Available online at www.sciencedirect.com
ScienceDirect
www.elsevier.com/locate/jmbbm

Research Paper

Biomechanical fatigue analysis of an advanced new carbon fiber/flax/epoxy plate for bone fracture repair using conventional fatigue tests and thermography

Zahra S. Bagheri[a], *Ihab El Sawi*[a], *Habiba Bougherara*[a,*], *Radovan Zdero*[a,b]

[a]*Department of Mechanical and Industrial Engineering (Eric Palin Hall), Ryerson University, 350 Victoria Street, Toronto, ON, Canada M5B-2K3*
[b]*Martin Orthopaedic Biomechanics Lab, St. Michael's Hospital, Toronto, ON, Canada M5B-1W8*

ARTICLE INFO

Article history:
Received 22 January 2014
Received in revised form
2 March 2014
Accepted 9 March 2014
Available online 26 March 2014

Keywords:
Mechanical properties
Fatigue
Non-destructive technique
Composite
Carbon fiber
Flax
Epoxy

ABSTRACT

The current study is part of an ongoing research program to develop an advanced new carbon fiber/flax/epoxy (CF/flax/epoxy) hybrid composite with a “sandwich structure” as a substitute for metallic materials for orthopedic long bone fracture plate applications. The purpose of this study was to assess the fatigue properties of this composite, since cyclic loading is one of the main types of loads carried by a femur fracture plate during normal daily activities. Conventional fatigue testing, thermographic analysis, and scanning electron microscopy (SEM) were used to analyze the damage progress that occurred during fatigue loading. Fatigue strength obtained using thermography analysis (51% of ultimate tensile strength) was confirmed using the conventional fatigue test (50–55% of ultimate tensile strength). The dynamic modulus (E^*) was found to stay almost constant at 47 GPa versus the number of cycles, which can be related to the contribution of both flax/epoxy and CF/epoxy laminae to the stiffness of the composite. SEM images showed solid bonding at the CF/epoxy and flax/epoxy laminae, with a crack density of only 0.48% for the plate loaded for 2 million cycles. The current composite plate showed much higher fatigue strength than the main loads experienced by a typical patient during cyclic activities; thus, it may be a potential candidate for bone fracture plate applications. Moreover, the fatigue strength from thermographic analysis was the same as that obtained by the conventional fatigue tests, thus demonstrating its potential use as an alternate tool to rapidly evaluate fatigue strength of composite biomaterials.

1. Introduction

Metallic implants are the most widely used implants clinically today, since other suitable implant materials and designs have yet to be developed which can successfully address the drawbacks in using metallic biomaterials. First of all, metallic implants have higher stiffness compared to cortical bone, thus producing adverse “stress shielding”

*Corresponding author. Tel.: +1 416 979 5000x17092.
E-mail address: habiba.bougherara@ryerson.ca (H. Bougherara).

http://dx.doi.org/10.1016/j.jmbbm.2014.03.008
1751-6161/

(Akeson et al., 1975; Foux et al., 1997; Ganesh et al., 2005; Tayton et al., 1982). Stress shielding can cause extensive reduction in bone mass and subsequent implant loosening, as a long-term effect (Akeson et al., 1975; Foux et al., 1997; Ganesh et al., 2005; Tayton et al., 1982). Second, during the monitoring process of an injured bone using computerized tomography (CT) and magnetic resonance imaging (MRI), these metallic materials appear white in color, which limits the visibility of bone which also appears white in color. Finally, the fatigue strength of metallic materials is highly dependent on how quickly they can repassivate when oxide layers are removed by fatigue cracks (Teoh, 2000; Brunner and Simpson, 1980). The inability of metallic implants to repassivate quickly exposes unprotected regions to corrosion, which immediately results in corrosion-fatigue. This can cause a considerable drop in fatigue endurance limit, which is one of the main reasons for bone plate failure (Teoh, 2000; Brunner and Simpson, 1980). To address these drawbacks, a new generation of biomaterials, i.e. composite materials, has been introduced, which consist of a polymer matrix reinforced with fibers (Akeson et al., 1975; Tayton et al., 1982; Woo et al., 1974). Although composite biomaterials appear as very attractive solutions for orthopedic implants due to their noncorrosiveness, tailorability, flexibility, and radiolucency (Christel et al., 1987; Adam et al., 2002; Ali et al., 1990), they have not yet replaced metallic materials for clinical applications because of their early failure due to poor surface properties (Christel et al., 1987; Adam et al., 2002; Ali et al., 1990; Kurtz and Devine, 2007; Barry et al., 1995; Howling et al., 2004; Jockisch et al., 1992; Bougherara et al., 2007). Moreover, some evidence of inflammation, osteolysis, and cytotoxicity caused by carbon-fiber based composites exists in the literature (Ali et al., 1990; Barry et al., 1995; Howling et al., 2004; Jockisch et al., 1992). Although most studies on composite materials for medical applications have been at the experimental level due to the aforementioned challenges, composite materials may have a beneficial contribution in future development of load bearing orthopedic implants and, thus, some are being examined at the clinical trials stage (Evans and Gregson, 1998; Horak et al., 2010; Pokorny et al., 2010).

Even so, over the past 30 years there is continual interest among many researchers to develop composite implants that will eventually become a successful alternative to metal devices. Some of these devices have advanced to the clinical trials phase (Horak et al., 2010; Pokorny et al., 2010). Briefly, experimental studies have considered composite materials for various non-load bearing and load bearing orthopedic applications such as spinal cage for degenerative discs (Brantigan et al., 2000; Brantigan and Steffee 1993), filling bone defects for anchoring into bone for dental implants (Ballo et al., 2009, 2007, 2011), intramedullary implants for fixing subtrochanteric defects (Zhao et al., 2009), longbone fracture repair plates (Fujihara et al., 2004; Saidpour, 2006; Huang and Fujihara, 2005; Saikku-Backstrom et al., 2005; Steinberg et al., 2013), high tibial osteotomy (Cotic et al., 2014), and total hip replacements (Pokorny et al., 2010; Skinner, 1988). These composite materials were mainly reinforced by one type of synthetic fiber (i.e. carbon and glass fibers), which can accompany the emission of pollutants and result in numerous environmental and occupational health issues during the fabrication process (Le Duigou et al., 2010). Therefore, natural fibers have recently gained attention for biomedical applications (Bagheri et al., 2013; Chandramohan and Marimuthu, 2011). For bone plate applications, for example, hybrid composites with a "sandwich structure" may potentially be used, as they can simultaneously reduce the stiffness of the plate and the subsequent stress shielding effect, yet retain adequate bending stiffness to immobilize the fracture site (Bagheri et al., 2013; Bartel et al., 2006). Mechanical properties of hybrid composites have a sufficiently established research history (Amico et al., 2010; Fiore et al., 2012; Sayer et al., 2010; Valenza et al., 2010; Noorunnisa Khanam et al., 2010). Although a few investigations have been done on the fatigue behavior of hybrid composites made of natural fibers and carbon fibers, none have done so for bone plate applications (Fiore et al., 2012; Noorunnisa Khanam et al., 2010).

As part of an ongoing research program for fabrication of orthopedic bone plates, the authors designed and manufactured an advanced new carbon fiber (CF)/flax/epoxy composite with a "sandwich structure" and a solid bond at the flax/epoxy and CF/epoxy interfaces. During quasi-static uniaxial tensile and quasi-static 3-point bending tests, this composite showed a comparable mechanical elastic modulus (tensile test, 42 GPa; 3-point bending test, 57 GPa) with superior mechanical strength (tensile test, 400 MPa; 3-point bending test, 511 MPa) (Bagheri et al., 2013) to that of human cortical bone (elastic modulus, 7–25 GPa; strength, 50–150 MPa) (Brydone et al., 2010). Moreover, in a prior pre-clinical biomechanical study, the current authors have used this plate to fix simulated Vancouver B1 femoral fracture on synthetic femurs under clinical-type static and dynamic loading conditions with comparable results to a standard metal fixation plate (Bagheri et al., 2014). Thus, it can be a potential candidate for fabricating bone fracture plates. However, no prior studies exist which have assessed the mechanical fatigue properties of this unique CF/flax/epoxy composite developed by the current authors.

Therefore, the purpose of this study was to determine the fatigue behavior of the authors' new CF/flax/epoxy composite with both conventional experimental fatigue tests and infrared thermography analysis. The authors hypothesized that the composite plate would have high cycle fatigue strength (HCFS) that is much higher than the main loads experienced by a femur bone fracture plate during normal daily activities, such as running and walking.

2. Materials and methods

2.1. General approach

Fatigue tests were performed on CF/flax/epoxy composite plates to determine the fatigue strength using both the conventional Stress–Number of cycles (S–N) approach and thermography analysis. The purpose was to evaluate the bonding strength at the flax/epoxy and CF/epoxy interfaces, as well as the fatigue strength of the composite plate under clinical-type cyclic loading conditions. The application of thermography analysis has been proven previously as a