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Frequency-dependent random fatigue of panel-type structures made of ceramic matrix composites

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ABSTRACT

The panel-type structures used in aerospace engineering can be subjected to severe high-frequency acoustic loadings in service. This paper evaluates the frequency-dependent random fatigue of panel-type structures made of ceramic matrix composites (CMCs) under acoustic loadings. Firstly, the high-frequency random responses from the broadband random excitation will result in more stress cycles in a definite period of time. The probability density distributions of stress amplitudes will be different in different frequency bandwidths, though the peak stress estimations are identical. Secondly, the fatigue properties of CMCs can be highly frequency-dependent. The fatigue evaluation method for the random vibration case is adopted to evaluate the fatigue damage of a representative stiffened panel structure. The frequency effect through S-N curves on random fatigue damage is numerically verified. Finally, a parameter is demonstrated to characterize the mean vibration frequency of a random process, and hence this parameter can further be considered as a reasonable loading frequency in the fatigue tests of CMCs to obtain more reliable S-N curves. Therefore, the influence of vibration frequency can be incorporated in the random fatigue model from the two perspectives.

1. Introduction

Ceramic matrix composites (CMCs) are an attractive option for high-temperature structural applications. The carbon-fiber/SiC-matrix (C/SiC) composites, as a typical class of CMCs, exhibit eminent mechanical properties, such as low density, high specific strength, high stiffness to density ratio, good performance in heat stability, and so on [1–3]. For these

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Nomenclature

C	constant of S-N curve
CMCs	ceramic matrix composites
dB	decibels
$\bar{D}$	fatigue damage intensity
E	elastic modulus (MPa)
f	frequency (Hz)
$G(f)$	single-side PSD function
k	slope coefficient of S-N curve
m_i	ith spectral moment of PSD function
N	cycles to failure
$p(s)$	PDF of stress amplitudes
PDF	probability density function
PSD	power spectral density
RMS	root mean square
s	stress amplitude
SPL	sound pressure level
TPS	thermal protection system
T	fatigue life
v_{0^+}	zero up-crossing rate
v_p	peak rate

reasons, C/SiC composites are considered to be excellent materials for hot structures and the thermal protection system (TPS) of hypersonic vehicles and spacecraft. The panel-type TPS structures are widely used in the wings and rudders of flight vehicles, etc. However, the case of these applications will involve severe random dynamic loadings characterized by high frequencies and excessive cycle accumulations [4,5]. The broadband and highly intense aero-acoustic loadings acting on panel-type structures are distinctly different from the conventional vibration loads [5,6]. Firstly, the frequency bandwidth of random acoustic loading can cover from a few tens of Hertz to several thousand Hertz, while the highest frequency that the conventional random vibration loads can generally reach is only hundreds of Hertz, e.g. the base excitation. Secondly, the input energy of the acoustic pressure is proportional to the area of structural surface; however, in terms of conventional random vibration loads, the input energy mainly depends on the power of the vibration source. Thirdly, the motion transmission paths on the structure can be different. The thin-walled panels are excited at the beginning and then the motion is transmitted to the frames of the structure under aero-acoustic and aerodynamic pressure loads; while in the case of conventional random vibration, the motion is transmitted from frames to panels. Consequently, the excitation efficiency of aero-acoustic and aerodynamic pressure loads is quite significant for panel-type structures characterized by large surface area-to-mass ratio. Therefore, thin panels will be subjected to random fatigue loads which are at relatively high frequency and can accumulate a large number of cycles during a short period of time. Since the bandwidth of the aero-acoustic loading can extend up to several kHz, acoustic fatigue of structures can occur in a relatively short period of time due to the growth of initial defects and/or formation of new cracks in the process of high-frequency vibrations. Therefore, fatigue evaluation of panel-type structures under random acoustic loadings is an important issue at the design stage and has aroused considerable research interest [4,7–9]. Furthermore, a better understanding of the material fatigue properties is also highly requisite.

It is noted that higher loading frequency will result in larger fatigue damage if the stresses in structures have an identical level in a definite period of time. Furthermore, it is worthwhile to note that the fatigue properties of some composite materials, e.g. CMCs, are characterized by great frequency-dependence due to the creep effect or the internal heating by friction [10]. Research work done by Holmes and Shuler [11] demonstrated that the cyclic loading of a woven C/SiC composite at frequencies ranging from 1 to 85 Hz resulted in a significant temperature rise in the material with the increase in loading frequency. The increased temperatures were attributed to the internal friction caused by the relative motion between fiber-fiber and fiber-matrix interfaces. The tension-tension fatigue experiments were conducted on a woven C/SiC composite at sinusoidal frequencies of 1, 10, and 50 Hz, and the fatigue limit was lower at 50 Hz than those at 1 Hz and 10 Hz [12]. Similar trends have been observed with the unidirectional SiC-fiber/calcium aluminosilicate-matrix composites when cycled from 25 to 350 Hz [13]. Fatigue lives of CMCs decrease sharply as the loading frequency increases. Staehler et al. [14] investigated the effect of loading frequency on the high-cycle fatigue behavior of a chemical vapor infiltrated (CVI) C/SiC composite at room temperature. Frequency-dependent fatigue behaviors were observed between the lower frequencies (4 Hz and 40 Hz) and the higher frequency (375 Hz). The decrease of fatigue life at higher frequency was attributed to the frictional heating at higher frequency and the weak bond between the carbon fibers and the matrix. Similar research work has been done by Mall et al. [15] at an elevated temperature of 550 °C, the trend of cycles to failure at different loading frequencies was quite opposite to that at room temperature, which is due to the absence of oxidation of carbon fibers at higher frequency and elevated temperature. Ruggles–Wrenn et al. [16] studied the frequency effect on the fatigue behavior of an oxide-oxide continuous fiber ceramic composite at 1200 °C in laboratory air and steam environment. Tension-tension fatigue tests were performed at frequencies of 0.1 and 10 Hz for fatigue stresses ranging from 75 to 170 MPa. Examination of the fracture surfaces revealed higher degrees of fiber pull-out in specimens tested at 10 Hz, which indicated the weakening of the fiber/matrix interface. In the further research done by Ruggles–Wrenn et al. [17], the effects of frequency and environment on the fatigue behavior of a CVI SiC/SiC composite were investigated at 1200 °C in air and steam environments. In air environment, the fatigue performance improved with the decrease in loading frequency; also, the fatigue performance deteriorated with the increase in loading frequency in steam environment, and the presence of steam noticeably degraded the fatigue performance. To summarize, the frequency of cyclic stresses can be a vital issue for the fatigue evaluation and life prediction of the panel-type structures made of CMCs. Within this scenario, the excitation frequency of dynamic loadings will affect not only the structural dynamic responses (and hence the stress amplitudes and cycle numbers), but also the fatigue properties of composite materials. Therefore, at which frequency to