Ceramics International xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ceramics International

journal homepage: www.elsevier.com/locate/ceramint

Numerical and experimental study on the nonlinear dynamic response of a ceramic matrix composites beam

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ARTICLE INFO

Keywords:
Ceramic matrix composites
Shear-lag model
Dynamic
Finite element method

ABSTRACT

In this paper, nonlinear dynamic responses of a unidirectional ceramic matrix composite (CMC) beam are studied both experimentally and numerically. Frequency-sweep tests are performed to study the dynamic response of a CMC beam under swept harmonic loads. Constitutive tests, which include axial loading and unloading, were performed to study the constitutive response of a unidirectional CMC under a complicated load history. The shear-lag model is extended to three-dimension (3D) and the values of parameters in this model are certificated by experimental result. The finite element method combined with the shear-lag model is used to simulate the dynamic response of CMC beams under swept harmonic loads. The experimental and numerical results revealed that the variable stiffness of the CMC leads to amplitude saltation under swept harmonic load. The natural frequency of the CMC beams changed with the magnitudes of the external load. Based on the dynamic simulation model, the effects of parameters in constitutive model on the dynamic response of CMC beam are also discussed.

1. Introduction

Fiber-reinforced ceramic matrix composites possess a number of excellent mechanical properties at elevated temperatures [1–3]. For high temperature structures, the development of CMCs is attractive for many reasons. Compared with metal, CMCs possess high strength-to-weight ratio and high temperature capability [4].

Dynamic problems should be considered in the design of a CMC structure, as dynamic external loads may lead to serious damage to the CMC structure [5,6]. Therefore, more and more researches have been performed in this field.

Lankford et al. [7] investigated the effect of high-strain-rate loading on tensile strength and failure mechanisms of CMCs. The results suggested that the stress to fail the composite for high-strain-rate loading can be much smaller than that under quasi-static conditions. Birman et al. [8] elucidated the methods to estimate damping in CMC with matrix cracks. The frictional energy dissipation density attributed to the interfacial friction was obtained from Cho et al. [9]. They found that damping increases dramatically in unidirectional CMC with bridging matrix cracks while the damping increases in cross-ply CMC with tunneling matrix cracks in transverse layers are negligible. Wang et al. [10] investigated the effects of the fiber volume fraction and the density of composite on the damping characteristics of the C/C composites fabricated with CVI techniques. Similar studies on estimating the damping of CMCs can be found in [11,12]. Birman et al. [13] studied the effect of matrix cracking on the stiffness and natural frequency of CMC beams. The results indicated that the changes in stiffness and natural frequencies due to matrix cracks were quite small. While if the matrix cracking saturation in transverse layers is reached within the interior of beam, the changes of stiffness and natural frequencies can be large enough to be detected.

Based on the above literature review, it can be seen that previous studies have concentrated on the dynamic failure mechanism, damping capacity, elastic modulus and natural frequency of CMCs. In fact, most of these researches were based on the linear theory. Nevertheless, little work has been devoted to simulate the nonlinear dynamic response of CMC structure. The difficulty lies in the lack of appropriate constitutive models of CMCs. Previous studies have shown that CMCs exhibit obvious nonlinear constitutive behaviors upon loading due to the combined effect of matrix cracking [14,15], fiber-matrix interfacial debonding [16], interfacial slip [17] and fiber failure [18]. Many models have been presented to simulate these complicated constitutive behaviors of CMCs. However, most of them can only be applied in the situation when the external load is only tensile or constant amplitude

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https://doi.org/10.1016/j.ceramint.2018.01.007
Received 7 December 2017; Accepted 2 January 2018

Please cite this article as: Gao, X., Ceramics International (2018), https://doi.org/10.1016/j.ceramint.2018.01.007

cyclic. As the load applied on the CMC structure is dynamic in vibration process, these models cannot be used to simulate the dynamic response of CMC structure.

Before this paper, we have simulated the nonlinear response of a CMC beam subjected to a dynamic axial load using a two-scale method [19]. A constitutive model for unidirectional CMCs using the finite element method was established to model the interface friction and crack closure effects. By combining the constitutive model and directly integral method, the axial displacement response of a CMC beam was obtained. However, the above model was performed in one dimension and could only model the axial displacement response of a CMC beam and lacked experimental validation. Recently, we also developed a distribution model of slip regions on the fiber-matrix interface of unidirectional CMCs [20]. Based on this model, the stress-strain response of unidirectional CMCs under arbitrary loading and unloading can be obtained.

In this paper, the nonlinear dynamic responses of CMC beam are investigated both experimentally and numerically. A tensile test is performed to obtain the stress-strain response of CMCs under loading and unloading. Frequency sweep tests are performed to study the amplitude-frequency response of CMC beam. In the numerical calculation part, the constitutive model in [20] is extended to 3D in this paper. The values of parameters in this constitutive model can be determined by the results of tensile test. In addition, a 3D finite element method combined with the constitutive model is developed to simulate the dynamic response of a CMC beam. The simulation results can be validated by the experimental results. Based on this dynamic analysis model, the effects of interface shear stress and matrix crack spacing on the dynamic response of CMC beam are also discussed.

2. Experiments

2.1. Materials

A unidirectional carbon fiber reinforced silicon matrix composite was selected for this study. A T700-6k carbon fiber fabricated by the TORAY Company (Tokyo, Japan) with an average fiber diameter of 6 μm was used as the reinforcement. Then, Chemical Vapor Infiltration (CVI) technology was used to infiltrate the silicon matrix. To increase the mass density of the material, the SiC matrix on the surface is removed to expose voids in the material. Afterwards, the CVI process was used again to fill the voids with SiC. After several infiltrating and surface removal cycles, the mass density of the material was approximately 1.8 g/cm^3.

2.2. Axial tensile test

The test has been performed at room temperature. The stress-strain response of the material was obtained using an MTS hydraulic servo testing system. The axial normal strain was measured using a strain extensometer. The sizes and shape of tensile test specimen are shown in Fig. 1.

Unidirectional cyclic loading and unloading tests were performed at the speed of 0.05 kN/s. The load history included several rounds of tensile loading and unloading. As is shown in Fig. 2, the stress-strain response shows obvious nonlinear behaviors. The stress-strain response

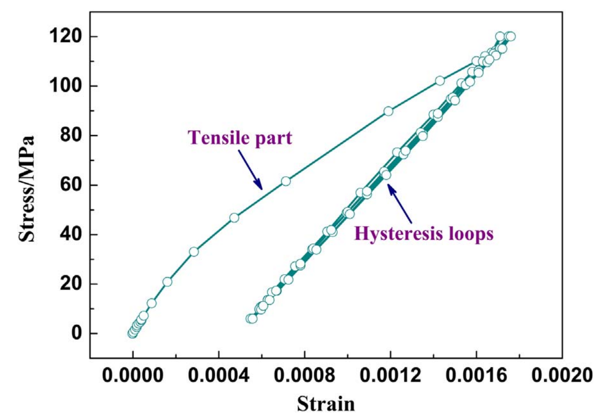

Fig. 2. Experimental constitutive response of the CMCs under tension and unloading.

of the unidirectional CMCs includes two typical parts, i.e. tensile part and hysteresis loops. The stress-strain relationship will be used to get the values of parameters in the constitutive model of CMCs.

2.3. Dynamic tests

The dynamic tests were conducted on a DC-600 vibrostand. The testing system is shown in Fig. 3. One end of the specimen was fixed on the shaker by the support. An accelerometer was fixed on the support to detect the acceleration of the shaker. A laser displacement sensor (OPTEX CD33-85N) was used to detect the real-time displacement of the specimen's free end.

The photo of specimen for dynamic tests is shown in Fig. 4. One end of the CMC beam is pasted by the end tab to protect the specimen and improve the quality of fixing.

A series of frequency sweeps were performed around the first natural frequency of the specimen. The bandwidth swept was 20 Hz, and the frequency sweep rate was 0.025 Hz/s. An increasing frequency sweep was performed and the acceleration of shaker was set as 10 m/s^2. Then a decreasing frequency sweep was performed. The bandwidth, frequency sweep rate and acceleration of shaker were set as same as those in the increasing sweep. After three increasing and decreasing frequency sweep iterations, the acceleration of the shaker was increased to 20 m/s^2. This procedure above was repeated until increasing the acceleration to 70 m/s^2.

What are shown in Fig. 5 are the displacement responses of the CMC beam's free end in three increasing frequency sweeps. The acceleration of shaker was 70 m/s^2. From the first sweep to the third, the results indicate that the amplitude-frequency responses approach to be stable. Along with the number of sweeps increasing, there is less new damage on the CMCs if the level of external load is unchanged. So the amplitude-frequency curves of the second and third sweeps are very similar.

The amplitude-frequency responses under different levels of external loads are shown in Fig. 6. The results indicate that the natural frequency of the CMC beam decreases from 241.4 to 229.3 Hz as the external load increases from 10 m/s^2 to 70 m/s^2. The natural frequency decreases because the damage on CMCs results in the degradation of stiffness.

There is a huge difference between the amplitude-frequency

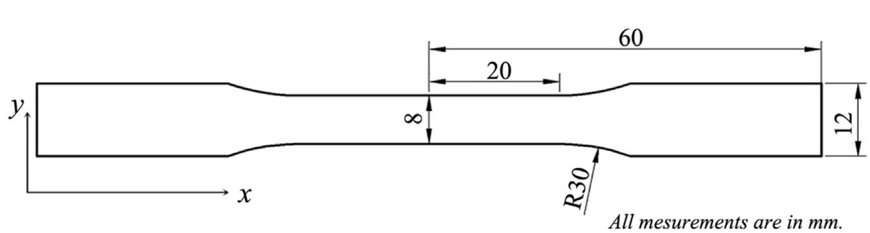

Fig. 1. Shape and size of the specimen for the axial test.