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Experimental investigation of thermal shock effects on carbon–carbon composites

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ABSTRACT

In this paper, both compressive properties and oxidation behavior of pristine and thermal shock exposed 2D C/C composite specimens were examined. Pristine test specimens were exposed to thermal shock conditions with temperatures ranging from 400 °C to 1000 °C in an oxidizing environment, followed by compression tests on pristine and thermal shock exposed specimens to obtain their compressive responses. The experimental results showed that 2D C/C composite compressive stiffness and strength decreased with increasing thermal shock temperature. Also, upon exposure to thermal shock, the stress–strain response displayed a non-linear behavior prior to failure as compared to the pristine C/C composite that failed in a brittle manner. Furthermore, it was observed by microstructural analysis that at low temperatures, i.e., 400 °C, the oxidation attack was uniform through the interior of the composite. On the other hand, at moderate temperatures, i.e., 600 °C, oxidation occurred rigorously at the surface of the composite. At high temperatures, i.e., above 600 °C, the specimens experienced the two aforementioned oxidation mechanisms. Therefore, it was concluded that carbon matrix degraded rapidly when exposed to thermal shock conditions in oxidizing environments and protective coating is required to maintain the quality of the composite under such conditions.

1. Introduction

Carbon fiber reinforced carbon matrix composites, called carbon–carbon (C/C) composites retain exceptional thermal and mechanical properties such as high modulus, high thermal shock resistance and high specific strength at high temperatures in non-oxidizing environments. C/C composites have demonstrated to be very promising candidates to be used as structural components in many defense applications, like navy and aerospace structures. However, most of these components are exposed to thermal shock conditions in oxidizing environments with temperatures above 450 °C, under which carbon constituents burn away rapidly [1]. Zhao et al. [2] have demonstrated that oxidation has a strong effect on the C/C composite mechanical properties, nevertheless, limited studies have been conducted to analyze the properties and microstructure of unprotected C/C composites under thermal shock conditions in oxidizing environments [1–3]. Manocha [1] states that when C/C composites are exposed to high temperature tests in oxidizing environments, their properties degrade around 10 to 20% depending on the temperature and time under which they are exposed. Similarly, numerous studies have investigated the tensile and flexural strength of C/C composites at high temperatures [4–10], but there is seldom information available about through-thickness compressive properties of 2D C/C composites after being exposed to thermal shock conditions. Therefore, there is a great interest in analyzing the effects of oxidation on the properties and microstructure of C/C composites in order to assure their good performance in high temperature structural applications.

With the increasing thickness of laminates used in naval and aerospace structures, primarily for ballistic applications, understanding the influence of through-thickness and lateral impact loads on the mechanical response and failure has become very critical [11–13]. Lateral loads often result in delamination type failure due to the presence of weak interfaces. Though these delaminations may not cause catastrophic failure of structures, they jeopardize the structural integrity by reducing their resistance to buckling failure. Therefore, the purpose of this work is to investigate the through-thickness compressive properties of 2D woven C/C composites when exposed to thermal shock conditions in an oxidizing environment.

An overview of the experimental procedure followed in the present study is shown in Fig. 1. First, pristine C/C composite specimens were thermally exposed to five different thermal shock

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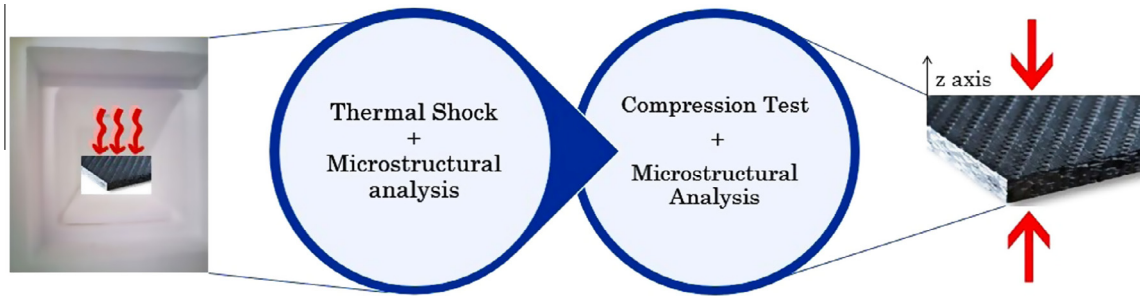

Fig. 1. Schematic representation of experimental procedure.

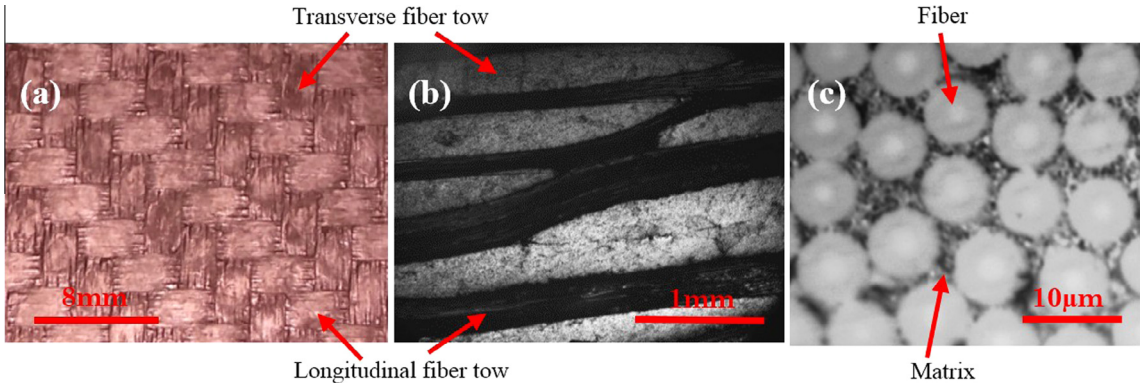

Fig. 2. Optical Micrograph of 2D C/C Composite (a) top surface (b) cross-section and (c) magnified cross-section.

conditions, each with peak temperature of 400 °C, 600 °C, 700 °C, 800 °C and 1000 °C, respectively. Then, through-thickness compression tests were conducted to determine the compressive stiffness and strength of pristine and exposed C/C composite specimens. Finally, a microstructural analysis of C/C composite specimens exposed to different thermal shock conditions was carried out to analyze the carbon morphology due to oxidation. Similarly, the microstructure of the C/C composite was analyzed after each compression test to identify possible modes of failure.

2. C/C Composite oxidation

Several previous research efforts have been made to understand the oxidation kinetics of unprotected C/C composites [14–19]. However, the oxidation behavior of C/C composites varies depending on the desired weave geometry, type of carbon materials, microstructure and processing condition [2,20]. Luthra [21] summarizes the oxidation behavior of unprotected C/C composites with three main stages. First, oxidizing gas (e.g., O_2) starts diffusing across the boundary layer at the surface of the composite. Following this, oxygen can either react chemically with carbon materials located at the surface of the composite, producing gases in form of CO and CO_2, or oxygen can diffuse through existing cracks in the composite. Luthra [21] states that at low temperatures, gas diffusion is the main mode of oxidation, whereas at high temperatures, both chemical reaction and diffusion of gaseous species through cracks in the composite control the oxidation process. At this stage, oxidation attack occurs at the surface and within the interior of the composite.

In addition to this, fiber/matrix interface along the fiber tows possesses preferential oxidation due a mismatch of coefficient of thermal expansion between the matrix and fiber, as explained by Crocker and McEnaney [15]. Also, the fiber edges are more sensitive to oxidize than the center or bulk of the fibers, creating a pointed morphology at the exposed ends of the fibers [17,18,22].

Moreover, Bacos [3] affirms that for 2D C/C composites, carbon matrix degradation prevails during an oxidation process, since the reactivity of the carbon matrix is higher than that of the carbon fibers. This author also states that at low temperatures, oxidation damage is distributed uniformly throughout the interior of the composite and swollen cracks/voids are observed more frequently in the tows due to gaseous species transport. This oxidation behavior usually leads to the propagation of consumed channels along the fiber tows. On the other hand, at high temperatures, Bacos [3] declares that only the first layers of the composite are extensively oxidized, while the fiber tows and matrix within the exposed surfaces show minimal evidence of oxidation.

3. C/C Composite compressive response

Though there are no ASTM standards available to perform through-thickness compression tests on 2D fiber-reinforced composites [23,24], through-thickness compressive stiffness of fiber-reinforced composites has been measured by Lodeiro et al. [25]. Difficulties faced during determining the compressive strength of 2D fiber-reinforced composites are reported in the literature. For instance, high stresses develop at the ends of the specimens during compression test [25], strength is sensitive to changes in the cross-sectional area [26], friction within the loading plates and the specimen affects the strength values [27], strain measurements from crosshead displacements and strain gauges provide different strength results [23] and the strength is easily affected by the specimen geometry [27], among others. Conversely, Hodgkinson [28] affirms the feasibility of testing