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Uniaxial ratchetting of polymer and polymer matrix composites: Time-dependent experimental observations

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ABSTRACT

The uniaxial time-dependent ratchetting of polyester resin and glass fiber reinforced polyester resin matrix composites was observed by the stress-controlled cyclic tension–compression with non-zero tensile mean stress and tension–tension tests at room temperature. After the ratchetting of the polyester resin had been observed by the cyclic tests with different loading conditions including some time-related factors, such as stress rate and peak stress hold, the ratchetting evolutions of the continuous and short glass fiber reinforced resin matrix composites were also investigated by the stress-controlled cyclic tests, respectively. It is concluded that: both the polyester resin and its composites present apparent ratchetting deformation, i.e., the ratchetting strain accumulates progressively in the tensile direction during the cyclic tension–compression with non-zero tensile mean stress and tension–tension tests; the ratchetting depends on the applied stress amplitude, mean stress, stress rate and peak stress hold, and the time-dependent ratchetting is obvious even for the continuous glass fiber reinforced resin matrix composites with high fiber volume fraction (such as 40% and 50%); the time-dependent ratchetting of the polyester resin and its composites mainly stems from the viscosity of the polyester resin, while the addition of glass fiber into the resin matrix improves the resistance of the composites to the ratchetting deformation and lowers the time-dependence of the ratchetting simultaneously.

1. Introduction

Polymer matrix composites (PMCs) have been extensively used in the automotive industry, aerospace and civil engineering structures due to their high specific stiffness and strength as well as other excellent properties. These composite structure components are often subjected to a kind of cyclic loading. It means that there is an urgent need to assess the cyclic deformation and fatigue behaviour of polymer matrix composites. In the last two or three decades, the cyclic deformation and fatigue behaviour of glass or carbon fiber reinforced polymer composites were experimentally and theoretically observed in many literatures [1–10]. However, the existing experimental and simulated results were mainly obtained under a strain-controlled cyclic loading. The cyclic responses of polymer matrix composites are hardly discussed under a stress-controlled cyclic loading, especially for the cyclic stressing with non-zero mean stress. Therefore, it is necessary to discuss the cyclic responses of the composites under stress-controlled cyclic loading first by detailed experimental observations.

Ratchetting, a cyclic accumulation of inelastic deformation will occur in the materials and structures subjected to a stress-controlled cyclic loading with non-zero mean stress, if the applied stress level is high enough. Since its importance in the design and safety assessment of the structure components, the ratchetting was extensively studied by many experiments (which were first performed by Benham [11,12] and Coffin [13,14] in 1960s) and constitutive models (first constructed by Dafalias and PoPov [15,16], Chaboche et al. [17,18] and Chaboche [19,20], and Yoshida et al. [21,22] in 1970–1980s). The progresses in the researches of ratchetting in the last two decades can be found in several review works done by Ohno [23,24], Chen et al. [25], Abdel-Karim [26], Kang [27] and Chaboche [28]. It should be noted that the results in the above referred literatures were obtained mainly for some monolithic metals or alloys. Recently, some experimental observations have been performed for the ratchetting of metal matrix composites as done by Jansson and Leckie [29], Daehn et al. [30], Zhang et al. [31,32], Ponter and Leckie [33,34], Kang [35] and Kang and Liu [36]. It is seen that the ratchetting of metal matrix composites depends greatly on the ratchetting of metal matrix. Since the mechanical performance of polymer matrix is different from that of metal matrix, it is necessary to discuss the ratchetting of polymer matrix first, before the ratchetting of polymer matrix composites is performed.

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Recently, the ratchetting of polymer materials has been discussed by some researchers. For example, Chen and his coworkers [37–41] provided some uniaxial and multiaxial experimental results of the ratchetting of PTFE polymer material and vulcanized natural rubber and constructed a simple constitutive model describing the ratchetting. The results show that the ratchetting of the polymer materials presents a great time-dependence, and also depends on the applied mean stress and stress amplitude. Similar results were obtained by Liu et al. [42], Tao and Xia [43], Shen et al. [44], Xia et al. [45,46] and Averett et al. [47] for other polymer materials such as epoxy resin, PMMA polymer and nylon 66 fiber. Thus, it is necessary to investigate the time-dependent ratchetting of polymer matrix composites by the tests accounting for some time-related factors.

Therefore, in this work, the time-dependent ratchetting of polyester resin and its composites reinforced by continuous and short glass fibers is studied by the uniaxial stress-controlled cyclic loading tests at room temperature. The dependence of the ratchetting on the applied mean stress, stress amplitude, stress rate and peak stress hold is discussed. Some significant conclusions useful to construct a constitutive model for the ratchetting of the composites are obtained.

2. Experimental procedure

The polyester resin (No. 196) and its composites reinforced by continuous and short glass fibers were used in this work. The polyester resin bars were obtained from the raw materials by the method of moulding with heating to 333 K and remaining for 4 h. The plates of polyester matrix composites were manufactured by the traditional paste method, using continuous glass fiber cloths and short glass fiber felts, and also experienced the heat treatment identical to the polyester resin bars. Round solid bar specimens with the gauge length of 30 mm and gauge section diameter of 10 mm for the tests of polyester resin were machined from the moulded bars, and plate-shaped specimens with the gauge length of 30 mm and gauge section width of 10 mm and thickness of 6 mm for the tests of polymer matrix composites were obtained from the composites plates. The volume fractions of short glass fiber in the short fiber reinforced polymer matrix composites are prescribed as about 28% and 40%, and those of continuous glass fiber in the continuous fiber reinforced composites are about 40% and 50%, respectively. To distinguish the results of different composites in a compact way, we employ: Composite A1—short glass fiber composites with $V_f = 28\%$; Composite A2—short glass fiber composites with $V_f = 40\%$; Composite B1—continuous glass fiber composites with $V_f = 40\%$; Composite B2—continuous glass fiber composites with $V_f = 50\%$, in the figures as the legends.

The specimens were tested by MTS809-25KN; and the loading process was controlled and the data were collected by Teststar-II control system attached to the machine. The axial strain was measured by a tensile extensometer. The specimens were tested by monotonic tension, and stress-controlled cyclic tension–compression with non-zero tensile mean stress and tension–tension tests at room temperature, respectively. A triangle-typed loading wave was employed. To discuss the time-dependent ratchetting of the polyester resin and its composites, different stress rates and some peak stress holds with different hold times were prescribed, respectively.

In this paper, axial ratchetting strain ε_r is defined as following for uniaxial cyclic stressing:

$$\varepsilon_r = \frac{1}{2}(\varepsilon_{max} + \varepsilon_{min}) \tag{1}$$

where, ε_{max} and ε_{min} are the maximum and the minimum of axial strain in each cycle, respectively. Ratchetting strain-rate is defined as the increment of ratchetting strain ε_r in each cycle. The ε_{max} and ε_{min} of each cycle were obtained from the experimental data; thus, the ratchetting strain ε_r is calculated by Eq. (1).

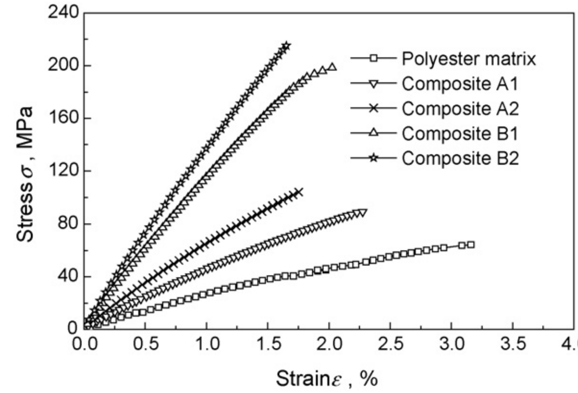

Fig. 1. Tensile stress–strain curves of the polyester resin and its composites at the strain-rate of 0.0002/s: Composite A1—short glass fiber composite with $V_f = 28\%$; Composite A2—short glass fiber composite with $V_f = 40\%$; Composite B1—continuous glass fiber composite with $V_f = 40\%$; Composite B2—continuous glass fiber composite with $V_f = 50\%$ (the same simplification is used in the subsequent figures of this paper).

3. Results and discussions

Before the cyclic tests, the polyester resin and its composites are first tested by the strain-controlled monotonic tension at different strain-rates. The results are shown in Figs. 1 and 2. From the monotonic tensile results at certain strain-rate shown in Fig. 1,

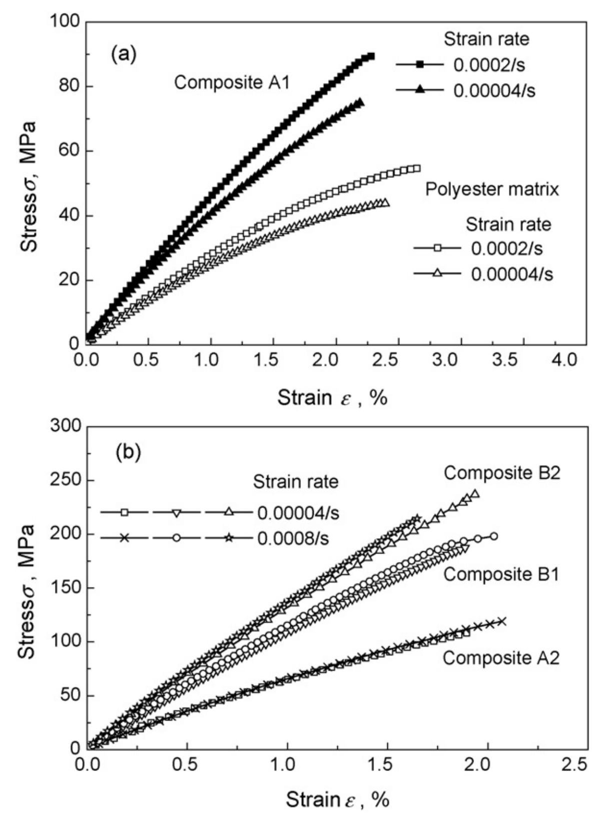

Fig. 2. Tensile stress–strain curves of the polyester resin and its composites at different strain-rates: (a) for polyester resin and Composite A1; (b) for Composites A2, B1 and B2.