Changes of SG readings in damaged sheet - (f)

The changes in stress-strain state in the damaged and undamaged sheets at the beginning and end of the tests, obtained taking into account fatigue cracks, are shown in Fig. 2.



(a)

(b)

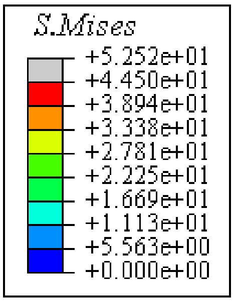


Fig. 3 – Stress-strain state of joint elements at the beginning of tests - (a); Stress-strain state of joint elements at the end of the tests taking into account the fixed fatigue cracks - (б)

The research of longitudinal joint samples confirmed the efficiency of monitoring, because the structural damage was discovered in advance, herewith the changes in stress-strain state registered using sensors throughout the outer and inner surfaces of the destroyed sheet. A significant part of the detected damage was of a multiple site nature and in view of the small size of individual cracks that developed from the inner surface of the joint at the place of contact of the sheets, was not recorded visually the entire period of slow growth.

Research of the impact on stress-strain state of surface cracks hidden in the elements of the compound was carried out by analyzing the finite element (FE) model of the joint (fig. 3). Calculation with the help of FE method allows to investigate a large number of possible damages and to provide the subsequent calculation of optimum scheme of sensors location. Verification of the modeling results was carried out by comparing the calculated deformations with the deformations recorded in the experiment.

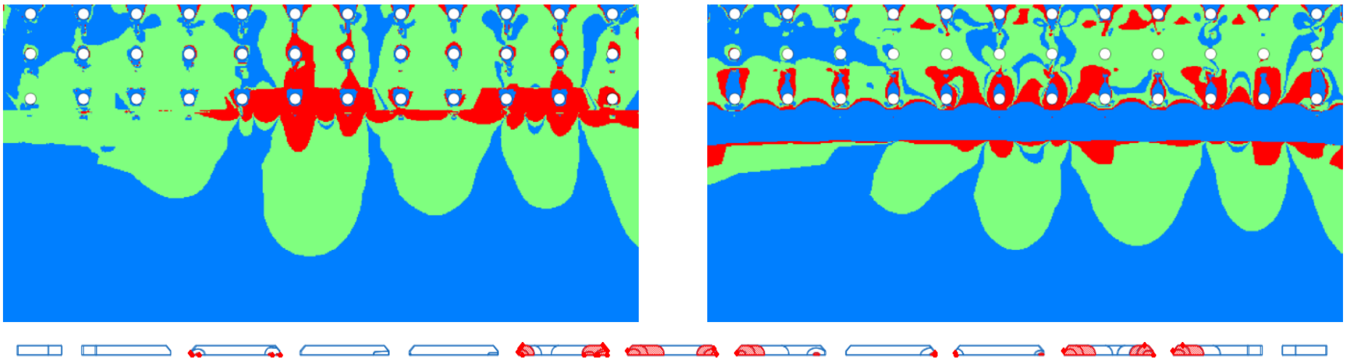
Figure 4 shows the zones of the most significant changes in stress-strain state elements of the longitudinal joint resulting from the analysis of the FE model (the effect of fatigue cracks on the stress-strain state is considered in more detail in [5]). As a result of the calculation, an estimate of the number of sensors required to monitor the integrity of the joint was proposed. In accordance with the calculated estimates, the most optimal number of sensors is one sensor for every 10-15 mm along connection of the skin sheets or one sensor for every five holes.

4 Method of determining the optimal places of control for the construction with multiple site damages

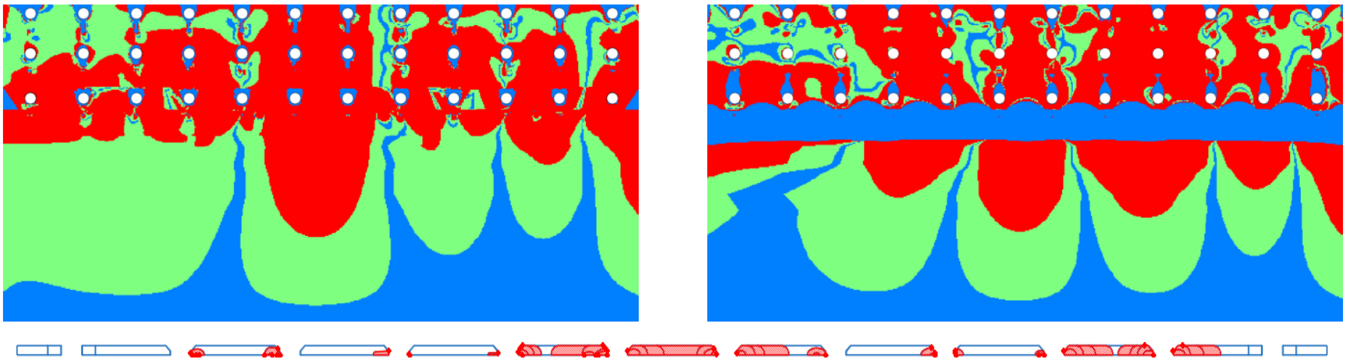
For the safe operation of the damaged structure, it is necessary to confirm that the residual strength lies within the permissible limits. In the papers [6, 7] as a criterion of residual strength of sealed fuselage with multiple site cracks in the longitudinal lap joint of fuselage skin is proposed to use the product of the yield strength of the skin material on dimensionless correction factor (2):

$$\sigma_{fract} = \alpha\sigma_{0.2} \qquad (2)$$

The value a proposed for the calculation according to the data of paper [6] is ~1, the experimental studies presented in paper [5] give a more accurate value $\alpha \simeq 0.5$.

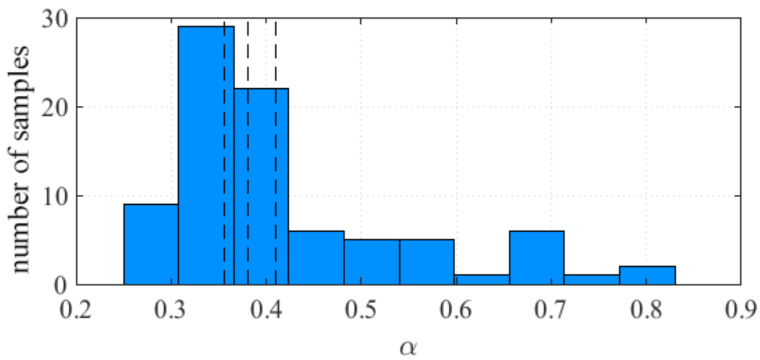


scheme of the fracture of the destroyed sheet of the longitudinal joint at $N = N_T - 5.5$ thousand flight cycles



scheme of the fracture of the destroyed sheet of the longitudinal joint at $N = N_T$

Fig. 4 Relative change of deformations on the lower and upper surfaces of the damaged sheet (blue – less than 5%, green – more than 15%, red – more than 30%) at different numbers of flight cycles (N_T – total number of flight cycles to failure); cracks location scheme (below the images)



(lower and upper limits of 1 per cent confidence interval, mean value - 0.36, 0.41, 0.38)

Fig. 5 A histogram of the distribution of the samples as a function of α, defined by the area occupied by the cracks

Research of the fractures of longitudinal joints samples carried out in TsAGI allows to determine the values of α with the requirements for residual strength. Figure 5 shows the dependence of the number of samples on the value of α determined by the results of the experiment. In contrast to [4, 5], the value of α was determined not by the size of the critical crack, but by the size of the damages corresponding to the transition between the stages of rapid and slow crack growth (fig. 6). Thus, the maximum safe size of cracks was determined.

Using the α value for the joints of longitudinal joints, the relative area that can be occupied by cracks in the bearing sheets was determined:

$$\gamma = 1 - \beta - \sigma_{reg} / \left(\alpha \sigma_{0.2} \right) \simeq 0.2 \qquad (3)$$

where γ - the ratio of the area of cracks to the area of the sheet in the regular part - $\gamma = S_{crack}/S_{reg}$; β - the ratio of the area of holes to the area of the sheet in the regular part - $\beta = S_{riv}/S_{reg} = 0.2$; σ_{reg} - stresses in the regular part of the sheet - 8 kgf/mm^2; $\sigma_{0.2}$ - yield strength of skin material - 34.8 kgf/mm^2; α according to the experimental results was assumed to be equal to 0.4.

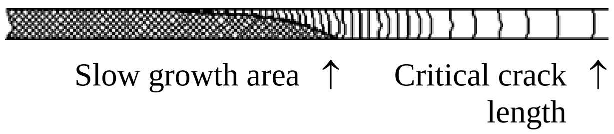


Fig. 6 The definition of the boundaries of the safe area of the cracks

Based on the obtained results, taking into account the possible safe area that can be occupied by fatigue cracks (~20% of the cross-sectional area of the load-bearing sheet in the regular part), stress-strain state was calculated and the degree of damage effect on the sensor readings on finite element models with different options for crack location was estimated.

Figure 7 shows the areas of the greatest change in the stress-strain state sheets of joint for several variants of crack location.

The main reasons why cracks with the above properties can be considered safe are the following:

- duration of the growth of the analyzed cracks from the moment of transition to the fatigue zone with a growth rate of more than 5 μm/cycle to a critical size is more than 100 flight cycles;
- the fronts of the cracks are in the area of fatigue with the slow growth rate of less than 5 μm/cycle (fig. 6).

The flight in which the specified cracks will be detected will be completed without the risk of a change in the residual strength below the permissible level, such a flight and the considered fatigue damages can be taken safe.

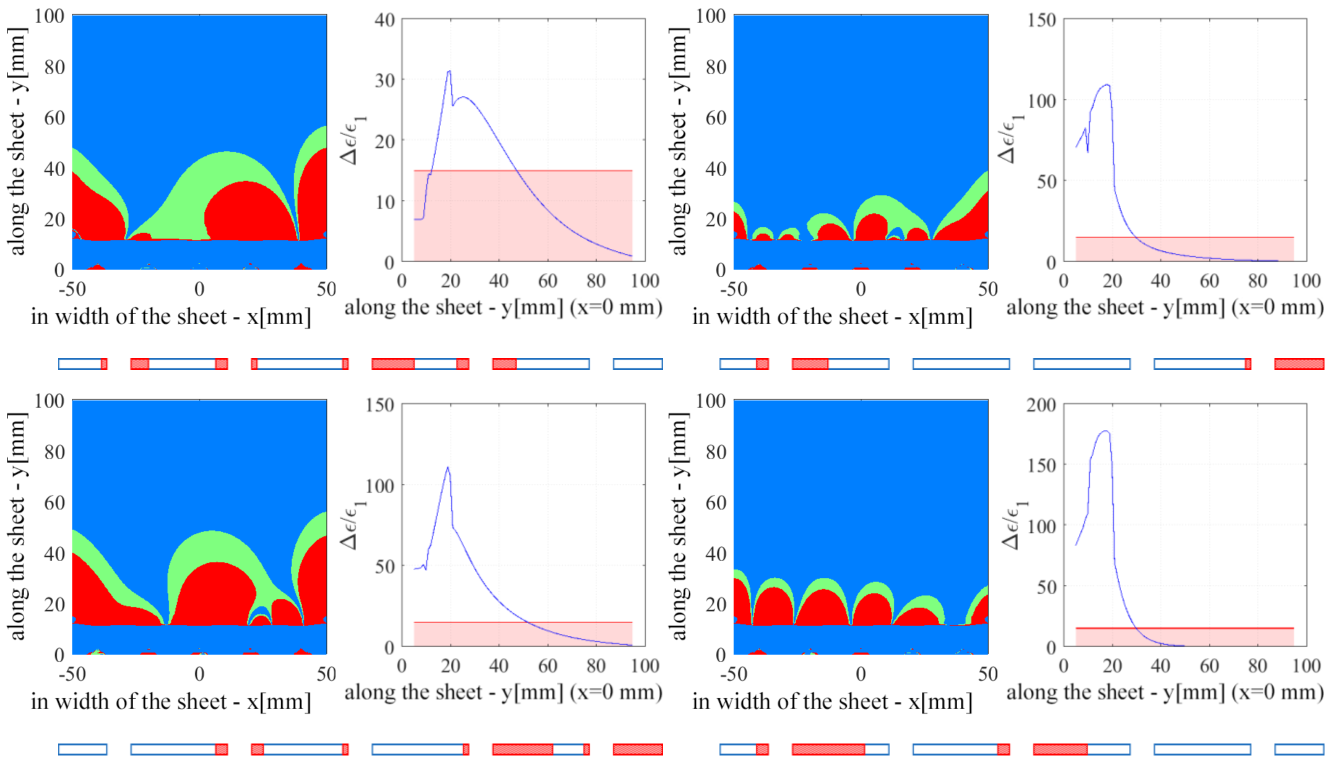


Fig. 7 Area of the greatest change of stress-strain state (in the right part of the figures: blue – less than 5%, green – more than 15%, red – more than 30%) at different variants of location of cracks (at the bottom of the pictures) and the dependence of the SG readings on its location (in the left part of the figures)

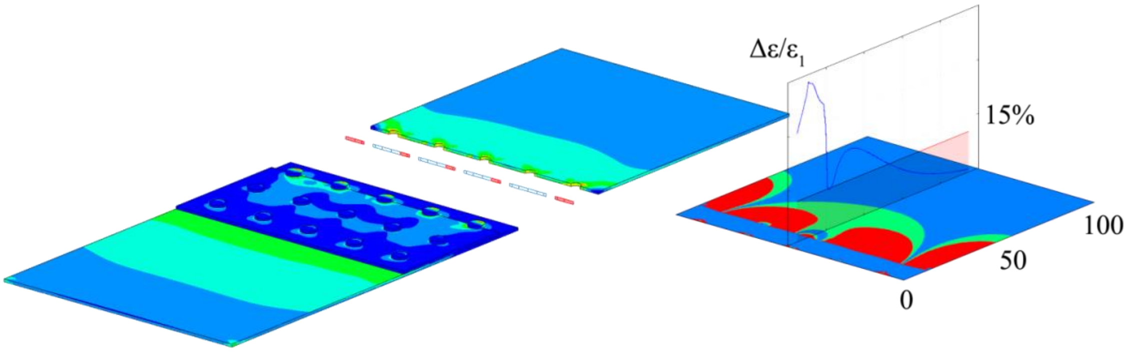


Fig. 8 Scheme for determining the initial data for the formation of a training set based on the SG readings and the parameters of fatigue cracks

Plenty of FE models of stress-strain state received for safe cracks was used as training set to make the neural network (fig. 7). The element of the training set is a pair of vectors consisting of the input data, which determines the size and location of fatigue cracks and the resulting data, consisting of SG readings located along the axis of symmetry of the damaged sheet (fig. 8).

The result of neural network training is a generalizing dependence of the sensor readings on the resulting damage, obtained in numerical form. Determination of the possibility of control a given number of holes and the calculation of the optimal location of the sensors, carried out by searching and analyzing the values of the obtained relationship between the readings of SG and accumulated cracks.

Conclusions

The paper considers the possibility of monitoring the integrity of the damaged structure on the example of longitudinal fuselage joints. The following conclusions can be made from the calculated and experimental results:

- The possibility of early detection of damage in the structure of longitudinal joints is shown experimentally;
- The total area of safe cracks that can occur in the longitudinal joint as a result of cyclic operating time is determined experimentally. The resulting total area of the damaged part is about 20% of the cross-section area in the regular part of the sheet;
- The numerical dependency between the damages occurring in the longitudinal joint and the SG readings is developed. By analyzing the obtained dependence, the optimal location of sensors is determined, which implies the location of one sensor for every five holes at a distance of 1-1.5 cm from the most loaded row in the longitudinal joint.

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