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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.

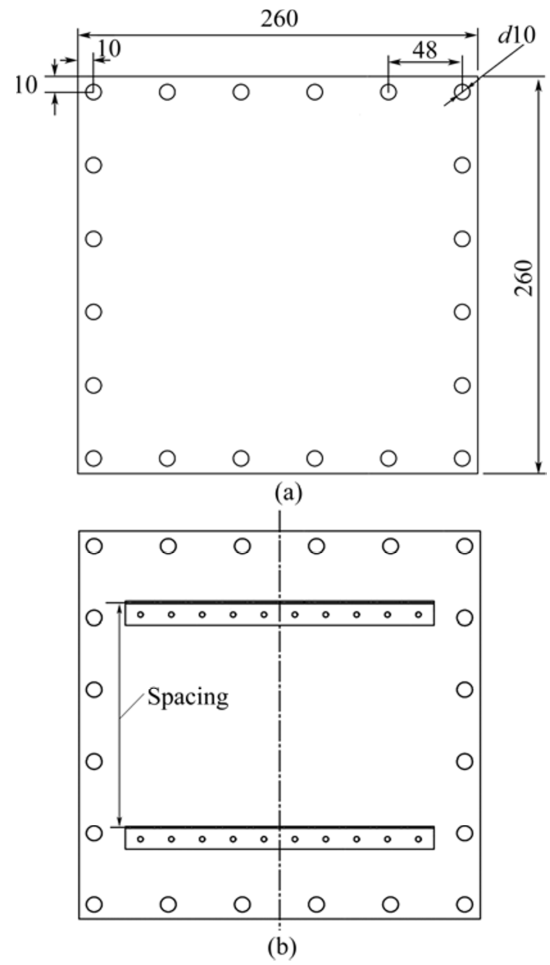

Fig. 1 Dimensions of different specimens (unit: mm): (a) 2024-T3 plate specimen; (b) Stiffened plate specimen

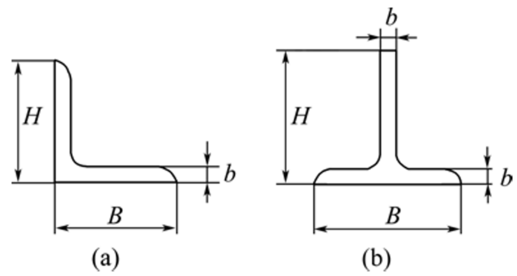

Fig. 2 Cross section and dimension of stiffener: (a) L type, B=H=16 mm, b=1.2 mm; (b) T type, B=25 mm, H=15 mm, b=1 mm