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Study on the possibility of optimizing technology for repairing aircraft skin using riveting according to strength criteria

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Abstract. Flight safety plays a decisive role in passenger comfort and security. It mostly depends on the reliability of the aircraft. During operation, this reliability is maintained by the effectiveness of repair technology and the quality of the repair. The implementation of new repair technologies and the optimization of existing ones is a key aspect of this process.
For this reason, this study examines the possibility of optimizing a well-known technology for aircraft structural repair, namely the repair of the aircraft fuselage using riveting. The article presents the methodology, the experiment, and the results of a study conducted to optimize the repair technology for aircraft structural components. The significant factors affecting the quality of riveted repairs have been identified. A full-scale experiment was planned and conducted to investigate the strength of a thin-walled reinforced panel simulating the aircraft skin. Several different reinforcement and riveting configurations were tested. The maximum failure stresses for the various riveting configurations have been determined. An optimization problem for multidimensional optimization using the Simplex method has been formulated. The results obtained are presented in tabular and graphical form. The relevant conclusions and findings related to the study have been drawn.
Keywords: aviation, crack, flight safety, riveting, stress and strength, yield strength

1. Introduction

Modern aircraft, including airplanes, are complex engineering structures built using the latest advances in science and technology (Aleksandrov, 1975), (Kuzmov, at al., 1979). The complexity of aircraft stems from the specific nature of their designs, dimensions, and technical characteristics, as well as the requirements for ensuring high flight reliability and safety and maintaining this reliability during operation and repair. Due to these design and technological features, the labor intensity required to manufacture a single large transport or passenger aircraft can reach several hundred thousand man-hours.

During operation, the technical condition of aircraft is constantly changing. Failures and malfunctions occur, which is why the probability of trouble-free operation decreases, and their operational reliability also decreases (Stoyanov et al., 2004). The development of this process is associated with the accumulation of microdefects in the structure of structural elements. This leads to material fatigue, the development and appearance of structural defects such as cracks, intergranular corrosion, deep indentations (deformations), dents, loosening of rivets, etc. (Lavchiev, 2003). Analysis of the available statistical data shows that even relatively new aircraft with relatively low flight hours develop such defects. They occur in various structural areas of the aircraft's skin and load-bearing frame. The causes of such defects are diverse—material fatigue is due to prolonged cyclic loads, while micro-cracks are due to defects in the material's structure. Defects caused by errors in operating procedures are also not uncommon, for example, mechanical penetration through the skin by tools, fixtures, or foreign objects (Figure 1). Moisture penetration into enclosed spaces within the aircraft structure very often leads to the development of pitting corrosion (Figure 2).

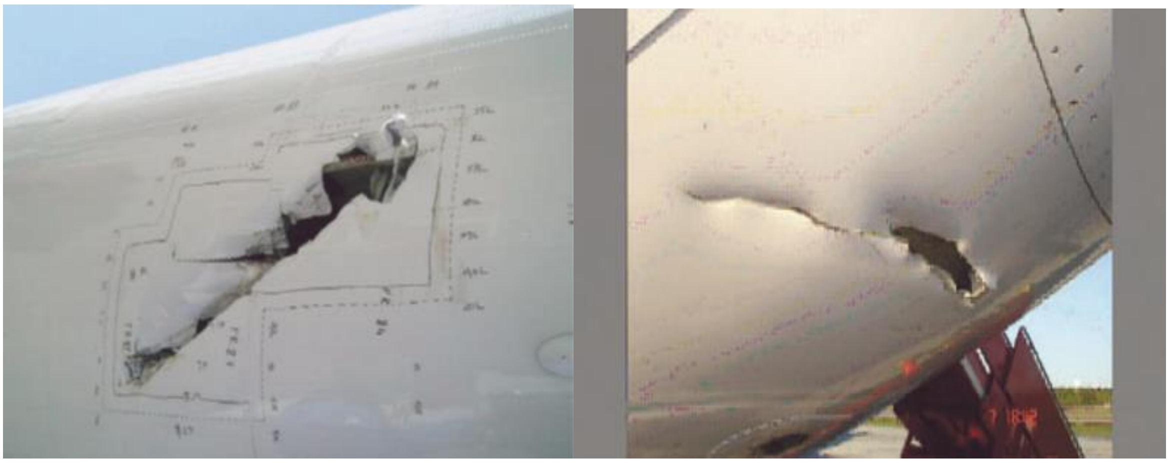

Figure 1. Damage to an aircraft's skin caused by improper use of ground support equipment

Figure 2. Corroded aircraft structural components

The presence of such structural defects requires timely and high-quality repairs. This is the only way to maintain the aircraft's intended reliability and ensure the necessary flight safety.

These defects can occur in various areas and structural elements of the aircraft, which is why their impact on reliability and flight safety also varies. Sometimes they are located in the glazing area, service hatches, and doors, while in other cases they may appear in the tail section, the wings, or the control surfaces. For most structural areas, such defects are categorized, and standard repair procedures have been developed for them, which are described in the Structural Repair Manuals (SRM) for the specific aircraft type (Aleksandrov, 1975). Nevertheless, in many cases, such defects occur in areas and sections for which no specific repair technology is specified in the repair documentation (SRM). In such cases, the engineering staff of the operating organizations must develop their own repair technology. In doing so, the strength and reliability of the structure in the repair area must be maintained without altering the aircraft's aerodynamics and balance. In such cases, a precise understanding of the stress-strain state (SSS) of the repaired components, as well as the influence of certain factors on it, would allow for the optimization of the quality and effectiveness of the repair. Defects of the type shown in Figs. 1 and 2—cracks, deep deformations, and intense, deep-penetrating corrosion—are typically repaired by removing the damaged section, fabricating repair patches, and riveting them to the aircraft structure.

Riveting repair technology is not new, but an analysis of existing information on this issue shows that in many cases the quality and adequacy of such repairs are subpar, resulting in defects (most commonly cracks in the skin) continuing to grow, which sometimes has catastrophic consequences. For example, in 2002, a China Airlines Boeing 747 crashed into the ocean following rapid decompression. The cause was material fatigue in structural components of the aircraft's airframe that had been repaired improperly. An analysis of the causes of the crash shows that the reinforcement in the defective area was not performed properly. Instead of removing the damaged section, fabricating new components, and reinforcing them with a patch, only a reinforcing patch was installed over the damaged structure (Aviation Safety Council, 2005). There are a number of other similar cases in which the causes of the crash were poorly planned and substandard structural repairs to components of the aircraft fuselage. These "dark" statistics demonstrate the immense importance of properly developed repair technology and the quality of the repair work performed for flight safety.

Objective: In this sense, the task facing the engineering and technical staff boils down to minimizing repair resources (number of rivets used, holes, replaced panels, etc.) while strictly adhering to the conditions for structural equivalence between the repaired section (component) and the undamaged part of the structure.

2. Materials and methods

Achieving the research objective requires formulating and solving a multidimensional optimization problem for unconditional minimization (Myers et al., 2016). When developing and validating the optimization model, either statistical data or experimental data obtained from a field experiment (Lavchiev & Lavchiev, 2003). Since we do not have the necessary statistical data, we had to plan and conduct a field experiment to assess the influence of a few factors on the strength of riveted joints and to build a database for the development and validation of an optimization model. Structurally, the aircraft fuselage is a semi-monocoque structure, generally consisting of a load-bearing frame and skin. This type of structure belongs to the structural group of thin-walled supported panels (Kuzmov, at al., 1979), the degree of strength restoration of which depends on a number of factors—the sophistication of the repair technology, the skill of the repair personnel, the quality of the materials and repair equipment used, and several others. Generally, these factors are divided into technological and structural. The study examines the influence of structural factors that directly affect the strength of structures repaired by riveting. Some of the most significant are: the rivet seam pitch – t, mm; the number of rivets in a row – n; the diameter of the rivet body – d, mm; structural features of the repair zone; and others.

During the experiment, the influence of the following structural factors was investigated: the rivet seam pitch – **t**, mm; the number of rivets in a row – **n**; and the structural repair scheme unaffected part of the structure.

The subject of the study is a reinforced thin-walled panel (Kuzmov, at al., 1979), (Montgomery, 2021) with technical and structural characteristics like those of an aircraft. The results obtained from the experiment were used to evaluate and analyze the possibility of optimizing repair technology through riveting based on strength criteria for zones and sections of aircraft structures for which no standard repair technologies have been developed (Lavchiev, 2003). During the experiment, the behavior of experimental specimens, fabricated in the form of a thin-walled reinforced panel, was investigated. Based on their structural characteristics, they were divided into three structural groups: the first group - a thin-walled panel, insert, and overlay; the second group - a thin-walled panel with a cut-out opening and overlay; and the third group - a thin-walled panel with a slit simulating a crack and an overlay (Figure 3).

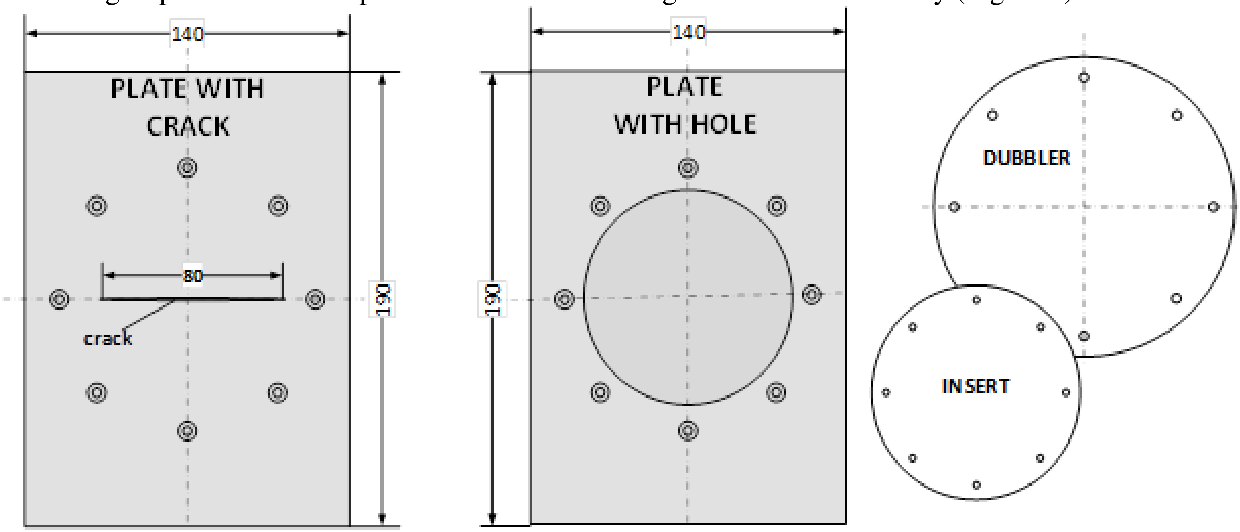

Figure 3. Geometric parameters and elements for the individual groups of samples

The test specimens (test tubes) are made of the high-strength aluminum alloy 2024-T3, which is primarily used in aviation and aerospace. The mechanical properties of the material are taken from an aviation reference manual (Lavchiev, 2003). The dimensions of the test specimens are shown in Fig. 3. The riveting of the individual components of the test specimens was performed using the straight riveting method, with a pneumatic hammer and a suitable 8-kg anvil (Lavchiev, 2003). This riveting method is used when there is access to both sides of the riveting area, as it is considered that the strength of a riveted joint made using this method is the highest. Rivets made of 2117-T4 alloy were used. This is a standard alloy from the 2000 series (aluminum-copper alloys), widely used for the production of rivets. Structurally, the rivets have a flat-countersunk head, a body diameter of 4 mm, and a length of 8 mm. Before riveting, they were heat-treated in accordance with the manufacturer's technical requirements. Seven series of samples were produced from each design group, with five elements tested from each series. The number of rivets in the different series is:

$$n = 4; 6; 8; 10; 12; 14; 16 \text{ pcs.} \quad (1)$$

The tests were performed on a hydraulic tensile/compression testing machine. The specimens were loaded once, with the load increasing smoothly from zero to the maximum value at which failure occurred. The ultimate tensile stresses were recorded for the various specimens from the three structural groups for seventh different variations of pitch and number of rivets on the elements. Five specimens from each series (variant) were tested, and the results for the ultimate stresses were averaged. A schematic diagram of the test and photographs of some of the test specimens (structural group 1, series 3) that failed after testing are shown in Figure 4.

Figure 4. Schematic diagram of the test and photographs of the already destroyed samples

3. Results and discussions

The average values of the ultimate stresses and loads under which the experiment was conducted are presented in tabular and graphical form. Table 1 shows the values of the applied forces and the average values of the ultimate strength for the different structural groups of tested specimens.

Table 1

Structural Group 1 /plate. Dubler, insert/					**Structural Group 2 /plate whit hole and Dubler/**					**Structural Group 3 /plate whit crack/**				
serial №	**rivet, n**	**pitch, t mm**	**P, kPa**	**σB, Mpa**	**serial №**	**rivet, n**	**pitch, t mm**	**P, kPa**	**σB, Mpa**	**serial №**	**rivet, n**	**pitch, t mm**	**P, kPa**	**σB, Mpa**
1	4	66	17,5	220,5	1	4	66	16,66	218,6	1	4	66	24,4	319,6
2	6	47	21,56	271,2	2	6	47	17,4	227,4	2	6	47	26,7	328,8
3	8	36	24,99	320,1	3	8	36	22,05	245,3	3	8	36	27,3	329,8
4	10	29	29,45	357,1	4	10	29	23,03	295,3	4	10	29	30,2	370
5	12	24	27,44	331,5	5	12	24	19,11	232	5	12	24	28,2	332,1
6	14	21	27,8	331,3	6	14	21	18,82	223,3	6	14	21	28,5	332,9
7	16	18	27,15	330,9	7	16	18	18,28	220,1	7	16	18	28,2	331

The average values of ultimate stresses for the tested samples, grouped by category, are shown in Figure 5.

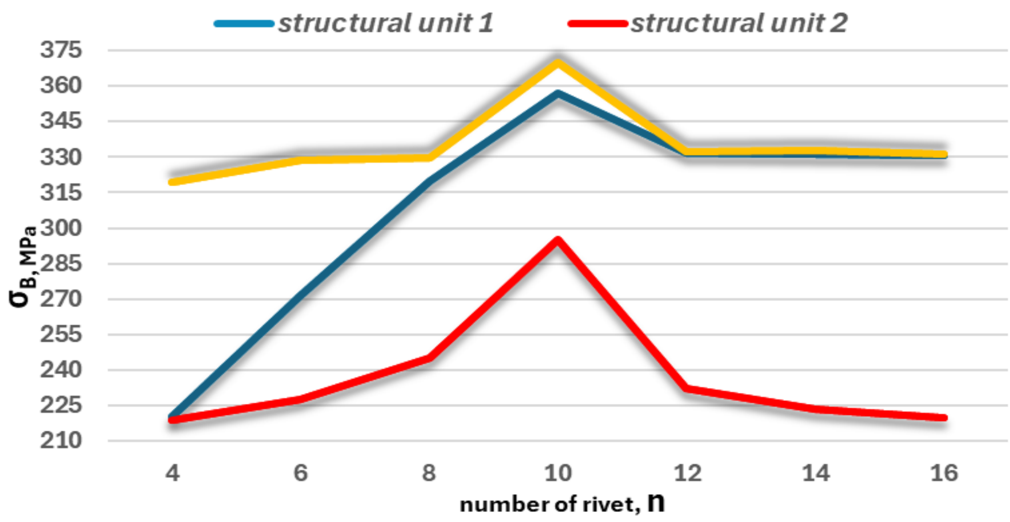

Figure 5. Maximum failure stresses for the tested components across the three structural groups

The data obtained from the field experiment can be used to develop an optimization model for minimizing repair resources while maintaining the required ultimate strength of the structure.
Creating such a model requires formulating and solving a multidimensional optimization problem (Myers et al., 2016).
A methodology for creating such an optimization model has been developed and proposed by applying the Simplex method for multidimensional unconstrained optimization (Adler, 1980).

According to the proposed methodology, the formulation of the optimization problem requires (Sovetov & Yakovlev, 1985):

- Determination of input data
- Definition of the objective function
- Introduction of constraints
- Determination of the necessary model parameters
- Validation of the model

Input data - The design load on the structure in the defective zone, the specified safety factor, the geometric parameters of the rivets, the repair elements, and the physical-mechanical characteristics of the materials used (shear strength, tensile strength) can be used as input data.

Objective function - The formulation of the objective function is based on the goal of the study—minimizing repair resources while maintaining the design strength of the repaired section. In this case, the variables are the factors determining the repair resources—number of rivets, number of holes, and thickness of the elements. Given that each hole is a stress concentration point, the most appropriate objective is to minimize the number of holes -**N**, and, respectively, the number of rivets - **n**.

In general form, the objective function can be written as:

$$\min N = n \tag{2}$$

Constraints - As boundary parameters for the optimization model, we will use the maximum allowable compressive and shear strengths of the structural material, expressed by the ultimate normal compressive stresses - σ_B and the ultimate tangential shear stresses $-\tau_{sh}$.
The compressive stresses are determined by the expression:

$$\sigma_B = F/d.t, \tag{3}$$

where: F – shear force, depending on the load
d – rivet diameter
t – thickness of the riveted bundle.

The constraint implies that:

$$\sigma_B \leq \sigma_B \, allowable; \quad \tau_{sh} \leq \tau_{sh} \, allowable \tag{4}$$

$$\tau_{sh} = F/A; \tag{5}$$

where: $A = \pi d^2/4$ – shear area, depending on the rivet diameter and the thickness of the part
$F -$ shear force, depending of the load.

In addition to these constraints, sheet tear constraints, a constraint for the minimum allowable distance to the end of the repair element, and material fatigue constraints can also be introduced.

Variables - The following quantities can be used as variables:

$$X_1 = n, number\ of\ rivets\ per\ row;$$
$$X_2 = number\ of\ rows;$$
$$X_3 = rivet\ diameter\ (discrete\ selection)$$

Based on data from the field experiment, the number of rivets in a row varies from four to sixteen. The number of rivet rows is for design series 1 – two; for design series 2 – one; and for design series 3 – one.

Validation - The adequacy of the model is demonstrated by assessing the reliability of the results obtained. Mathematically, the task of verifying the model's adequacy is formulated as a task of verifying the assumption that the model's response W_M differs from the actual response W_O of the object being modeled by no more than a predefined value ϵ^*:

$$W(x) - Wm(x) = \varepsilon \leq \varepsilon *, \tag{6}$$

where: $W(x)$ – response function of the modeled object to input disturbances
$Wm(x)$ – the response function of the model
ε – the difference between the response values of the modeled object and the model
$\varepsilon *$ – a predefined accuracy threshold for evaluation.

Based on Eq.6, several criteria have been derived for evaluating the adequacy of identification models. These include Pearson's χ^2 criterion, which is based on the least squares method; the Kolmogorov-Smirnov criterion, based on minimizing the maximum error; Fisher's criterion; and so on. Most often, the criterion proposed by Pearson—χ^2 (Preobrazhenskiy & Tsurpal, 1984) is used for structural and optimization models in aviation. This criterion is based on minimizing the relative error between the results, obtained from the full-scale experiment and those, obtained using the optimization model. The safety factor must also be verified. In conclusion, it can be said that the proposed optimization model balances between the minimum number of rivets, the maximum load-bearing capacity (strength) of the structure, and the preservation of the net cross-section of the repaired section.

4. Conclusions

Based on the results of the study, the following conclusions have been drawn:

- A riveted joint achieves its maximum strength with a specific number of rivets, which can be considered optimal. This means that for each specific case of skin repair in areas and sections where repair technologies (SRM) do not specify specific repair measures, the optimization problem must be solved with a minimum number of fasteners.

- The study conducted pertains to a specific case of loading and rivet placement. Under real-world conditions, the loading is complex, and the behavior of a skin repaired in this manner would differ. A complete and more accurate analysis of the structural integrity is possible only when the actual loading of the structure in the repair zone is known.
- A methodology is proposed for implementing an optimization model to optimize repair technology through riveting based on repair resources while maintaining the design strength of the structure. The creation of such a model is a task whose solution allows for the modeling of various combinations of the number and arrangement of fasteners, loads, structural materials, etc., i.e., an in-depth study of the stress-strain behavior of the components and the optimal selection of repair technology parameters.

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Conceptualization: H.Ch. and D.D

- Methodology: H.Ch.
- Investigation: H.Ch.
- Writing original draft: H.Ch.
- Writing review and editing: H.Ch.
- Supervision: H.Ch. and D.D.

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