Residual Strength of Stiffened LY12CZ Aluminum Alloy Panels with Widespread Fatigue Damage

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Abstract

Experimental and analytical investigations on the residual strength of the stiffened LY12CZ aluminum alloy panels with widespread fatigue damage (WFD) are conducted. Nine stiffened LY12CZ aluminum alloy panels with three different types of damage are tested for residual strength. Each specimen is pre-cracked at rivet holes by saw cuts and subjected to a monotonically increasing tensile load until failure is occurred and the failure load is recorded. The stress intensity factors at the tips of the lead crack and the adjacent WFD cracks of the stiffened aluminum alloy panels are calculated by compounding approach and finite element method (FEM) respectively. The residual strength of the stiffened panels with WFD is evaluated by the engineering method with plastic zone linkup criterion and the FEM with apparent fracture toughness criterion respectively. The predicted residual strength agrees well with the experiment results. It indicates that in engineering practice these methods can be used for residual strength evaluation with the acceptable accuracy. It can be seen from this research that WFD can significantly reduce the residual strength and the critical crack length of the stiffened panels with WFD. The effect of WFD crack length on residual strength is also studied.

Keywords: stiffened panel; widespread fatigue damage (WFD); residual strength; stress intensity factor; plastic zone linkup criterion

1 Introduction

An aging aircraft accumulates fatigue damage in the form of small scale cracks at the places of high stress concentration. This type of damage is commonly referred to as widespread fatigue damage (WFD). The two types of WFD are multiple site damage (MSD) and multiple element damage (MED) [1]. The residual strength of an aircraft structure will be significantly reduced by the existence of the small cracks adjacent to the rivet holes and much lower than that of only a single lead crack being concerned without considering the interaction with the surrounding cracks [2].

The economic factors have impelled the commercial and military aircrafts to be used beyond their original design life. And the WFD of these aircrafts is an issue of great concern. Data have shown that for the aging aircrafts the WFD may reduce the residual strength for about 25% comparing with the case of only a lead crack being involved [3]. Considerable efforts have been devoted to studying the WFD behavior of aging aircraft panels and its effects on aircraft structure integrity. Several approaches have been used to estimate the residual strength of aircraft with WFD [4-7]. Swift [8] developed an analytical method to determine the residual strength of a panel based on the yield stress with taking into account the plasticity and crack interaction effects. Several other techniques have...
also been proposed for establishing stress intensity factors of WFD cracks, for example the finite element method (FEM)\(^9\).

In this paper, the residual strength of stiffened LY12CZ aluminum alloy panels with WFD is calculated by both analytical method and FEM. The effects of WFD on the residual strength of the stiffened panels are studied. The tests of the stiffened panels with WFD are conducted to confirm these analyses.

2 Plastic Zone Linkup Criterion

Residual strength is defined as the maximum load a panel can bear before complete failure occurs. In comparison with the case of only a lead crack being involved, it is very difficult to evaluate the residual strength of the stiffened panel with WFD because of the interaction of the cracks. To this day, different residual strength criteria have been presented for the WFD\(^10\). The plastic zone linkup criterion proposed by Swift is used here for its convenience and applicability\(^8\).

The plastic zone linkup criterion assumes that when the plastic zone at the lead crack tip linkup with the plastic zones of the adjacent WFD crack as shown in Fig.1, the structure will fail. This can be expressed by

\[ R_{\text{lead}} + R_{\text{msd}} = b \]  

(1)

where \( R_{\text{lead}} \) is the size of lead crack plastic zone, \( R_{\text{msd}} \) is the size of multiple crack plastic zones, and \( b \) is the distance between lead crack tip and the adjacent WFD crack tip.

\[ \begin{align*}
   R_{\text{lead}} & = \frac{\pi}{8} (K/\sigma) \sqrt{8b} \\
   R_{\text{msd}} & = \frac{\pi}{8} a_{\text{msd}} \beta_{\text{msd}}
\end{align*} \]

where \( K \) is the stress intensity factor at the crack tip, \( \sigma \) is the yield strength of the material. When the plastic zone radius of Dugdale expression is adapted, the residual strength of stiffened panels with WFD can be expressed as

\[ \sigma = \frac{\sigma_y}{\pi \sqrt{a_{\text{lead}}^2 \beta_{\text{lead}}^2 + a_{\text{msd}}^2 \beta_{\text{msd}}^2}} \]  

(3)

where \( \sigma \) is the predicted residual strength of stiffened panel, \( a_{\text{lead}} \) is the half of the lead crack length, \( a_{\text{msd}} \) is the half of the adjacent multiple crack length, \( \beta_{\text{lead}} \) is the correction coefficient of the stress intensity factor of lead crack, and \( \beta_{\text{msd}} \) is the correction coefficient of the stress intensity factor of adjacent multiple crack. \( \beta_{\text{lead}} \) and \( \beta_{\text{msd}} \) can be obtained through Eqs.(4)-(5) respectively:

\[ K_{\text{lead}} = \sqrt{\pi a_{\text{lead}} \beta_{\text{lead}}} \]  

(4)

\[ K_{\text{msd}} = \sqrt{\pi a_{\text{msd}} \beta_{\text{msd}}} \]  

(5)

where \( K_{\text{lead}} \) and \( K_{\text{msd}} \) are the stress intensity factors of the lead crack and the adjacent multiple crack tips respectively. The stress intensity factors at crack tips can be calculated with engineering compounding method\(^{11}\):

\[ K = K_0 + \sum_{n=1}^{N} (K_n - K_0) \]  

(6)

where \( K_0 \) is the basic stress strength factor, \( K_n \) is the stress intensity factor for the \( n \)th simple boundary case, \( N \) is the total number of these simple boundary case.

3 Finite Element Analysis

The K-apparent criterion is used to determine the residual strength of the stiffened panels\(^{12}\). A simulated wing structure panel of transport aircraft is chosen for this analysis; the original “ I ” cross section stiffeners are considered as straps riveted on the stiffened panel. The structure and size are illustrated in Fig.2. The rivets is made of LY10.4×14
(GB867-67), and the straps and skin are made of LY12CZ. The thickness of skin is 2 mm and that of strap is 3 mm.

The eight-node and second order singular element is chosen at the crack tip, and the three-dimensional pin-joint elements are chosen to simulate the rivets joined skin and straps. The shear stiffness of the pin-joint element is obtained from the $P-\delta$ curves of Ø4 rivet given in Ref.[13]. The stress intensity factor at crack tip is calculated with the configuration factor and the load redistribution factor of the stiffened panel taking into account the interactions of cracks. K-apparent criterion is used to determine the residual strength of the stiffened panels as expressed by

$$K = \sigma \sqrt{\pi a \beta}$$

where $\beta = \beta_1 \times \beta_C$ is the correction factor[14], $\beta_1$ is the configuration factor considering the interactions of cracks in the same component, and $\beta_C$ is the load redistribution factor considering the effect of cracks in the adjacent components.

4 Experiments

Total nine stiffened panels with three different types of damage are tested for residual strength. The material used in this study is LY12CZ. The mechanical properties of skin and strap are shown in Table1. The structural shape and size are illustrated in Fig.2. Type A panel contains only a single crack in the skin, type B panel contains multiple cracks in the skin but without any cracks in the straps, and type C panel contains multiple cracks in the skin and with rivet hole cracks in the central strap. The crack configurations are shown in Fig.3. The lead crack and the small cracks are simulated by saw cuts. Each specimen is subjected to a monotonically increasing tensile load until failure occurred. The measured stress-crack curves are given in Fig.4.

<table>
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<th>Table 1 Material properties of skin and strap</th>
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<td>$E/\text{GPa}$</td>
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<td>skin</td>
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<td>strap</td>
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Fig.2 Schema of stiffened panel structure and size.

Fig.3 Schema of stiffened panel with cracks.
5 Results and Discussion

(1) The effect of strap on the residual strength of stiffened panel with WFD

It is shown from Fig.4 that when the cracks spread through the stiffeners, the sheet will fail. Panel failure then occurred under the load about 10% higher than that of the yield strength of sheet.

(2) The effects of different types of damage on residual strength of stiffened panels with WFD

The residual strengths of the stiffened panels with WFD are given in Fig.5. It shows that the residual strength of the stiffened panel with MSD is less than that of the panel without MSD for 9.6%, and the residual strength of the stiffened panel with MED is reduced further for 18.2%. The critical crack length of panels B and C are reduced from 66 mm to 60 mm and 59 mm respectively. It can be concluded that once a large amount of WFD occurs, the residual strength of aircraft structure will be reduced significantly, and will impair the integrity of the structure dramatically. It is therefore necessary to take into consideration of the influence of WFD on the integrity of the aircraft structure. The predicted results derived from plastic linkup criterion and FEM are agreed well with the experimental results.

(3) The effect of WFD crack length on the residual strength of stiffened panel.

The predicted results of residual strength of the stiffened panels with different size of MSD for type B by using Dugdale plastic zone linkup criterion are given in Fig.6. It is shown that the residual strength of the panels will decrease with the increasing of MSD crack size. When the half of MSD crack sizes are 4 mm and 5 mm the residual strength of the panels will decrease for about 3.74% and 6.95% respectively compared with that of without MSD. When the half of MSD crack size is 12 mm, the residual strength of the panel will be reduced for 29.77%.

6 Conclusions

(1) From the comparison between the predicted results and experimental results, it is found that the residual strength of type C and type B stiffened panels are lower than that of type A for 18.2% and 9.6% respectively. It can be concluded that once a large amount of WFD occurs, there will be significant influence on the residual strength of the structure and dramatically reduce the residual strength of the lead crack. It is therefore necessary to take into consideration of the influence of WFD.
on residual strength of the aircraft structure.

(2) The plastic linkup criterion for the evaluation of the residual strength of stiffened panels with WFD can provide satisfactory results with about 1% difference compared with the test results. Since its simplicity and effectiveness in practical use, significant saving in computation time and cost, it is a practical method in engineering applications. It should be noted that the residual strength of structure is somewhat overestimated by this method.

(3) The predicted results given by FEM also coincide well with the experimental results. It is shown that FEM is also an effective way for conducting the residual strength analysis of stiffened panels with WFD.

References


Biography:

Li Zhong  Born in 1964, he received B.S. and M.S. in 1986 and 1989 in Northwestern Polytechnical University. Presently he is a Ph.D. candidate in Northwestern Polytechnical University, Xi’an, Shanxi Province, China, in the field of structural integrity of aircraft structure.

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