Biomechanical Fatigue Analysis of a New Carbon Fiber/Flax/Epoxy Composite for Bone Fracture Plate Applications using Infrared Thermography

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Abstract:
The biomechanical fatigue properties of a new Carbon fiber (CF)/Flax/Epoxy composite material for bone fracture plate application have been investigated in this study using both conventional fatigue tests and thermography analysis. The CF/Flax/Epoxy composite showed high cycle fatigue strength over a range of 200-220 MPa, which is much higher than clinical loads on the femur during normal daily activities. Moreover, the fatigue strength obtained with thermography analysis was in exact accordance with the range from the conventional fatigue tests with a value of 205 MPa. This study confirmed that the developed CF/Flax/Epoxy composite has desirable biomechanical fatigue properties for bone fracture plate application. In addition, this study introduced the application of thermography analysis to rapidly determine the fatigue strength of biomedical materials without the need of too many specimens.

1. Introduction

Femur shaft fracture at the tip of a total hip arthroplasty is mainly treated by bone plates since antegrade or retrograde nailing are not actually feasible [1-3]. The problem with commonly used bone plates is that they are all made of metallic materials, like Titanium alloys, stainless steel or Co-Cr alloys, which have elastic moduli 5-10 times larger than that of human cortical bone [1-4]. According to Wolff's law, this mismatch between the Young's modulus may result in "stress shielding", where most body load is carried by bone plates rather than bone itself and causes subsequent bone atrophy, osteoporosis and implant loosening [1, 2, 4]. The application of metallic biomaterials is limited not only because of the "stress shielding" effect, but also due to the inherent disadvantages of corrosion-fatigue and being radio-opaque [5, 6]. To address the drawbacks of using metallic biomaterials, composite materials have been introduced and soon gained attention because of their flexibility, tailorabiliy, non-corrosiveness and radiolucency [4, 7].

Several studies have been done to develop composite materials for different biomedical applications especially for orthopaedic trauma implants using synthetic (carbon, aramid and glass) or natural (banana, sisal, roselle) fibers with various fiber orientations (unidirectional, discontinuous short fibers and braided) [4, 8-20]. All the above-mentioned studies used one type of materials to fabricate their composite plate with a closer elastic modulus to that of human cortical bone in order to eliminate the “stress shielding”. However, an ideal bone plate should have lower axial stiffness to reduce the subsequent stress shielding effect, yet retain adequate bending stiffness to immobilize the fracture site. This cannot be achieved using only one type of material [21]. Thus, a hybrid composite with a “sandwich” structure may be a potential candidate for bone fracture plate application.

Therefore, in this study a new CF/Flax/Epoxy hybrid composite material has been developed for bone fracture plate application. This hybrid composite has comparable stiffness (tensile test, 42 GPa; 3-point bending test, 57 GPa) with superior strength (tensile test, 400 MPa; 3-point bending test, 511 MPa) to that of human cortical bone (elastic modulus, 7–25 GPa; strength, 50–150 MPa) [21]. The purpose of this study was to determine CF/Flax/Epoxy fatigue properties using both conventional and thermography approaches, since cyclic loading is one of the main types of loads carried by a femur fracture plate during normal daily activities. The authors postulated that the composite plate would demonstrate fatigue strength much higher than clinical loads applied to the femur during running or walking. Another hypothesis was that the thermography analysis could be used, as an alternative to conventional fatigue testing, to quickly verify the fatigue strength of biomedical materials.

2. Methods

2.1. Composite Materials Preparation

The CF/Flax/Epoxy composite material was manufactured in a compression molding machine (Carver Press, Wabash, IN, USA) using 16 layers of Flax/Epoxy laminae and 2 layers of CF/Epoxy laminae which were added to the outer surface of the composite resulting in a sandwich structure. The detail of CF/Flax/Epoxy composite material production is given elsewhere by the current authors [21].

2.2. Conventional Fatigue Test

All fatigue tests were performed on a servo-hydraulic materials testing machine (Model 322.21, MTS System Corporation, Eden Prairie, MN USA), in which 45 mm of the test specimens at each end were gripped. Tests were conducted at 5 load levels (0.5-0.8 Ultimate tensile strength, 200-320 MPa) with 4 test specimens at each load level. The dimensions of the test specimens were selected based on the ASTM standard recommendations for tension-tension fatigue tests [22]. While load was automatically recorded via the testing machine, strain was measured using an extensometer (Model 634.12F-24, MTS System Corporation, Eden Prairie, MN, USA) placed at the middle of the specimens to accurately record the elongation of the samples, but not the grips. All tests were performed at room temperature (23 ºC) under the load control condition with a loading ratio of $R = 0.1$ ($R = S_{min} / S_{max}$), S=applied load, and a sinusoidal waveform at 5 Hz. Tests were terminated either at specimen breakage or at 6 million cycles.

2.3. Thermography Test

The thermography approach, as a non-destructive technique, was used to determine the fatigue strength of the composite material more rapidly in comparison to the conventional fatigue test. The latter is time consuming and also requires a large number of specimens, thus it could be very expensive [23, 24]. The test was started at 30% of UTS as the applied stress amplitude, which was incremented stepwise until specimen failure. At each step, the plate was subjected to cyclic loading for 7000 cycles in order to reach the stabilization temperature [25]. During the tests, the surface temperature of the tested specimens was recorded using an infrared thermography camera (Silver 420, FLIR Systems Canada, Burlington, ON, Canada). In order to avoid temperature variations caused by thermoelastic heating and trigger image recording at the maximum stress level, the camera was synchronized to the controller of the loading machine.

3. Results

3.1. Conventional Fatigue Tests

The S-N curve of the samples is depicted (Fig. 1). Samples that withstand more than $6x10^6$ cycles are depicted using points with arrows. The S-N curve for the current composite was linear in logarithmic scale with a gradual downward slope as the number of cycles increased. Unlike most metallic materials, the current composite does not show a true fatigue limit or endurance limit because it did not become horizontal in log-scale until $6x10^6$ cycles. Thus, the concept of high cycle fatigue strength (HCFS) at an arbitrary number of cycles ($6x10^6$) was used as the fatigue limit [25]. Using an HCFS approach, the fatigue strength was found to be approximately 200-220 MPa. Those plates loaded at applied stress amplitude smaller than HCFS had no failure until 6x106 cycles. The fatigue strength of the current composite (200-220 MPa) was found to be comparable to 316L stainless steel material, which is clinically-used to fabricate commercial bone fracture plates (i.e. around 200 MPa and 300 MPa for cast and forged 316L stainless steel, respectively)[5].

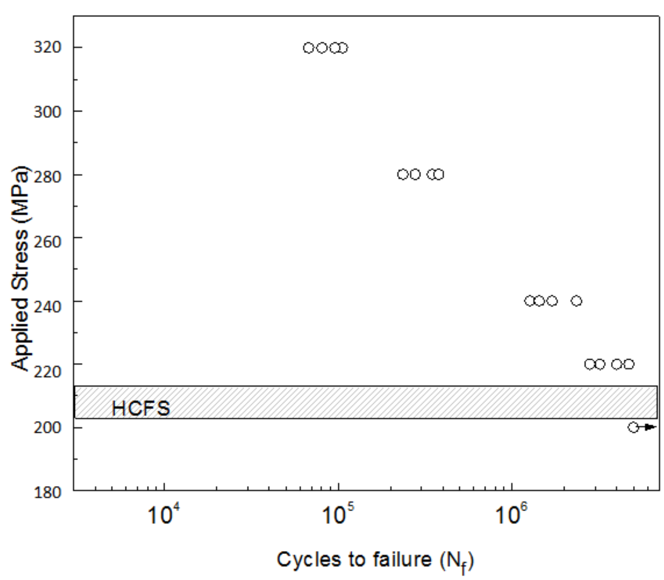

Fig. 1. S_N curve for CF/Flax/Epoxy hybrid composite

The stiffness was calculated using the linear slope of the stress-strain curve at each cycle for a given applied loading amplitude (Fig. 2). The stiffness was found to be almost constant up until failure and stayed around its initial value (47 GPa). For all composite materials, mechanical properties, i.e. stiffness, are usually degraded with increasing cycles. However, this is not the case for flax fiber reinforced composite. The Flax/Epoxy laminae would show hardening behaviour because of progressive reorientation of cellulose microfibrils towards the applied loading direction, thus increasing the stiffness of the current composite [26]. The contribution of both CF/Epoxy and Flax/Epoxy laminae of the composite during the fatigue loading caused the stiffness of the current composite to stay at an almost constant level up until failure. This is an important finding for composites with biomedical applications because one of the complications of using composite biomaterials is that their properties degrade over time, while they may remain structurally intact overall. The gradual loss of the stiffness caused by microstructural fatigue damage generates wear debris, which necessitates an immunological response [27, 28].

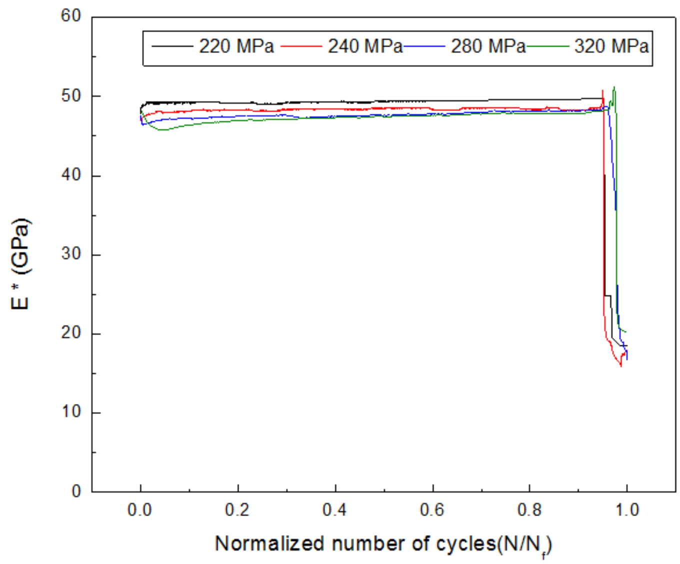

Fig. 2.Dynamic elastic modulus (E*) versus normalized number of cycles (N/Nf).

The damage behaviour of the current composite was depicted using strain (Fig. 3). The damage increases clearly in 3 stages as usually described for composite materials. A steep increase of the damage occurred in the early stages of the fatigue life, followed by another steady increase which remained for a relatively long number of cycles. Acceleration in damage took place at the final stages of the fatigue life. This indicated that the current CF/Flax/Epoxy composite would have a stable cyclic performance.

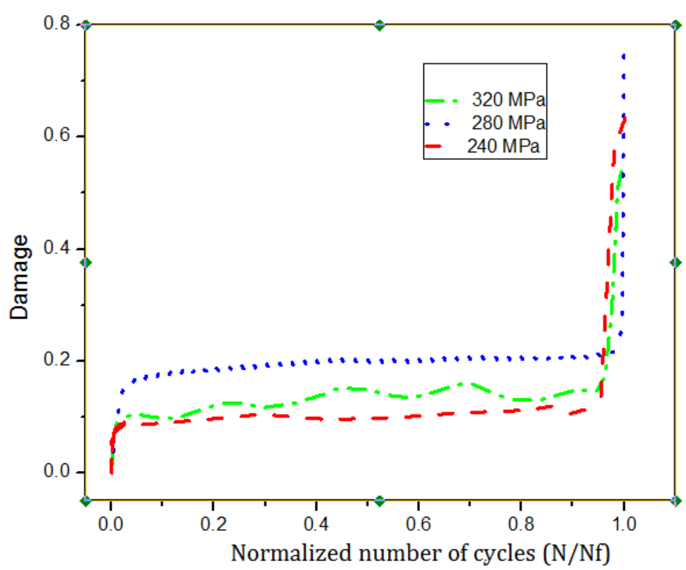

Fig. 3. Calculated damage versus normalized number of cycles (N/Nf)

3.2. Thermography Analysis

The temperature variations at each applied stress level were recorded as a function of the number of cycles using the thermography camera (Fig. 4). The temperature variation map at each applied stress, after the temperature stabilized, is depicted (Fig.5).

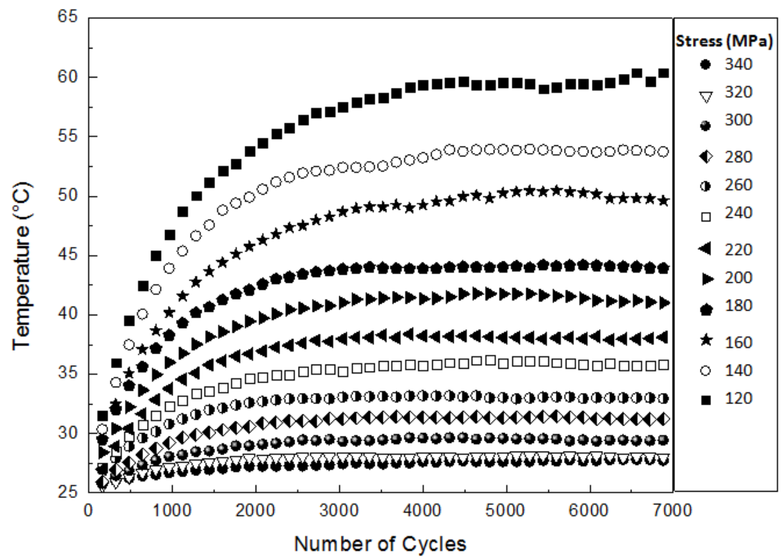

Fig.4. Thermal variation versus number of cycles for each applied stress.

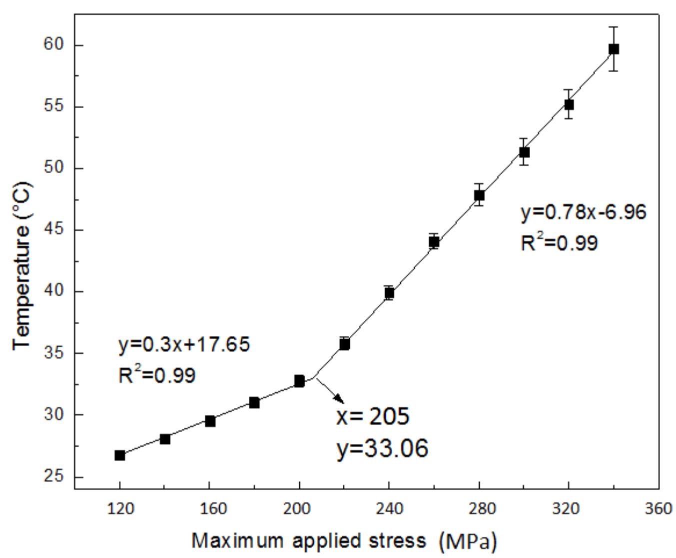

Fig. 5. Temperature distribution map after stabilization.

The data had a bilinear characteristic, where a uniform temperature rise at the surface of the plates was observed until 50% of UTS. However, for stress amplitudes above 50% of UTS, the temperature was no longer uniform. This occurred because the microstructural changes happened while the specimen was cyclically loaded. Although the sample was loaded in the elastic region, the stress may pass the elastic limit at a microstructural level and caused plastic deformation, such as fiber matrix debonding and matrix deformation. This would result in heat emanation and, consequently, a temperature rise on the surface of the samples. The temperature changes would have an increase with a constant slope up to the fatigue strength. However, the damage propagation would accelerate by loading at a stress level larger than the composite's fatigue strength and would change the slope of the temperature rise [25, 29]. The fatigue strength was found by intersecting the 2 linear regions of the curve, which was equal approximately 205 MPa. The fatigue limit obtained using thermography analysis was in good accordance with the range found for the fatigue limit of the current composite using conventional fatigue tests (200-220 MPa), thus indicating the possible use of thermography analysis for rapid determination of composite materials for biomedical applications.

4. Conclusion

The fatigue properties of an advance new CF/Flax/Epoxy hybrid composite manufactured by the current authors were determined. The composite showed fatigue strength much higher than actual clinical loads experienced by femurs during normal daily activities. The composite retained its stiffness up until failure, therefore this may result in less debris formation and minimize any immune system reaction. Based on these preliminary in-vitro results, the current CF/Flax/Epoxy composite has promising fatigue properties which make it a potential candidate for bone fracture plate applications. In addition, thermography analysis, as a non-destructive technique, may be a reliable method for rapid determination of the fatigue strength of composite materials for biomedical applications.

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