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Fatigue behavior of aluminum stiffened plate subjected to random vibration loading

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Abstract: Vibration tests were carried out on three types of stiffened aluminum plates with fully clamped boundaries under random base excitation. During the test, the response of the specimens was monitored using strain gauges. Based on the strain history, the accumulation of fatigue damage of the stiffened plates was estimated by means of the rainflow cycle counting technique and the Miner linear damage accumulation model in the time domain. Utilizing the change of natural frequencies, a nonlinear model was fitted for predicting the fatigue damage of plate and then the foregone failure criterion of 5% reduction in natural frequency is improved. The influence of section and spacing of the stiffeners on the vibration fatigue behavior of the aluminum plate was investigated. The results show that the fatigue life of aluminum plate increases with adding either T or L section riveted stiffeners. With the same cross-sectional area of stiffener, the T section stiffened plate shows longer fatigue life than L section stiffened plate. Meanwhile, the vibration fatigue life also shows great sensitivity to the spacing between the stiffeners.

Key words: stiffened plate; vibration fatigue; vibration test; fatigue life; natural frequency

1 Introduction

Aluminum alloys are widely used in aeronautic engineering in types of plate structures. During the structural design process, the serious fatigue loading must be considered [1], and the fatigue property should be tested or predicted. Random vibration testing is common for estimating the vibration fatigue durability of materials and structures. The methods for predicting fatigue life can be divided into time domain and frequency domain according to the data and parameters used in the analysis. The time-domain based analysis method depends on a cycle counting procedure and cumulative damage rule. The identification of cycles during loading history is usually accomplished by the rainflow counting method [2]. The accumulation of damage is then carried out according to the Miner linear damage accumulation rule [3]. The time-domain method has been accepted widely for fatigue life prediction; however, calculating the cycles of vibration loading process is very time consuming. The frequency-domain methods [4−6] aim to speed up the calculations substantially as they define the loading process by power spectral density function. Most of the existing spectral methods are limited to the stationary Gaussian loading process and cannot account for the changes in the frequency response of a structure resulting from fatigue damage.

Modal analysis has been widely used for damage evaluation by the parameters of natural frequency. Some researchers used the change of natural frequency to detect the damage and defects in metal or composite structures [7−9]. CAWLEY and ADAMS [10] pointed out that the defects in structures can be detected by the natural frequencies at different stages of the loading process. HEARN and TESTA [11] found that the ratio of changes of natural frequencies could be described by a function of damage location. Some investigations showed that the relationship between the loading cycles and the relative changes of natural frequency was non-linear [12−14], and natural frequency decreases dramatically in the end stage of fatigue life. SPOTTSWOOD and WOLFE [15] set a 5% reduction

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in fundamental frequency as the failure criterion to determine the fatigue life of plate. Fatigue damage analysis for multi-point spot-welded joints was carried out by HAN et al [16], based on the changes of frequency response.

In the present work, the relationship between the cumulative fatigue damage in time domain and natural frequency changes is analyzed. The failure criterion of 5% reduction in fundamental frequency is validated by several random vibration fatigue experiments of 2024-T3 plate. In order to improve the service life, the stiffeners were added on the plate. The factors of crossing shape and spacing which influence the enhanced effort of the stiffeners are discussed using the experimental results of vibration fatigue test.

2 Experimental

The plates were fabricated from 2024-T3 aluminum alloy and the chemical composition is given in Table 1. The dimensions of 4 groups of specimens are shown in Fig. 1 (1.6 mm in thickness) and Table 2. The riveted stiffeners were LY12 aluminum with L or T cross section, as shown in Fig. 2 (200 mm in length).

Table 1 Chemical composition of 2024-T3 alloy (mass fraction /%)

Si	Fe	Cu	Mn	Mg
0.5	0.59	3.5−4.9	0.3−0.9	1.2−1.8

Cr	Zn	Ti	Al
0.1	0.25	0.15	Res.

Table 2 Specimen for each group

Group	Section type of stiffener	Spacing/ mm	Natural frequency of specimens/Hz
A	–	–	317.9, 321.0, 311.5, 318.1, 313.2, 324.9
B	L	150.0	370.6, 378.3, 377.8, 377.5, 378.2, 382.2
C	T	150.0	372.9, 369.0, 380.0, 387.1, 378.0, 379.4
D	L	132.0	404.6, 410.3, 412.9, 413.0, 409.1, 406.3

Random vibration fatigue tests were conducted on fully clamped specimen, using a 49 kN electrodynamic shaker (ET-50W-445 Shaker System) as shown in Figs. 3 and 4. The natural frequency and root mean square (RMS) strain history of the specimens were monitored by strain gauges, labeled from 1 to 6 in Fig. 3, and an accelerometer was mounted on the shaker to measure the input acceleration. A sampling rate of 5000 samples per second was used for strain record throughout the test process. The spectrum range and the power spectral density (PSD) level of the input acceleration are shown in Fig. 5, and all of specimens are loaded for 2 h. In this study, a 5% reduction of natural frequency was defined as the fatigue failure of the specimen. After test, the cracks are clearly found along the clamped specimen boundaries.

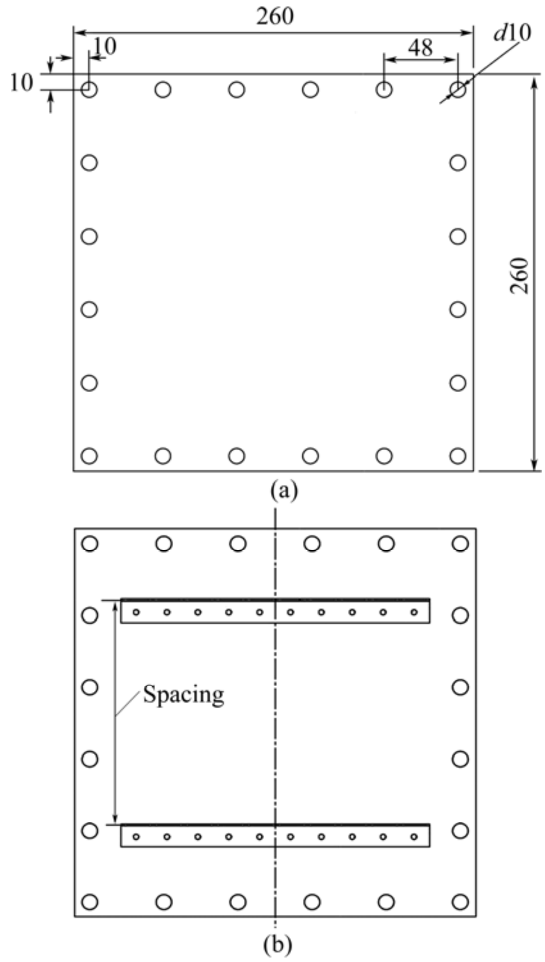

Fig. 1 Dimensions of different specimens (unit: mm): (a) 2024-T3 plate specimen; (b) Stiffened plate specimen

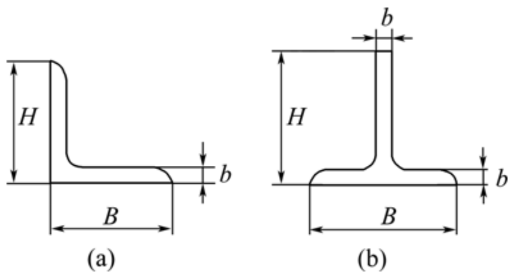

Fig. 2 Cross section and dimension of stiffener: (a) L type, $B=H=16$ mm, $b=1.2$ mm; (b) T type, $B=25$ mm, $H=15$ mm, $b=1$ mm

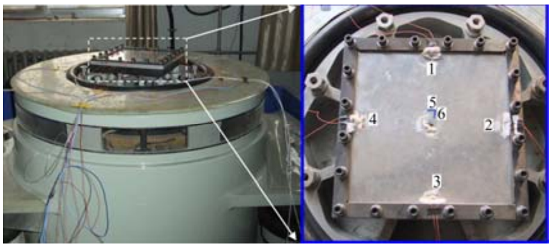

Fig. 3 Shaker and plate specimen (strain gauges is nearby number)

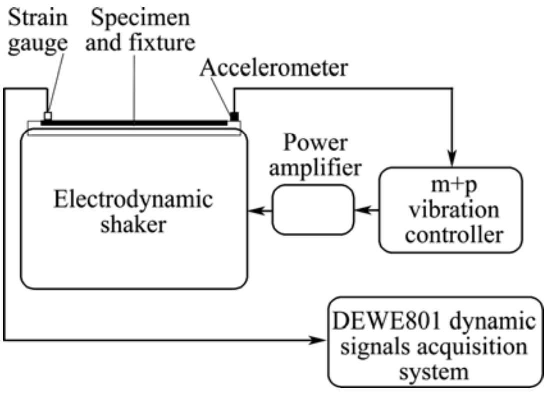

Fig. 4 Testing principle diagram

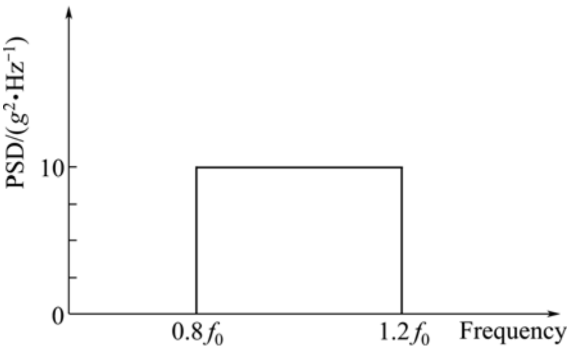

Fig. 5 Vibration loading condition (f_0 is the natural frequency of specimen)

3 Result and discussion

Figure 6 shows the RMS strain history of specimens (group A) during the vibration fatigue loading process. It can be observed that all specimens displayed an response of (700−850)×10^{-6}. With the increase of loading time, the RMS strain of different specimens tends to increase slightly. At the end of loading, the RMS strain falls down due to the reduction in the natural frequency.

Figure 7 shows the history of the natural frequency. It can be observed that the variation of the natural frequency is nonlinear and similar to the RMS strain history. The natural frequency decreases slowly in the first half of the fatigue process, but rapidly in the second half.

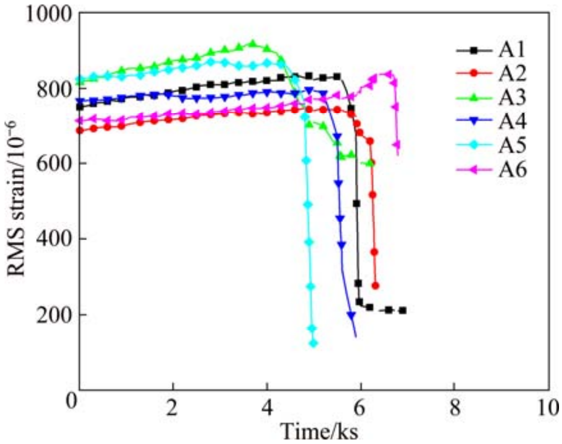

Fig. 6 RMS strain history of group A

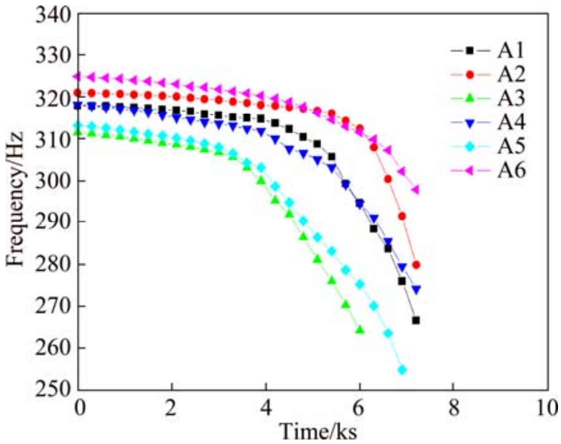

Fig. 7 Reduction in natural frequency of group A

The stress range and mean information are extracted from the strain history using the rainflow cycle counting method. The output from rainflow cycle counting analysis is expressed as a histogram shown in Fig. 8. The three axes are the stress range of each cycle, the mean stress and the number of cycle for each particular range and mean stress. Each cycle can induce a certain amount of fatigue damage in the specimen.

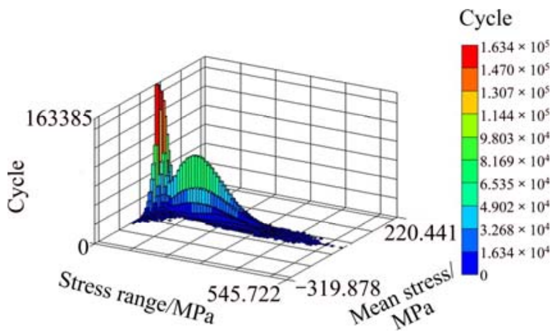

Fig. 8 Histogram of rainflow cycle counting analysis

The total damage can be calculated by the material S−N curve using the Miner rule [2] which can be expressed as equation (1):

$$D=\sum_i \frac{n_i}{N_i} \tag{1}$$

where D is the accumulation damage; n_i is the number of cycles with a particular stress range and mean value; i is a ranging variable; N_i is the number of cycles to failure for a particular stress range and mean stress. The fatigue life can be obtained in form of seconds during relevant loading duration as calculated in the time domain.

Table 3 shows the mean fatigue life for each group of specimen. It can be found that since the reduction in natural frequency is less than 5% when the specimen gets failure, the threshold of 5% can be improved. In order to get the relationship between the fatigue damage and the reduction in natural frequency, a nonlinear fitting was used. DORGEUILLE et al [7] proposed that the change of natural frequency could be used to estimate the damage in the composite. They suggested that the fundamental bending frequency could be related to the elastic modulus, hence it would be possible to use the changes of the natural frequency to define the damage variable. A further research was made by SHANG et al [12] in which the fatigue damage of spot-weld joints was described according to the change of the dynamic response frequency during the fatigue failure process. In the present work, it seems that the definition of fatigue damage variable D can be described as

$$D=1-\left(\frac{\Delta f_\mathrm{n}}{\Delta f_0}\right)^a \tag{2}$$

$$\Delta f_\mathrm{n}=f_\mathrm{n}-f_\mathrm{f};\quad \Delta f_0=f_0-f_\mathrm{f} \tag{3}$$

where f_n is the natural frequency of the plate in the current fatigue damage state; f_f is the natural frequency of the failed specimen; f_0 is the initial natural frequency of undamaged plate specimen. Then Eq. (2) can be used to predict the fatigue life of plate. Figure 9 illustrates the predicted and calculated experimental fatigue lives where a good agreement can be achieved when a=1.925.

Table 3 Mean fatigue life of each group

Group	Mean fatigue life/s	
	Time-domain method	5% reduction in natural frequency
A	4847	5446
B	5026	5503
C	5362	5729
D	5879	6237

In order to enhance the vibration fatigue life, the stiffeners were added on the plates. The riveted stiffeners increase the structural stiffness. As a result, the natural frequency of the stiffened plate is changed, which is usually higher than that of the original plate. Figure 10 gives the damage zones of the stiffened plate. It can be seen that the distribution of the damage zone has changed due to the stiffeners. The damage of the side vertical to the stiffeners is greater than that of adjacent side. Besides near the edges of the plate, the damage zone also can be observed around the rivets at both ends of the stiffeners (near the black arrows in Fig. 10).

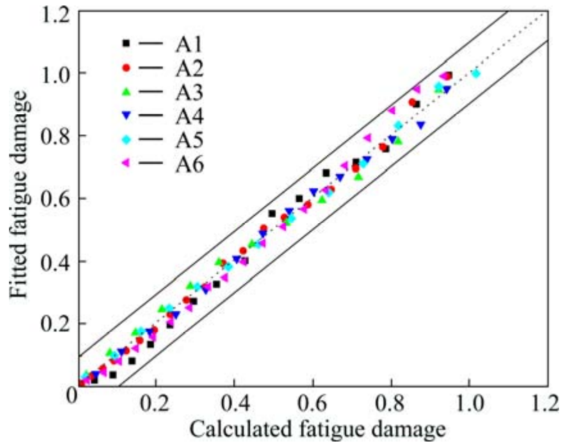

Fig. 9 Comparison of calculated experimental results with fitted results

Table 3 lists the fatigue life of stiffened plate with different cross-sections and spacings. It can be seen that the fatigue life of the stiffened plate with T cross-section is longer than that with L cross-section (groups B and C). This might be attributed to the different stiffness values of T and L cross-section stiffeners although they have the same cross-section area. If comparing the experimental results on plates stiffened with the same type of stiffeners but different spacings (groups B and D), it can be found that with the reduction of stiffener spacing (from 150 mm to 132 mm), the vibration fatigue life of stiffened plate increases.

4 Conclusions

It can be observed that when the specimen damaged absolutely (D=1), the natural frequency drops by about 2.8%, which means that the foregone threshold of 5% is too rough. A nonlinear model, based on the change of natural frequencies, was established for predicting the fatigue damage of plate. Strong enhancement to vibration fatigue life can be achieved through adding stiffeners to the plate. With the same cross-sectional area of stiffener, the T section stiffened plate has longer fatigue life than L section stiffened plate due to more enhancement of T section stiffener to the stiffness of plate. Besides, the spacing between adjacent stiffeners also plays an important role in the vibration fatigue behavior of 2024-T3 stiffened plate in the form that the smaller the stiffener spacing, the longer the vibration fatigue life.

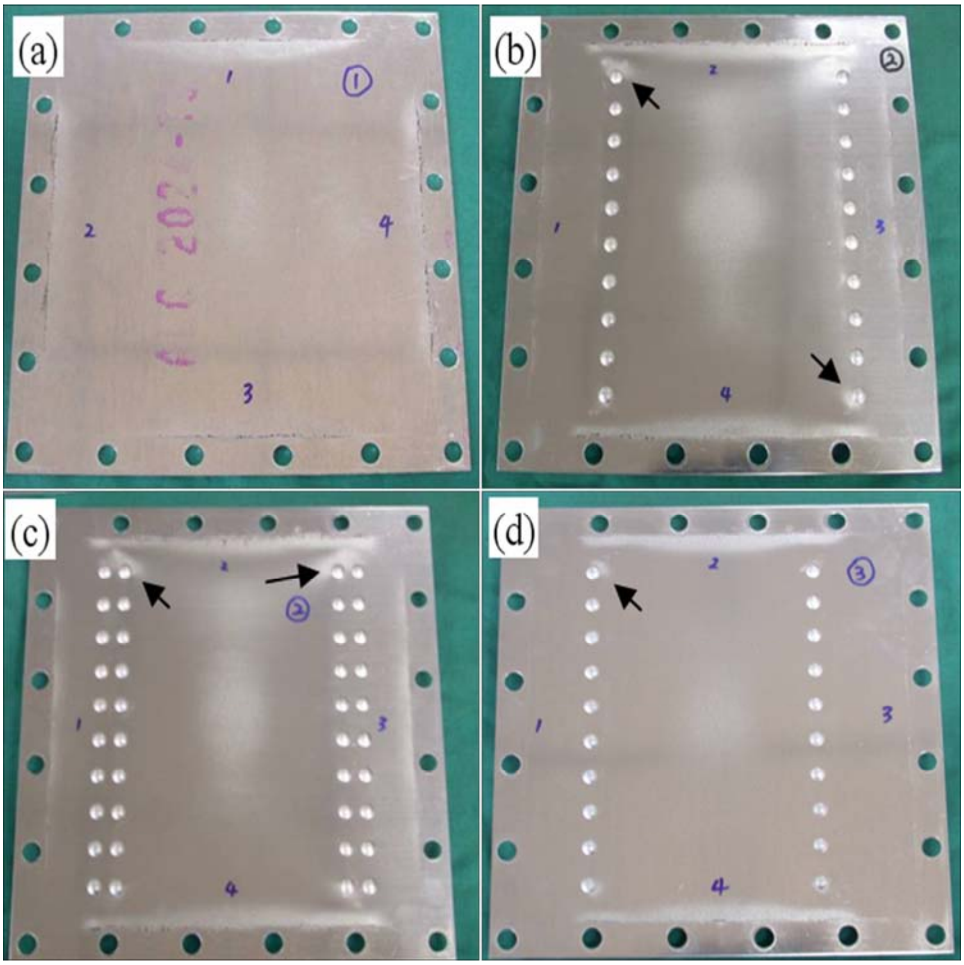

Fig. 10 Damage zone of plate and stiffened plate: (a) Group A; (b) Group B; (c) Group C; (d) Group D

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随机振动加载条件下铝合金加筋板的疲劳行为

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摘 要：基于基础激励对固支的 3 类铝合金加筋板进行振动测试。测试过程中采用应变片监测试样的动态响应。在应变历程的基础上用雨流计数法和 Miner 线性累积模型得到时域内加筋板的疲劳累积损伤。利用固有频率的改变，拟合用于预测板结构疲劳损伤的新模型，改进先前固有频率下降 5%的失效判据。同时，还研究了筋条截面形状与筋间距对铝合金板振动疲劳行为的影响。结果表明，加装 T 型或 L 型截面的铆接筋条后铝板的疲劳寿命延长，对于筋条截面积大小相同的筋条，T 型截面筋条的加筋板其疲劳寿命长于 L 型的。此外，振动疲劳寿命表现出对筋间距的敏感性。

关键词：加筋板；振动疲劳；振动测试；疲劳寿命；固有频率

(Edited by Hua YANG)