

# Equivalent Constant Amplitude Spectrum Design Method and Experimental Verification of Structural Crack Growth Flight-by-Flight Spectrum

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(Received 22 December 2025; revised 28 January 2026; accepted 14 February 2026)

**Abstract:** In fatigue damage tolerance verification tests of aircraft structures, the simulation and loading of flight-by-flight spectra require considerable time and resources. To improve the efficiency of load spectrum design and testing, an equivalent constant-amplitude spectrum design method for flight-by-flight spectra is proposed based on the equivalence of crack growth behavior. By combining the Paris crack growth model with the Walker stress ratio correction, the equivalent stress amplitude is directly calculated using structural parameters and load spectrum characteristics, enabling a rapid transformation from variable-amplitude spectra to constant-amplitude spectra. The original spectrum is discretized based on the load-exceedance curve, and the equivalence relationship between multi-level block spectra and constant-amplitude spectra is established. Taking a typical lower wing skin structure of a transport aircraft as an example, two equivalent spectra are designed and validated through fatigue crack growth tests on 2024-T351 center-hole plate specimens. The experimental results show that the fatigue life deviation between the equivalent spectra and the original flight-by-flight spectrum is within 10%, demonstrating the effectiveness of the proposed method. Moreover, the equivalent spectrum constructed under the condition of invariant mean flight stress exhibits higher equivalence accuracy. The influence of spectral shape on the equivalent stress amplitude is further analyzed, revealing that the equivalent stress amplitude increases with the spectrum shape coefficient. The proposed method provides a useful reference for load spectrum design in aircraft structural damage tolerance verification tests.

**Keywords:** aircraft structure; crack growth; fatigue load spectrum; equivalent test; stress intensity factor

**CLC number:** V215    **Document code:** A    **Article ID:** 1005-1120(2026)01-0085-10

## 0 Introduction

In modern aircraft design, the damage tolerance design principle has become a key concept for ensuring that aircraft structures can still operate safely even after initial defects or cracks occur<sup>[1]</sup>. Verifying the damage tolerance characteristics of structure through tests is an indispensable part of aircraft model development process<sup>[2]</sup>. In damage tolerance tests, the selection of load spectrum directly determines the reliability and economy of tests. Traditional verification methods require the compilation of

flight-by-flight spectra under simulated service load conditions<sup>[3-5]</sup>, but the actual flight load environment is complex, with variable spectra and large dispersion<sup>[6-8]</sup>. The design and testing of flight-by-flight spectra often consume a significant amount of time and resources, significantly affecting the efficiency of verifying the damage tolerance performance of aircraft structures. Therefore, developing simple and user-friendly equivalent load spectra has significant engineering application value and economic benefits.

Since the development of flight-by-flight spectrum compilation method, the simplification and

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**How to cite this article:** ZHU Gaoshang, ZHAO Qia, CAO Jing. Equivalent constant amplitude spectrum design method and experimental verification of structural crack growth flight-by-flight spectrum[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2026, 43(1): 85-94.

<http://dx.doi.org/10.16356/j.1005-1120.2026.01.007>

equivalence of load spectrum have extensive research. Short spectra such as the short-FALSTAFF and the mini-TWIST have significantly shortened the verification time<sup>[9-12]</sup>. Subsequent scholars have proposed different load spectrum equivalence methods based on different load spectrum characteristics, different structural material properties, and different fatigue damage models<sup>[13]</sup>. Among them, the construction of the constant amplitude spectrum has received considerable attention. Sui et al.<sup>[14]</sup> and Wang et al.<sup>[15]</sup> transformed the flight-by-flight random spectrum into a constant amplitude stress spectrum and calculated the equivalent damage, considering multiple fatigue critical parts, and established the constant amplitude load spectrum through optimization calculations. Liu et al.<sup>[16]</sup> based on the probabilistic fatigue damage model considering the load sequence effect, proposed an equivalent fatigue damage simplification model for multi-level load spectra. Xiang et al.<sup>[17]</sup> based on the equivalent stress transformation and inverse first-order reliability method (IFORM), converted the amplitude load of random variables into an equivalent constant amplitude load spectrum, and proposed a general probabilistic fatigue crack propagation prediction method. Sonsino et al.<sup>[18]</sup> compared two methods of converting stress or load spectra into damage equivalent constant amplitude loads, namely the modified equivalent stress (MES) and the required fatigue strength (RFS) concept. In addition to constructing the constant amplitude spectrum, some scholars have also conducted research on other load equivalence methods. Refs.[19-21] etc. constructed different load spectrum damage conversion methods based on the detail fatigue rating value (DFR) method. Zhao et al.<sup>[22]</sup> proposed a multi-axis fatigue test spectrum compilation method based on damage equivalence for the single-axis stress failure mode under multi-axis loads. Xiong et al.<sup>[23]</sup> proposed the identification principle of small loads and the equivalent damage fusion method, and accelerated the full-scale structure fatigue test while retaining the original load history. Jin et al.<sup>[24]</sup> considered the dispersion of fatigue life and established the equivalent damage spectrum by small loads damage con-

version, and measured the equivalent effect of load spectrum using the Bhattacharyya distance. Raoult et al.<sup>[25]</sup> proposed a general framework for constructing equivalent fatigue loads, aiming to consider some uncertainties of structure.

It can be seen that most of the existing studies adopt deterministic fatigue analysis theories to design equivalent load spectra, and most of them focus on the design of equivalent load spectra of the durability verification stage. There is relatively little research on the equivalent methods for complex load spectra in the damage tolerance verification test stage. The related research relies on complex damage accumulation iterative calculations and lacks direct representation and equivalence of structural crack propagation characteristics. This leads to the lack of a fast, convenient and efficient load spectrum equivalence method when dealing with complex and variable new flight mission profile load spectra.

This paper presents an equivalent constant amplitude spectrum design method for the flight-by-flight spectrum. Based on the direct calculation of equivalent loads using structural parameters and load spectrum parameters, an equivalent constant amplitude test spectrum is compiled to achieve rapid verification of structural crack propagation. A design example of equivalent spectrum is given in combination with typical transport aircraft load spectra, and fatigue crack propagation life tests of 2024-T351 center-hole plate specimens are conducted to verify the effectiveness of relevant equivalent methods. The variation laws of equivalent loads under different spectrum shape characteristics are further discussed to provide a reference for the design of load spectra in aircraft structural damage tolerance tests.

## 1 Equivalent Constant Amplitude Load Spectrum Design Method

### 1.1 Calculation of equivalent stress in the variable amplitude spectrum

The main variable that affects the structural crack propagation rate  $da/dN$  is the stress intensity factor range  $\Delta K$ . Crack propagation calculations are generally carried out based on the Paris equation<sup>[26]</sup>,

which is described as

$$\frac{da}{dN} = C\Delta K^m \quad (1)$$

where  $a$  represents the crack length and  $N$  the number of cycles;  $C$  and  $m$  are both material constants.

The crack propagation calculation under the variable amplitude load spectrum needs to take into account the influence of stress ratio. The Walker equation provides a method for modifying the stress intensity factor<sup>[27]</sup>. By making the modification, the equivalent stress intensity factor range  $\Delta K_{eq}$  under the stress ratio  $R=0$  is obtained, and the corresponding propagation rate is the same as the crack propagation rate under the actual stress intensity factor range.

$$\Delta K_{eq} = K_{max}(1-R)^\gamma \quad (2)$$

where  $K_{max}$  represents the peak stress intensity factor under actual stress cycles,  $R$  the stress ratio, and  $\gamma$  a material constant.

The stress intensity factor is calculated as

$$K = FS\sqrt{\pi a} \quad (3)$$

where  $F$  represents the structural shape factor. For a center-through crack in a flat tensile specimen,  $F$  can be calculated as<sup>[28]</sup>

$$F = \frac{1 - 0.5r + 0.326r^2}{\sqrt{1-r}} \quad (4)$$

where  $r$  is the ratio of central crack full length  $2a$  to the plate width  $W$ , that is,  $r = 2a/W$ .

Based on Eqs.(2, 3), the equivalent stress cycle can be calculated as

$$\Delta S_{eq} = S_{max}(1-R)^\gamma \quad (5)$$

Combining Eqs.(1, 2), the crack propagation rate can be calculated as

$$\frac{da}{dN} = C_0(1-R)^{m(\gamma-1)}\Delta K^m \quad (6)$$

where  $C_0$  is a constant, which is obtained by fitting the fatigue crack propagation performance test data of the relevant material specimens under the stress ratio  $R=0$ .

Assuming that the load spectrum consists of  $k$  load cycles, the crack propagation length under the  $i$ th load cycle  $\Delta a_i$ , can be equivalently regarded as the crack propagation length under a stress cycle with  $R=0$ . Then

$$\Delta a_i = C_0\Delta K_{eq,i}^m \quad (7)$$

where  $\Delta K_{eq,i}$  represents the equivalent stress intensity factor range.

If the crack length does not change significantly within a block spectrum period, then the  $F$  can be approximately regarded as constant. The crack propagation length under a block spectrum  $\Delta a_s$  can be expressed as

$$\Delta a_s = \sum_{i=1}^k \Delta a_i = \sum_{i=1}^k C_0 \Delta K_{eq,i}^m \quad (8)$$

The average crack propagation rate within a block spectrum period is

$$\left(\frac{da}{dN}\right)_s = \frac{\Delta a_s}{k} = \frac{C_0 \sum_{i=1}^k \Delta K_{eq,i}^m}{k} = C_0 \Delta K_{eq}^m \quad (9)$$

where  $\Delta K_{eq}$  represents the equivalent stress intensity factor range for a constant amplitude load spectrum

$$\Delta K_{eq} = \left(\frac{\sum_{i=1}^k \Delta K_{eq,i}^m}{k}\right)^{\frac{1}{m}} \quad (10)$$

Consequently, the equivalent stress range of constant amplitude load spectrum can be determined as

$$\Delta S_{eq} = \frac{\Delta K_{eq}}{F\sqrt{\pi a}} = \left(\frac{\sum_{i=1}^k \Delta S_{eq,i}^m}{k}\right)^{\frac{1}{m}} = \left[\frac{\sum_{i=1}^k (S_{max,i}(1-R_i)^\gamma)^m}{k}\right]^{\frac{1}{m}} \quad (11)$$

where  $\Delta S_{eq,i}$  represents the equivalent stress range of the  $i$ th stress cycle when it is corrected to  $R=0$ . The stress peak and stress ratio of the  $i$ th stress cycle are respectively  $S_{max,i}$  and  $R_i$ .

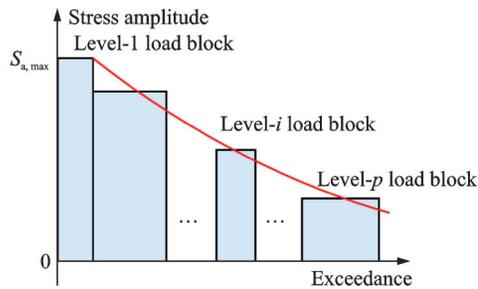
## 1.2 Discretization and equivalence of load spectrum

The fatigue load spectrum of aircraft structure is generally compiled based on the discrete load-exceedance curve obtained through actual measurement statistics<sup>[29]</sup>. The exceedance represents the number of fatigue loads that exceed a certain level in the load spectrum, and the load-exceedance curve visually represents the composition of different levels of loads in the load spectrum. Particularly, under the condition that the mean load value is constant,

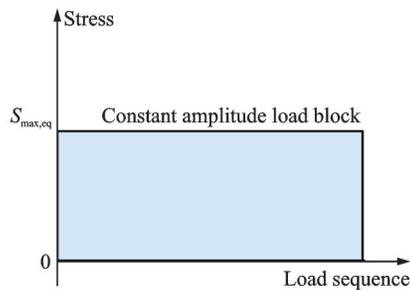
for the multi-level block spectrum composed of  $p$ -level loads obtained by discretizing the load amplitude-exceedance curve<sup>[30]</sup>, as shown in Fig.1(a). Assuming that the stress peak, stress valley, stress ratio, stress amplitude, and quantity of the  $i$ th level load are  $S_{\max,i}$ ,  $S_{\min,i}$ ,  $R_i$ ,  $S_{a,i}$ ,  $n_i$ , respectively, where  $i \in [1, p]$ , the total number of load cycles of the multi-level block spectrum is  $k$ . This load spectrum can be equivalent to a set of constant amplitude load spectra (stress ratio  $R=0$ ), and similar crack propagation effects can be achieved. The stress peak of the equivalent constant amplitude load spectrum is  $S_{\max,eq}$ , which can be calculated as

$$S_{\max,eq} = \Delta S_{eq} = \left[ \frac{\sum_{i=1}^p \left\{ \left[ S_{\max,i} (1 - R_i)^\gamma \right]^m \cdot n_i \right\}}{\sum_{i=1}^p n_i} \right]^{\frac{1}{m}} \quad (12)$$

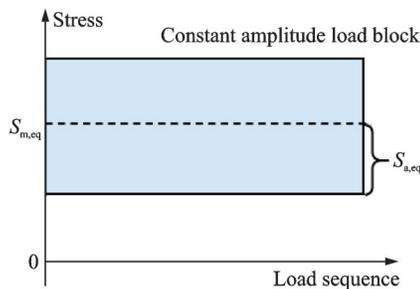
Based on the above method, the flight-by-



(a) A multi-level block spectrum obtained from the discretization of load-exceedance curve



(b) Equivalent constant amplitude load spectrum ( $R=0$ )



(c) Equivalent constant amplitude load spectrum (specified mean stress  $S_{m,eq}$ )

Fig.1 Discretization and equivalence of load spectrum

flight spectrum can be equivalently regarded as a constant amplitude spectrum for fatigue crack propagation tests, as shown in Fig.1(b). Further, if it is necessary to establish an equivalent constant amplitude load spectrum under a specified mean stress  $S_{m,eq}$ , as shown in Fig.1(c). By combining Eq.(5), the corresponding equivalent stress amplitude  $S_{a,eq}$  can be calculated as follows, and it is solved through numerical methods

$$\Delta S_{eq} = S_{\max} (1 - R)^\gamma = (S_{a,eq} + S_{m,eq}) \left( \frac{2S_{a,eq}}{S_{a,eq} + S_{m,eq}} \right)^\gamma \quad (13)$$

Finally, the flowchart of generating an equivalent constant amplitude load spectrum based on the flight-by-flight spectrum is shown in Fig.2.

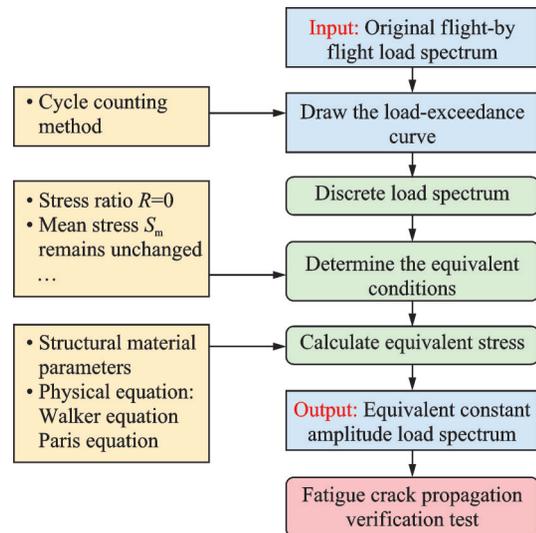


Fig.2 Equivalent constant amplitude load spectrum design flowchart

## 2 Experimental Verification

### 2.1 Specimen and material

To verify the implementation effect of the above load spectrum equivalent method, crack propagation tests are conducted on typical structures under the flight-by-flight spectrum and the equivalent spectrum. The specimens are taken and designed from the lower skin panel of a transport aircraft wing, using 2024-T351 aluminum alloy material. The specimen dimensions are shown in Fig.3. By using wire-cutting to pre-form cracks at the center

hole and loading them with the E-type flight load spectrum given in Section 2.2 of this paper to form natural cracks. The loading is stopped when the new increase in the length of single-sided crack reached 1 mm, and this length is taken as the initial crack length. The crack propagation rate curves and material parameters are shown in Fig.4 and Table 1, which are obtained from the material performance data provided by the specimen supplier.

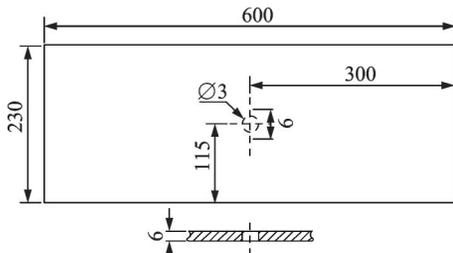


Fig.3 Specimen dimensions

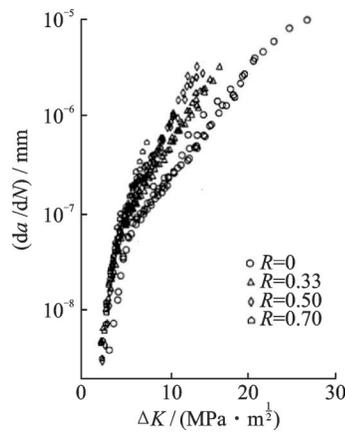


Fig.4 Crack propagation rate curves of 2024-T351

**Table 1** Material parameters of 2024-T351 ( $R=0$ )

fracture toughness	$C_0 / (\text{mm} \cdot (\text{MPa} \cdot \text{m}^{\frac{1}{2}})^{-m} \cdot \text{cycle}^{-1})$	$m$	$\gamma$
$K_{Ic} / (\text{MPa} \cdot \text{m}^{\frac{1}{2}})$	$\text{m}^{\frac{1}{2}} \cdot \text{cycle}^{-1}$		
34	$1.42 \times 10^{-8}$	3.59	0.68

## 2.2 Load spectrum

### 2.2.1 Development of original load spectrum

The original test load spectrum SP0 is compiled based on the service load measured data of this transport aircraft and then transformed into a stress spectrum. The stress spectrum of specimen represents the actual stress conditions of the critical part of aircraft. The entire flight-by-flight spectrum block includes 5 types of flights and 6 000 take-offs and landings, as shown in Fig.5. The quantity and

length of the flight spectrum, as well as the stress peak values, are presented in Table 2. The mean flight stress of specimen (corresponding to the stress at 1g load factor of aircraft) is  $S_{mf}=66$  MPa. Assuming that the compressive load has no effect on crack propagation, the minimum stress of the stress spectrum is set to 0. Under the entire spectrum block, the stress amplitude vs. exceedance curve of flight load and the stress peak vs. exceedance curve of ground-air-ground cyclic load are shown in Fig.6. The stress amplitude of flight load spectrum is randomly distributed. The load-exceedance curve is smooth. There are 5 types of flights in 6 000 flights.

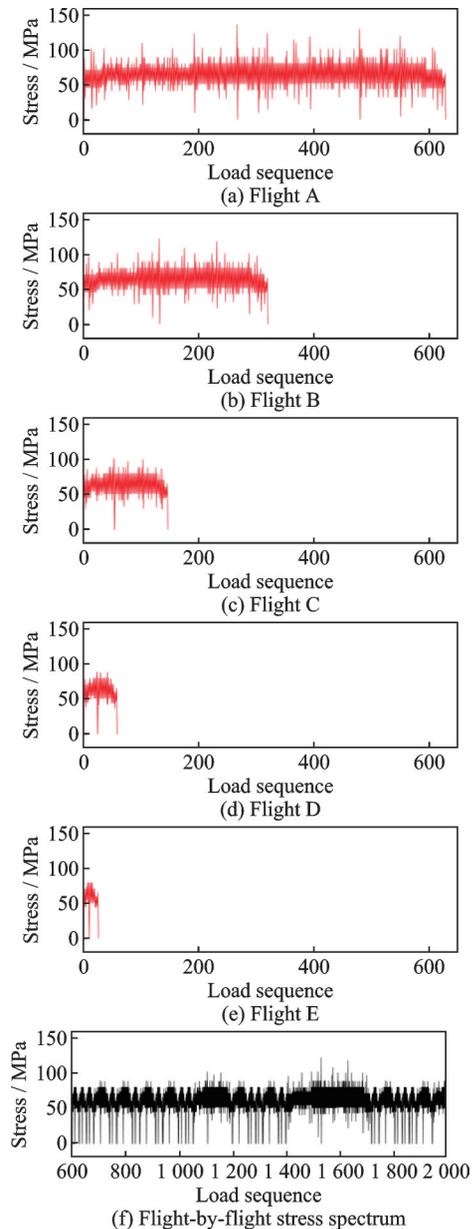
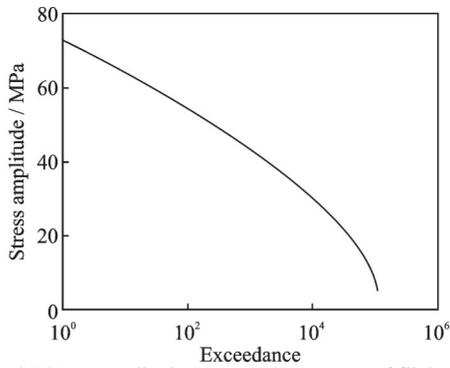


Fig.5 Generation of flight-by-flight spectrum

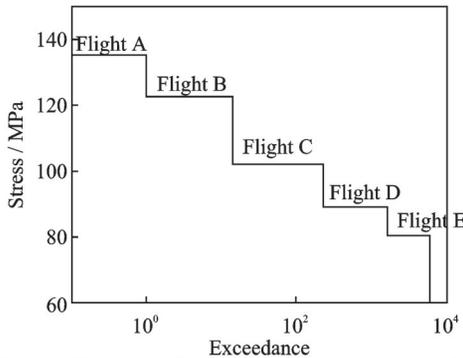
The maximum and minimum stress values for each flight type are fixed. The stress peak-exceedance curve of ground-air-ground load presents a discrete step-like shape.

**Table 2 Statistics on various flight types in a block spectrum**

Flight type	Flight cycle	Load spectrum length	Peak stress/MPa
A	1	627	135
B	13	321	123
C	215	147	102
D	1 431	59	89
E	4 340	27	81
Total	6 000	23 8014	—



(a) Stress amplitude vs. exceedance curve of flight load

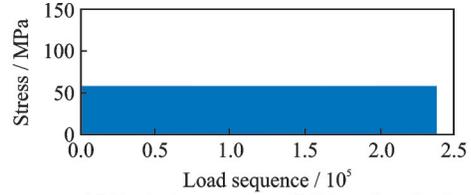


(b) Stress peak vs. exceedance curve of ground-air-ground cyclic load  
Fig.6 Load composition of flight load and ground-air-ground cyclic load in the spectrum block

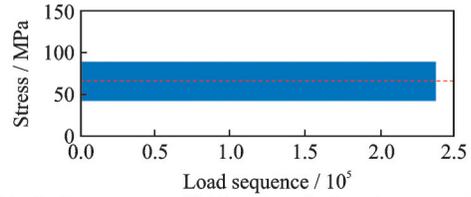
### 2.2.2 Equivalent load spectrum design

Based on the load spectrum given in Fig.6 and the discretization and equivalence methods of load spectrum presented in Section 1, the equivalent constant amplitude spectrum SP1 with a stress ratio  $R=0$  is designed according to Eq.(12), as shown in Fig.7(a), and the peak stress  $S_{\max,eq}=57.2$  MPa. Furthermore, if the mean flight stress remains unchanged, the equivalent constant amplitude spec-

trum SP2 can be designed based on Eq.(13), as shown in Fig.7(b), and the stress amplitude  $S_{a,eq}=23.3$  MPa.



(a) Equivalent spectrum SP1 based on  $R=0$

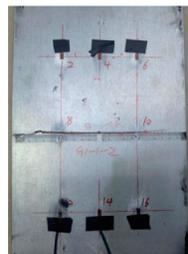


(b) Equivalent spectrum SP2 based on the invariant mean flight stress

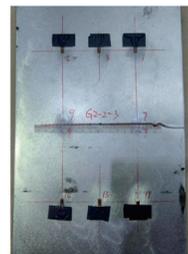
Fig.7 Equivalent constant amplitude spectrum

### 2.3 Fatigue test and results

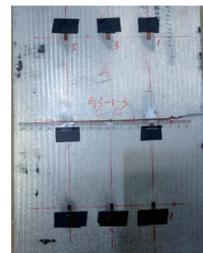
The fatigue crack propagation test on the 2024-T351 plate specimens is conducted using the electro-hydraulic servo fatigue test system MTS 370.10. Three specimens are tested under each spectrum of the original spectrum SP0, equivalent spectrum SP1, and equivalent spectrum SP2. The test frequency is 5 Hz. The crack propagation process is observed and recorded until fracture. The typical morphologies of the specimens after fracture and the curves of crack length varying with the flight cycles are shown in Fig.8 and Fig.9. The cracks in the



(a) Under the SP0 spectrum



(b) Under the SP1 spectrum



(c) Under the SP2 spectrum

Fig.8 Morphologies of typical failure specimens

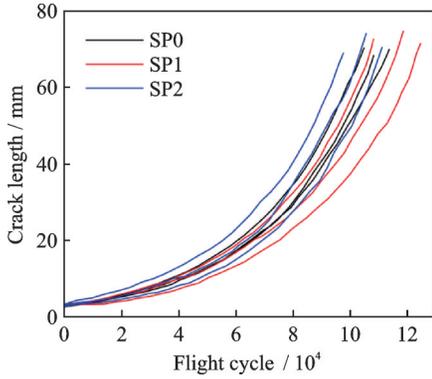


Fig.9 Crack propagation curves of specimens

specimens all start from the center and extend perpendicularly to the tensile load direction to the edge of the plate. The crack growth begins at the initial location and gradually accelerated. The crack growth paths and growth curves of specimens are relatively consistent. The crack lengths, fatigue lives at the moment of fracture, and the corresponding deviation data of the equivalent spectra compared to the original spectrum are statistically shown in Table 3.

**Table 3 Statistics of crack length and fatigue life for failed specimens**

Load spectrum	Failure crack length			Fatigue life		
	Failure crack length $a_f$ / mm	Mean failure crack length $a_{f,m}$ / mm	Relative deviation $\delta$ / %	Fatigue life $N_f$ (Flight cycles)	Mean fatigue life $N_{f,m}$ (Flight cycles)	Relative deviation $\delta$ / %
SP0	70.4	69.6	—	104 889	108 963	—
	68.3			108 265		
	70.0			113 734		
SP1	72.7	73.0	4.9	108 196	117 153	7.5
	74.7			118 619		
	71.5			124 643		
SP2	69.0	71.2	2.3	97 680	104 840	-3.7
	74.1			105 639		
	70.5			111 201		

## 2.4 Discussion

As can be seen from Table 3, the relative deviations of failure crack lengths and fatigue lives of specimens between the equivalent spectra and the original spectrum are all within 10%, indicating that the equivalent spectrum design method presented in this paper can effectively simplify the structural damage tolerance verification tests. The mean failure crack length under the equivalent spectrum is slightly greater than that under the original spectrum, which is related to the maximum loads of the equivalent spectra SP1 and SP2 being lower than that of the original spectrum. The relative deviation of the mean fatigue life between the equivalent spectrum SP2 and the original spectrum is small, indicating that the equivalent load spectrum established by maintaining the mean flight stress unchanged and retaining the original characteristics of spectrum has a better equivalent effect. Meanwhile, the fatigue life under SP2 is slightly shorter than that under the original spectrum. The test results under this spec-

trum are relatively conservative, and therefore it is also the more recommended equivalent spectrum.

It is worth noting that the classical Walker equation is primarily formulated for uniaxial loading conditions and mode I crack growth. Therefore, for multiaxial stress states or mixed-mode crack growth (mode I - II - III), the applicability of this method is limited and further validation is required.

## 2.5 Influence of spectral shape

Obviously, as can be seen from Eq.(12) and Fig.1, the determination of equivalent load level is influenced by the load distribution characteristics in the load spectrum. These distribution characteristics are reflected in the shape of load-exceedance curve. The load-exceedance curve of stress spectrum of structural details can be described as<sup>[31]</sup>

$$\ln H_i = \ln H_0 \cdot [1 - (S_{a,i}/S_{a,max})^\nu] \quad (14)$$

where  $H_i$  represents the exceedances of the  $i$ th amplitude stress  $S_{a,i}$ ,  $H_0$  the total number of cycles in the load spectrum,  $S_{a,max}$  the maximum stress amplitude in the load spectrum, and  $\nu$  the spectral shape

coefficient. The magnitude of  $\nu$  reflects the concavity or convexity degree of load-exceedance curve<sup>[32]</sup>. As shown in Fig.10, in a steep spectrum ( $\nu < 1$ ), there are fewer high-load quantities and more low-load quantities, while in a flat spectrum ( $\nu > 1$ ), the quantity of high loads significantly increases.

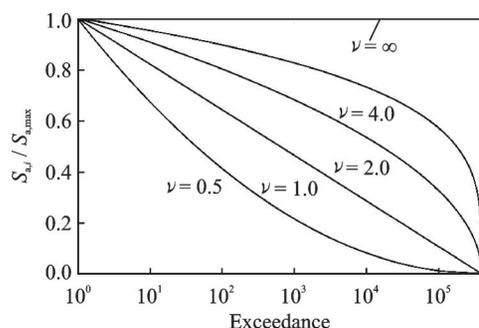


Fig.10 Load-exceedance curves under typical spectral shape coefficient

The equivalent spectrum stress levels corresponding to different spectral shapes are also different. For the load spectrum given in Fig.6, assuming that the maximum stress, minimum stress, length, mean flight stress and other characteristic parameters of the spectral blocks remain unchanged, only the spectral shape is changed. Taking the spectral shape coefficient of 0.3—5 as the calculation condition, based on the mean flight stress unchanged in Fig.7(b), equivalent constant amplitude spectra are designed, and the corresponding equivalent stress spectrum amplitudes are given. The curve of equivalent stress amplitude varying with the spectral shape coefficient is established, as shown in Fig.11. It can be seen that as the spectral shape coefficient increases, the proportion of high load in the load spectrum

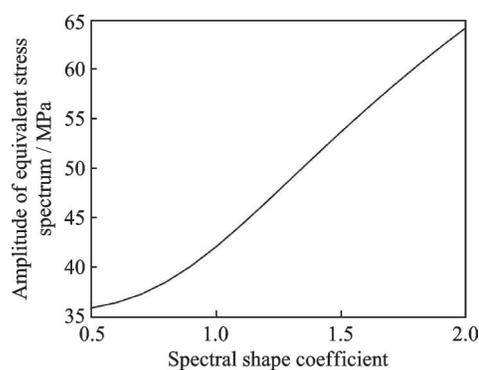


Fig.11 Variation relationship curve between amplitude of equivalent stress spectrum and spectral shape coefficient

gradually increases, and the corresponding equivalent stress spectrum amplitude also increases. Based on this curve, the equivalent spectrum corresponding to different spectral shapes can be quickly determined to meet the needs of rapid verification tests for structural damage tolerance under different flight tasks.

### 3 Conclusions

This paper presents a constant amplitude equivalent spectrum design method for the flight-by-flight spectrum, providing a reference for the load spectrum design in fatigue damage tolerance verification tests for aircraft structures. The specific conclusions are as follows:

(1) The crack propagation test results of the 2024-T351 center-hole plate specimens show that the crack propagation life deviation under the equivalent spectrum compared to the original spectrum is within 10%, verifying the feasibility and reliability of the method proposed in this paper.

(2) The equivalent spectrum based on the mean stress invariance has a smaller crack propagation life deviation compared to the equivalent spectrum based on the stress ratio  $R=0$ , indicating that the design of equivalent spectrum should try to maintain the characteristics of original load spectrum as much as possible.

(3) The amplitude of equivalent load spectrum increases with the increase of spectral shape coefficient of load-exceedance curve. By establishing the curve of equivalent load versus spectrum shape coefficient, the equivalent constant amplitude spectrum design under different flight mission spectral shapes can be quickly achieved.

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**Acknowledgement** This work was supported by the National Natural Science Foundation of China (No.52075244).

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**Author contributions** Mr. ZHU Gaoshang was responsible for conducting the experiments, analyzing and calculating, processing the data, and writing the manuscript. Ms. ZHAO Qia was responsible for editing the text, checking and proofreading. Dr. CAO Jing designed the framework and ideas of the article. All authors commented on the manuscript draft and approved the submission.

**Competing interests** The authors declare no competing interests.

(Production Editor: WANG Jie)

## 结构裂纹扩展飞续飞谱的等效常幅谱设计与试验验证

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**摘要:**为提高飞机结构损伤容限验证试验加载效率,针对飞续飞载荷谱试验资源消耗大、实施复杂的问题,提出一种等效常幅载荷谱设计方法。该方法以应力强度因子范围等效为基础,结合Paris裂纹扩展模型和Walker应力比修正关系,通过结构参数与载荷谱参数直接计算等效应力幅值,实现飞续飞载荷谱向常幅载荷谱的快速等效转换。基于载荷超越曲线对原始载荷谱进行离散化处理,建立多级载荷块谱与常幅载荷谱之间的等效关系,并提出在保持平均飞行应力不变条件下的等效谱构建方法。以某型运输机机翼下壁板典型结构为研究对象,构建飞续飞载荷谱,并设计两种等效常幅载荷谱方案。通过2024-T351铝合金中心孔板试件疲劳裂纹扩展试验,对原始谱与等效谱下的裂纹扩展行为和疲劳寿命进行了对比验证。试验结果表明:所提出方法得到的等效常幅载荷谱与原始飞续飞载荷谱在裂纹扩展寿命上的偏差均小于10%,验证了该方法的可行性与有效性;在保持平均飞行应力不变条件下构建的等效谱具有更高的等效精度。此外,通过改变载荷谱超越曲线的谱形系数,分析了谱形特征对等效应力幅值的影响规律,结果表明等效应力幅值随谱形系数增大而增加。研究结果可为飞机结构损伤容限验证试验中的载荷谱简化设计提供参考。

**关键词:**飞机结构;裂纹扩展;疲劳载荷谱;等效试验;应力强度因子

**研究亮点:**

1. 提出一种结构裂纹扩展飞续飞谱的等效常幅谱设计方法。
2. 通过2024-T351铝合金中心孔板裂纹扩展试验验证了方法有效性。
3. 保持平均飞行应力不变的等效谱具有更高的等效精度。
4. 揭示了载荷谱谱形系数对等效应力幅值的影响规律。