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Anisomorphic constant fatigue life diagrams of constant probability of failure and prediction of P–S–N curves for unidirectional carbon/epoxy laminates

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ABSTRACT

The effect of stress ratio on statistical distribution of fatigue life of a unidirectional carbon/epoxy composite has been examined. Furthermore, a method for efficiently predicting a family of S–N curves with probability of failure as the parameter for any stress ratio of constant amplitude loading has been developed. For this purpose, fatigue life data are first collected at each of different stress levels for tension–tension (TT), tension–compression (TC) and compression–compression (CC) fatigue loadings, respectively. The experimental results show that the scatter in fatigue life tends to become larger in order of TT, TC and CC loading. Lognormal distribution is used to quantify the statistics of the static tensile and compressive strength data and the fatigue life data for each of different stress levels and stress ratios. It is found that lognormal distribution is applicable approximately not only to the static strength data in tension and compression, but also to the fatigue life data for each of different stress levels and stress ratios. The parameters of the distribution of fatigue life are shown to be dependent on the stress ratio of fatigue loading. The experimental P–S–N curves are established for each of different stress ratios using the distributions fitted to the static strength and fatigue life data. Then, a method for constructing the anisomorphic constant fatigue life (CFL) diagrams of constant probability of failure is developed. The proposed probabilistic anisomorphic CFL diagram approach allows not only accurately predicting the P–S–N curves for different stress ratios, but also adequately describing the stress-ratio dependent scatter in fatigue life of the unidirectional composite.

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1. Introduction

Carbon fiber-reinforced polymer matrix composites (CFRPs) are increasingly and widely used in various sectors, including not only the aerospace sector but also the wind energy, offshore and vehicle sectors [1–3]. When applying structural elements made of CFRPs in those sectors, one of the most important concerns is about their failure due to fatigue during service [4]. Machines and structures usually operate under repeated loading conditions. Accordingly, it should be carefully checked whether they include some components that should be treated as being fatigue sensitive. In engineering practice, they usually include some fatigue sensitive elements that are subjected fatigue loading not only at different alternating stress amplitudes but also at different mean stress levels. For the fatigue-affected elements made of CFRPs which are the key to normal operation of machines and structures, therefore, it is an essential prerequisite to establish a method for efficiently predicting their fatigue lives under constant amplitude cyclic loadings at different alternating stress amplitudes and mean stress levels that constitute complex loading spectra experienced during service.

The S–N curve for a material employed constitutes a basic design tool for engineering fatigue life analysis of structural components as well as machine parts, regardless of the scale of application. For any given material, however, the S–N curve cannot uniquely be identified. It is not only because of the change in fatigue life of a given material with the stress ratio and frequency of fatigue loading as well as with temperature, but also because of the statistical scatter in fatigue life under the same cyclic loading condition [4]. In the fatigue design of CFRP elements, therefore, we need the information of a family of S–N curves for CFRPs not only with the stress ratio and frequency of fatigue loading as well as temperature as the parameters, but also with probability of failure as the parameter as well. Experimental identification of P–S–N curves for each of different values of stress ratio, frequency and temperature requires a lot of testing. It is not practical to do it

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relying on only experiments. We have already come across a similar problem in the experimental identification of S–N curves for different values of stress ratio, frequency and temperature [5]. The additional consideration of the scatter in fatigue life makes the problem much harder. For the fatigue design of CFRP elements, therefore, it is of great significance to develop an engineering method for efficiently and accurately evaluating and quantifying not only the influence of thermo-mechanical factors but also the influence of a statistical factor on the fatigue life of CFRPs.

One of the practical techniques to take into account the effect of fatigue loading factors on fatigue life of a given composite material is to use a constant fatigue life (CFL) diagram [6,7] constructed in the alternating stress amplitude versus mean stress plane. What should be reminded in this context is that the ultimate strengths of composites in tension and compression are often different in magnitude, from which it follows that the CFL diagram becomes asymmetric about the alternating stress amplitude axis [8,9]. Furthermore, the CFL envelopes for different constant values of life often have nonlinear shapes that depend on mean stress. These facts thus suggest that the mean stress dependence of fatigue life of composites cannot always be described accurately by means of the so-called Goodman diagram [10], apart from a historical perspective [11], that is constructed relying on the fatigue life data for completely reversed cyclic loading and assuming linear envelopes for different constant values of life in the plane of alternating stress amplitude versus mean stress.

To describe the asymmetric and nonlinear CFL diagrams for composite materials, Harris et al. [12–17] have developed the so-called bell-shape CFL diagram. This was the outcome of their systematic studies on the fatigue behavior of composite materials at different stress ratios. Recently, Kawai et al. [18,19] have proposed a different and more efficient method for describing the asymmetric and nonlinear CFL diagrams for composites in the alternating stress amplitude versus mean stress plane, and it is called the anisomorphic CFL diagram approach. The anisomorphic CFL diagram approach has an advantage of easy construction of CFL diagram using the static strengths in tension and compression and the S–N curve for a particular stress ratio called the critical stress ratio. The anisomorphic CFL diagram approach was shown to be valid for the fiber-dominated fatigue behavior not only of non-woven quasi-isotropic and cross-ply CFRP laminates at room temperature [18,19], but also of woven fabric CFRP laminates at elevated temperatures [20,21]. It is emphasized that the anisomorphic CFL diagram approach provides a methodology for building a full shape of CFL diagram for a given composite over the whole range of mean stress, and thus it allows predicting the S–N curves for the composite under constant amplitude fatigue loading at any stress ratios.

To achieve a desired reliability in the design of fatigue sensitive elements of machines and structures, on the other hand, we need statistical tools to describe and analyze the scatter in fatigue life as well. For the statistical analysis of fatigue life, lognormal and Weibull distribution functions are often utilized. Kam et al. [22] have reported that lognormal and Weibull distributions are both applicable to the tension fatigue data for angle-plied CFRP laminates that were obtained for each of the stress ratios $R = 0.05$, 0.11, and 0.18. Lee et al. [23] have examined the goodness of fit of several cumulative distribution functions for the tension fatigue data at $R = 0.1$ on unidirectional and multidirectional CFRP laminates, and found that the experimental data best fit a Weibull distribution function. Shimokawa and Hamaguchi [24] have tested the goodness of fit of lognormal and Weibull distribution functions, respectively, to the tensile fatigue life data on composite laminates with a center hole, and found the goodness of fit of a lognormal distribution is better.

In contrast to the influence of stress ratio on the fatigue life of composites, however, the influence of stress ratio on the statistical variability in fatigue life of composites has not sufficiently been examined. Accordingly, the goodness of fit of cumulative distribution functions to fatigue life data at each of different stress levels over a range of stress ratio has not extensively been discussed. To fulfill the requirements of fatigue analysis of a given composite that have been briefly reviewed above, we need to establish an engineering methodology that allows not only predicting the S–N curves for constant amplitude loading at any stress ratios, but also predicting the S–N curves for any constant values of failure probability.

The present study aims to develop an engineering methodology to construct the anisomorphic CFL diagrams with probability of failure as the parameter for a unidirectional carbon/epoxy composite. It is applied to predict the constant probability-of-failure curves (i.e. P–S–N curves) for each of fatigue loadings at different stress ratios. First of all, constant amplitude fatigue tests are performed on a selected number of specimens for each of different constant values of stress level and stress ratio. Static tension and compression tests are also carried out on a selected number of specimens, respectively. Two-parameter lognormal distribution is applied to describe the distributions for the static strength data as well as the fatigue life data at each of different stress levels and stress ratios. In terms of the estimated parameters of the statistical distributions for those data, the scatters in the static strengths in tension and compression as well as in the fatigue life at each of different stress levels and stress ratios are quantified. The experimental P–S–N curves are identified by connecting S–N points of equal probability of failure that are evaluated by means of the lognormal distributions fitted to the fatigue life data at different stress levels for each of different stress ratios. Next, a method for building the anisomorphic CFL envelopes of constant probability of failure in the alternating stress amplitude versus mean stress plane is developed. By means of the lognormal distributions identified, the anisomorphic CFL diagrams of the 10%, 50% and 90% probability of failure are constructed for the unidirectional CFRP laminate. The P–S–N curves for $P = 10\%$, 50% and 90% are then predicted for constant amplitude loadings at different stress ratios, respectively, using the probabilistic anisomorphic CFL diagram approach. The validity of the proposed methodology is evaluated by comparing the predicted and experimental P–S–N curves for the unidirectional CFRP laminate.

2. Material and experimental procedure

2.1. Material and specimens

The material used in this study was a unidirectional composite laminate fabricated from T800H/2500 carbon/epoxy prepreg tapes (P2053-17, TORAY). The lay-up of virgin laminates is $[0]_{12}$, and they were cured in an autoclave. The thickness of as-received laminates was about 2 mm.

Unidirectional laminate panels were cut into parallel-sided coupon specimens. The longitudinal direction of specimens is parallel with fibers. Two kinds of coupon specimens of different nominal dimensions were utilized in this study, as shown in Fig. 1a and b. For static tension and tension–tension (T–T) fatigue tests in which only tensile load is applied to specimens, long specimens based on the testing standards JIS K7073 [25] and JIS K7083 [26] were employed; the dimensions of the long specimens were gauge length $L_G = 100$ mm and width $W = 10$ mm. In static compression tests and compression–compression (C–C) and tension–compression (T–C) fatigue tests, on the other hand, short specimens were used to reduce a risk of buckling under compressive load; the dimensions of the short specimens were gauge length $L_G = 10$ mm and width $W = 10$ mm. The nominal dimensions of the short

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