

RESIDUAL STRENGTH OF STIFFENED PANELS WITH MULTIPLE SITE DAMAGE

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Abstract

On the basis of boundary integral equations method the problem of residual strength definition of stiffened panels with multiple site damages is solved. Multiple site damages are characteristic of airplanes with large lifetime («aging» airplanes). Multiple site damages are very dangerous, because the critical sizes of cracks in this case can be rather small, that makes their detection by nondestructive examination methods of monitoring rather difficult.

In the present work on the basis of boundary integral equations method the solution of problem of stress-strain state and residual strength of elements of aircraft structures is considered. The essence of method consists in construction of general solution of problem as the sums of complex potentials, which base on Green function for anisotropic plate with elliptic hole. The substitution of obtained solution of problem in boundary conditions and reduction them to integral equations system allows to define stress-strain state of aircraft structures and stress intensity factors in crack tips. The effective algorithm of numerical solution of integral equations system is offered.

The numerical results of stress intensity factors account in crack tips in stiffened panels are presented. The influence to panel residual strength of mutual disposition of main and secondary cracks, disposition of stiffeners, exit of crack on rivet hole is investigated. Defined load, under which occurs a merging of nearby cracks.

Keywords: boundary integral equations method, residual strength, multiple site damages, stress-strain state, aircraft structures.

Multiple site damage (MSD) is typical of structures with mechanical fasteners, since these structures are characterized by large number of natural stress concentrators such as holes under fastening elements. An inspection shows that 50 % of airplanes with 75 % - 83 % design service goal have MSD [1]. In the past decade, methods of calculation of structures with MSD have been developed intensely. This problem can be decomposed into three parts: determination of location and moment of initiation of a crack, estimation of the residual strength, and determination of the residual durability of a structure with MSD. In this paper, an analytical method for determining the stress-strain state of structures and predicting the stresses at which linkup occurs is proposed. Knowledge of these stresses is necessary to calculate the residual strength and residual durability of structures.

To estimate the stress-strain state of a reinforced structure with defects of the type of a crack, the analytical method [2, 3, 4] was developed using the principles of the linear elastic mechanics of fracture and the method of boundary integral equations. The essence of this method is to construct the general solution of the problem in the form of a sum of complex potentials which give the solution for an anisotropic plate with an elliptical hole under point and distributed external loads. Substituting the general solution into boundary conditions for cracks, stiffeners, holes of an arbitrary shape, and external boundaries, one obtains a system of integral equations, which can be approximated by a system of algebraic equations. for unknown

functions which determine the stresses and strains on the boundaries of the region, including cracks and stiffeners. Once the boundary values of these functions have been determined, one can calculate the stress-strain state at any point of the structure and the stress intensity factors at crack tips.

To calculate the stresses at which neighboring cracks merge, the plastic-zone touch criterion (linkup model) proposed by Swift [5] was used. In accordance with this criterion, it is assumed that a ligament between neighboring cracks fails and a leading crack forms when their plastic zones meet. The size of the plastic-zone at a crack tip is calculated by the Irvine formula [6]

$$r = \frac{1}{2\pi} \left(\frac{K_I}{\sigma_y} \right)^2,$$

where r is the plastic-zone size, K_I is the stress intensity factor, and σ_y is the yield strength of the material.

The analytical method proposed was implemented in computer programs which can be used to estimate the stress-strain state of a flat panel weakened by an elliptical hole and a system of cracks and reinforced by stiffeners riveted or connected by means of bolts. The programs allow one to determine the stress intensity factors at crack tips and stresses at which linkup occurs and to construct residual-strength diagrams for reinforced panels.

To verify the method outlined above, comparison with the experimental data of [7] was performed and the residual strength of reinforced riveted panels with MSD and linkup stresses were calculated. Figure 1 shows schematically configurations of panels tested in [7]. Four-stringer (Fig. 2) and three-stringer (Fig. 3) panels reinforced by two-row riveted joints were calculated. The panels differed in size of the central crack and in size, quantity, and arrangement of the secondary cracks. In calculations, the following mechanical and geometrical characteristics of panels were used: the stringer material 7075-T6, the mechanical characteristics of stringers $E = 6832.55 \text{ kg/mm}^2$, $G = 2568.63 \text{ kg/mm}^2$, and $\nu = 0.33$, the ultimate strength $\sigma_u = 59.05 \text{ kg/mm}^2$, the cross-sectional area of stringers 92.7 mm^2 , the skin material 2024-T3; the mechanical characteristics $E = 7250.66 \text{ kg/mm}^2$, $G = 2725.8 \text{ kg/mm}^2$, and $\nu = 0.33$, the yield strength $\sigma_y = 37.32 \text{ kg/mm}^2$, the skin thickness $t = 1.27 \text{ mm}$, the diameter of rivets $d = 4 \text{ mm}$, and flexibility of rivets $q = 0.9931 \cdot 10^{-6} \text{ mm/kg}$. The real sizes and location of the leading and secondary cracks are given in [7]. In calculations, the stiffener riveted by two rows of rivets was modeled by two closely located stringers with single-row riveted joints whose rigidity was equivalent to that of the initial stiffener.

Table 1 compares the calculated and experimental values of the stresses at which ligaments between cracks fail and lists the relative error. For panels Id and IIIc containing four secondary cracks, the failure of the ligaments between the leading crack and internal secondary cracks (first linkup) and subsequent failure of the ligaments between the resulting leading crack (united with the internal secondary cracks) and external secondary cracks were analyzed. Figure 4 shows the calculation results. The solid curve refers to an ideal case of zero error. One can see that calculation gives a lower-bound estimate for the four-stringer panel with intact stiffeners and an upper-bound estimate for the three-stringer panel with broken central stiffener.

Numerical results show that the method described above is an effective procedure to calculate the residual strength of reinforced panels and linkup stresses. In contrast to the empirical method (see, e.g., [8]) which requires many tests to be performed and is applicable only to one material and specific structures, the method proposed can be used for any structure and material. It should be noted, that in the above analysis the simplest approach was used to estimate the size of plastic zones at the crack tips and static growth of the cracks under

increasing loads was ignored.

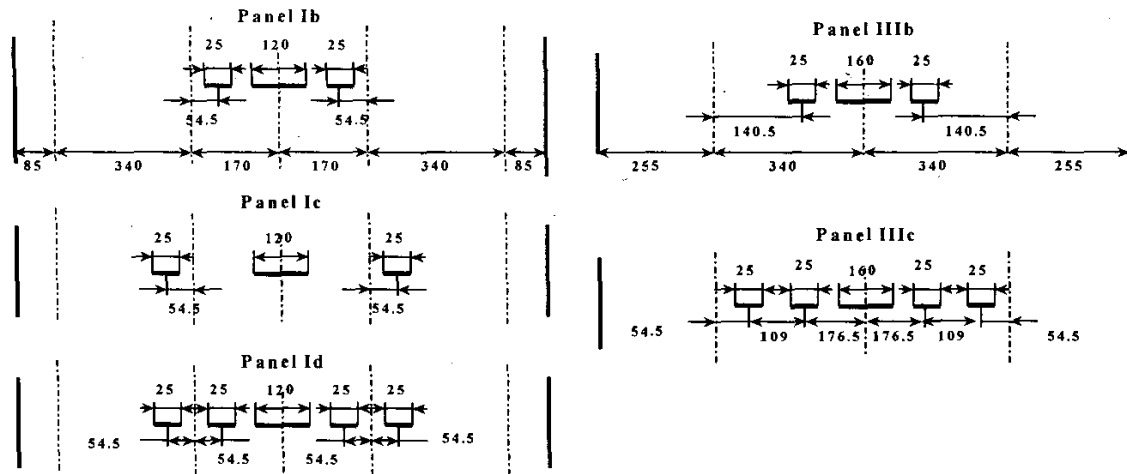


Fig. 1.

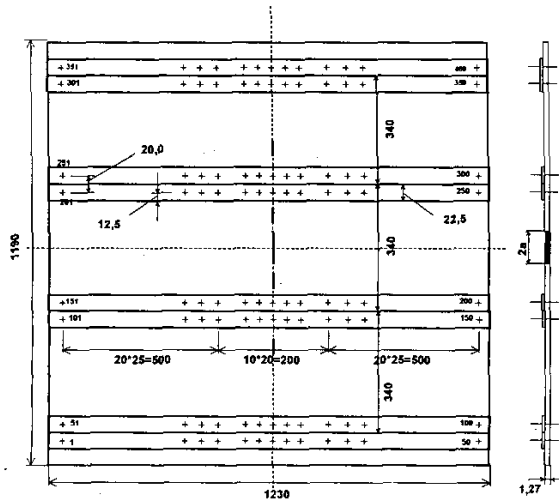


Fig. 2.

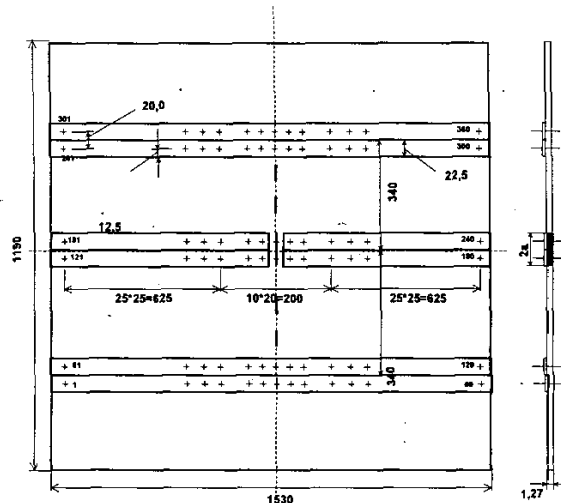


Fig. 3.

Table 1. Calculated and experimental values of linkup stresses (kg/mm^2)

	Panel Ib	Panel Ic	Panel Id1 (1-st linkup)	Panel Id1 (2-nd linkup)	Panel IIIb	Panel IIIc (1-st linkup)	Panel IIIc (2-nd linkup)
Calculation	19.00	30.00	19.17	21.73	20.78	18.18	15.37
Experiment [7]	21.13	28.14	20.89	26.17	17.77	17.4	14.94
Relative error of %	10.08	-6.61	8.23	20.60	-16.94	-4.28	-2.89

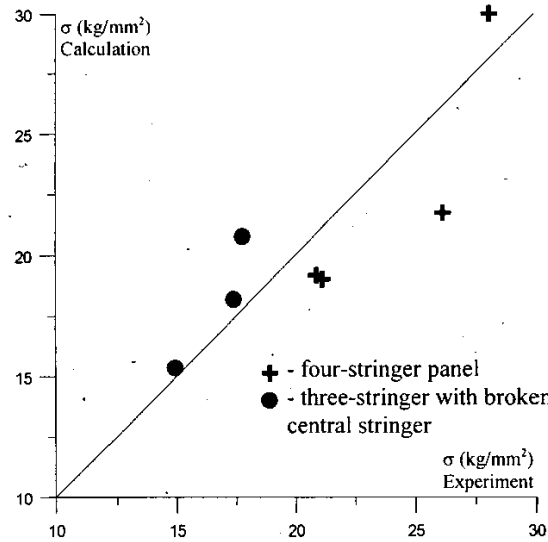


Fig. 4

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