THE EFFECT OF STRUCTURAL PARAMETERS OF AIRCRAFT PANEL ON VIBRATION FATIGUE LIFE

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Abstract

The vibration fatigue problem exists widely in the thin-plate structure of the aircraft, even the skin tearing will happen in some serious cases. In the article, firstly, based on the theoretical framework of damage mechanics, the secondary development of finite element software is carried out using PYTHON language, and a set of program which is suitable for vibration fatigue damage analysis has been obtained. Then, the program is used for simulating the vibration fatigue life of aircraft panel structure with different typical structural features. Finally, the simulation results are verified by vibration fatigue test. The maximum error is 31.63% compared with the simulation results, which prove the correctness and effectiveness of the program. The simulation and test results show that , the vibration fatigue life of aircraft panel will be affected by the height of the reinforcing rib and the existence of the chemical milling. The vibration fatigue life is maximum when the height of the C-shaped reinforcing rib is 30mm. The vibration fatigue life will be reduced when the rib height is too high or too low. In addition, the fatigue crack was more likely to appear when the panel structure with the chemical milling edge. Therefore, chemical milling is not recommended on the critical components with serious vibration fatigue problems.

1 General Introduction

During the entire flight, some parts of the aircraft will always be in a strong noise and strong vibration environment[1] , when the frequency of dynamic loads (such as vibration and noise load) have an intersection or be close to the natural frequency of structure, the structure will appear fatigue damage caused by resonance, which is called vibration fatigue[2].Vibration fatigue failure is one of the main destruction modes in aircraft structures, and it's also a common problem in the development and use process of aviation weapons and equipment. Previous research results show that, vibration fatigue is different from the conventional fatigue problem. Vibration fatigue is closely related to load frequency, structural vibration mode characteristics, alternating stress magnitude, structural modal damping and other factors. The lifetime of the resonance state is much lower than that in the conventional fatigue state, even if it is the same material at the same stress level, which shows that the damage mechanism and evolution law of vibration fatigue problem is different from that of conventional fatigue. Vibration fatigue damage accumulation is much more serious than the conventional fatigue problem.

Researchers have done a lot of analyses about vibration fatigue problem, but only some engineering prediction methods and semi-theoretical semi-empirical formulas have been obtained[3].The study on the damage mechanism of vibration fatigue problem is still in the beginning stage. In recent years, a new research method for the vibration fatigue analysis was provided as the rapid development of the continuous damage mechanics theory[4-11], which has been one of the key research subjects in the mechanics field at home and abroad.

We studied the vibration fatigue problem based on the continuous damage mechanics theory, combined with the critical components that may appear fatigue failure in current service and under developing aircraft. Firstly, a mechanical model considering the vibration fatigue damage evolution was established in the finite element software subroutine, and a set of program which is suitable for vibration fatigue damage analysis has been obtained. Then, a typical panel structure containing the dynamic characteristics has been extracted with reference to the critical components in aircraft , and the vibration fatigue damage analyses of the panel structure with different reinforcing rib height were carried out. Finally, the simulation results are verified by vibration fatigue test. The maximum error is 31.63% compared with the simulation results, which prove the correctness and effectiveness of the program. The simulation and test results show that , the vibration fatigue life is maximum when the height of the C-shaped reinforcing rib is 30mm. The vibration fatigue life will be reduced when the rib height is too high or too low. In addition, the fatigue crack was more likely to appear when the panel structure with the chemical milling edge. Therefore, chemical milling is not recommended on the critical components with serious vibration fatigue problems.

2 Basic Theory Of Continuous Damage Mechanics

2.1 Definition Of Damage Variable

Damage variable can describe the deterioration level of material or structural properties. Lemaitre[12] has defined the damage variable as:

$$D = \frac{E - E^d}{E} \qquad (1)$$

Where: E is the elastic modulus of the material without damage, E^d is the elastic modulus after the material is damaged.

2.2 Constitutive Equation Of Damaged Materials

In the finite element calculation process, the relationship between the stress increment $d\sigma$ and the strain increment $d\varepsilon$ is as follows :

$$[d\sigma] = (E^e - E^p)[d\varepsilon] \qquad (2)$$

Where: E^e is the material elasticity matrix, E^p is the material plasticity matrix.

The constitutive equation of damaged materials becomes:

$$[d\sigma] = (1-D)(E^e - E^p)[d\varepsilon] \qquad (3)$$

Where: D is the damage variable, or the deterioration degree of the material.

2.3Evolution Equation Of Fatigue Damage

Lemaitre has proposed a fatigue damage evolution equation:

$$\dot{D} = \begin{cases} \left(\frac{Y}{S}\right)^s \dot{p},\ p \ge p_{th},\ Y = \frac{\sigma^2_{eq}}{2E(1-D)^2} R_v \\ 0,\ p < p_{th} \end{cases} \qquad (4)$$

Failure criterion:

$$\int \dot{D} dt = D_c \qquad (5)$$

Where : Y is the energy release rate per unit volume, S, s is the material constant, p is the cumulative plastic strain, p_{th} is the damage threshold of plastic strain, σ_{eq} is the equivalent Mises stress, R_v is the triaxial stress factor.

2.4 Calculation Of Fatigue Damage Life

It is assumed that the fatigue life before damage is N_0. After the material is damaged, the damage is accumulated according to the formula (4). The life span from the occurrence of damage to failure is N_r. Then, the total life of the material is:

$$N_f = N_0 + N_r \qquad (6)$$

Where: $N_0 = W_s / \Delta W_e$, W_s is the threshold of material damage, ΔW_e is the distortion energy stored within a vibration period.

When the stored distortion energy reaches the damage threshold, the material begins to damage, and the damage is accumulated according to formula (4), while the damage variable in formula (3) is continuously updated until the damage reaches the threshold value D_c .Then the material is completely ineffective.

3 Establishment Of Finite Element Model for The Aircraft Panel Structure

3.1 Feature Extraction Of Aircraft Panel Structure

A typical panel structure, containing the dynamic characteristics, has been extracted with reference to the critical components that may appear to fatigue failure in current service and under developing aircraft,as shown in Figure 1. The panel structure has two typical characteristics , as shown in Figure 2: (1)the chemical milling edge, (2) the reinforcing rib with different height parameters, which are 15mm、30mm、45mm.

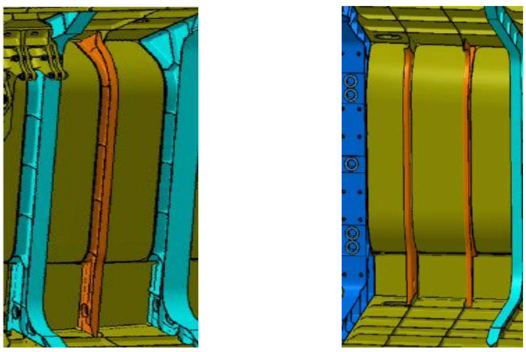


Fig.1 Real structure of aircraft vibration-fatigue critical region

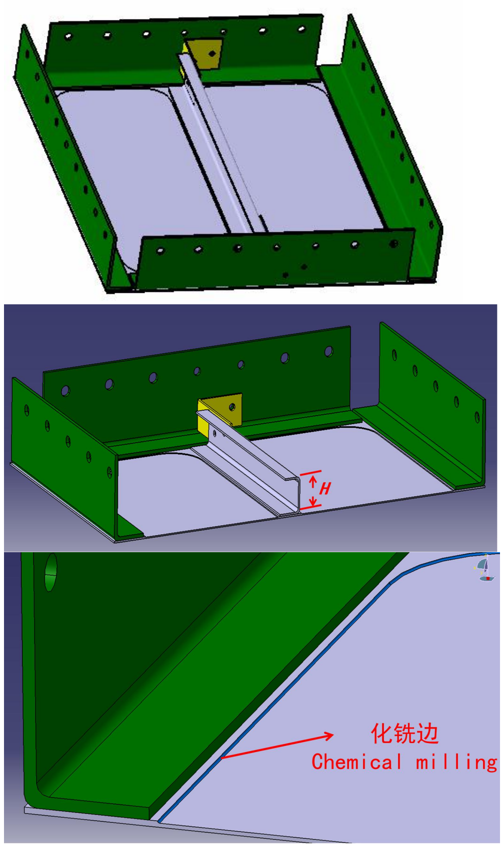


Fig.2 The panel structure with two typical characteristics

3.2 Establishment Of Finite Element Model For The Typical Panel Structure

S4R type element is used in the finite element model, which is a four node shell element. When modeling the chemical milling edge, the shell element should be offset. Mechanical connections such as bolts and rivets are simulated by means of Fasteners. The finite element model of the typical panel structure is shown in Figure 3.

Two analysis steps are defined in the simulation process. The first analysis step is used for the mode calculation, and the natural frequencies of the structure are extracted. The second analysis step applies the basic excitation or base motion perpendicular to the panel surface. The excitation frequency is always traced to the natural frequency of the structure to simulate the resonance state.

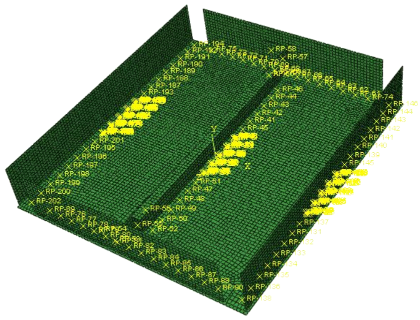


Fig.3 Finite element model of panel structure

4 Vibration Fatigue Damage Analysis Of The Typical Panel Structure

4.1 Vibration Fatigue Damage Evolution Analysis

On the subprogram interface provided by finite element software, a set of program has been written in PYTHON language, and the constitutive equation considering material damages is established[13]. The vibration fatigue life of the panel structure is obtained by using the program. The analysis results show that:

- When the C-shaped reinforcing rib height is 15mm and 30mm, the first failure element (or fatigue crack) appears at the chemical milling edge, and extends along the chemical milling edge. The development of the damage field is shown in Figure 4. The red elements indicate damage, and the blue elements indicate no damage;
- When the C-shaped reinforcement height is 45mm, the failure elements are possibly appear at both the chemical milling edge and the connection corner, as shown in Figure 5.

The vibration fatigue life of the panel structure with different reinforcing rib height are: 1.9e5 cycles 、 2.34e6 cycles 、 5.88e5 cycles. The simulation results show that ,the vibration fatigue life is longest when the height of the C-shaped reinforcing rib is 30mm. If the height of the reinforcing rib is too low, the enhanced effect will not be achieved. If the height of the reinforcing rib is too high, the torsional stiffness of the rib will decrease, so the vibration of the rib and the panel will be more intense, and the vibration fatigue life will also be reduced. In addition, we can see that when the panel structure has chemical milling edge, the fatigue crack will preferentially appear on the milling edge. Therefore, it is recommended to avoid using chemical milling on the components with more serious vibration fatigue problem.

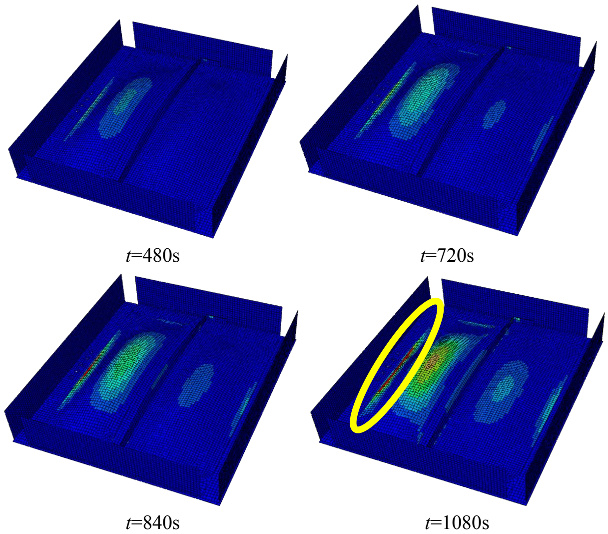


Fig.4 The damage field at different time (C-shaped reinforcing rib height is 15mm or 30mm)

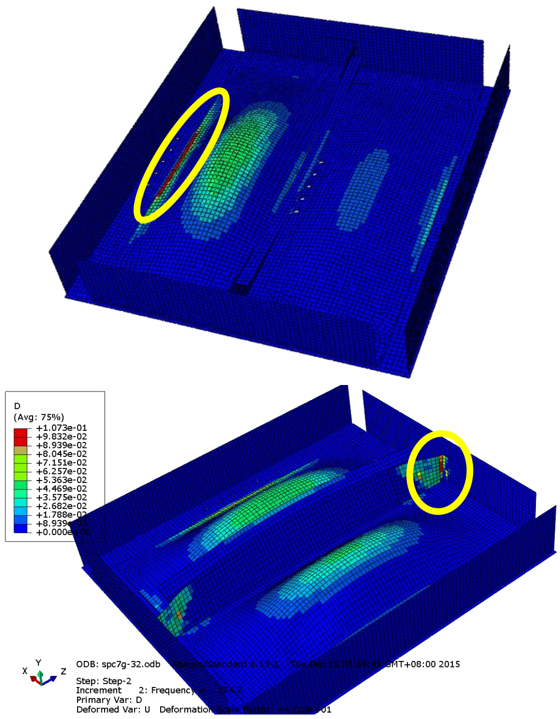


Fig.5 The location of the fatigue cracks (C-shaped reinforcing rib height is 45mm)

4.2 Results Of Vibration Fatigue Test

In order to compare with the numerical simulation results, the vibration fatigue tests were carried out by the electromagnetic vibrator. The installation of test specimen and test fixture is shown in figure 6.The loading mode is consistent with the numerical simulation. During the test, the visual crack was observed regularly. If there was a visual crack, the test will be terminated and the test time was recorded.

The test results show that: when the C-shaped reinforcing rib height is 15mm、30mm and 45mm respectively, the average fatigue lives of the test specimen are:1.62e5 cycles、2.4e6 cycles、8.6e5 cycles. The comparisons between the test results and the simulation results are shown in Table 1.We can see that, the maximum error is about 31.63%.

In addition, according to the statistics of fatigue crack location, 75% of the fatigue cracks appear on the chemical milling edge and extend along the milling edge, which is very consistent with the simulation results. A part of the test results are shown in Figure 7.

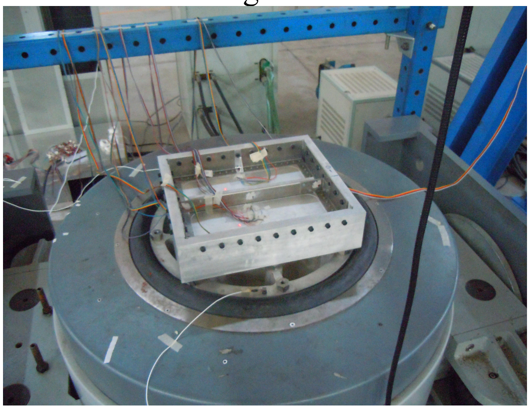
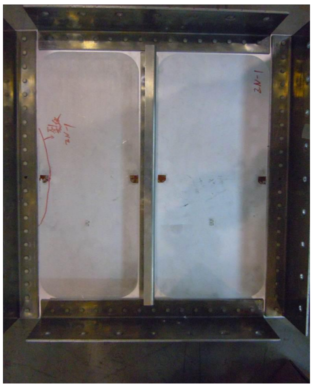


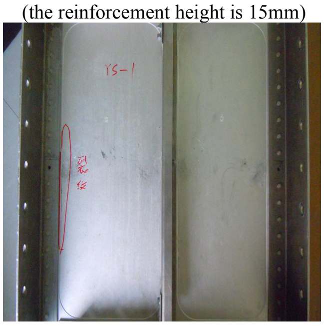
Fig. 6 Vibration fatigue test

Tab.1 Comparison of numerical simulation results and experimental results

	the reinforcement height is 15mm	the reinforcement height is 30mm	the reinforcement height is 45mm
numerical simulation results of vibration fatigue life	1.9×10^5 cycles	2.34×10^6 cycles	5.88×10^5 cycles
experimental results of vibration fatigue life	1.62×10^5 cycles	2.4×10^6 cycles	8.6×10^5 cycles



(the reinforcement height is 15mm)



(the reinforcement height is 30mm)

(the reinforcement height is 45mm)

Fig.7 Vibration fatigue damage location from the test results

It can be seen from the experimental results that, the vibration fatigue life of the panel structure does not increase with the reinforcing rib height, and the vibration fatigue life is maximum when the height of the C-shaped reinforcing rib is 30mm.

5 Conclusions

The vibration fatigue damage analysis of one typical aircraft panel structure was carried out based on the continuous damage mechanics theory, and the simulation results were well verified by the vibration fatigue test. The following main conclusions were obtained:

1) A set of program which was suitable for vibration fatigue damage analysis has been obtained, and the correctness and effectiveness of the program are verified by the test;
2) The panel structure with 30mm C-shaped reinforcing rib has the longest vibration fatigue life. If the height of the reinforcing rib is too low, the enhanced effect will not be achieved. If the height of the reinforcing rib is too high, the torsional stiffness of the rib will decrease, accordingly the vibration of the rib and the panel will be more intense, and the vibration fatigue life will also be reduced;
3) The fatigue crack was more likely to appear when the panel structure with the chemical milling edge. Therefore, chemical milling is not recommended on the critical components with serious vibration fatigue problems.

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