ASSESSMENT OF 4-POINT BENDING FATIGUE PERFORMANCE OF COMPOSITE SANDWICHES WITH REDUCED CARBON FOOTPRINT

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Abstract

In this work, 4-point bending fatigue performance including the fatigue damage evolution process, stiffness degradation process and fatigue lifetime of eco balsa cored composite sandwich structures have been investigated. An original triple dog-bone shape has been used to facilitate the observation of the induced laminate skin and core damages thanks to a localized bending or shear stress under 4-point bending loading. The microscopic images have been investigated to explain the fatigue damage evolution process in three stages of stiffness decrease curve during the whole fatigue process. The Glass-Fiber-Reinforced-Polymer (GFRP) skin damages are the predominant failure modes under the fatigue loading.

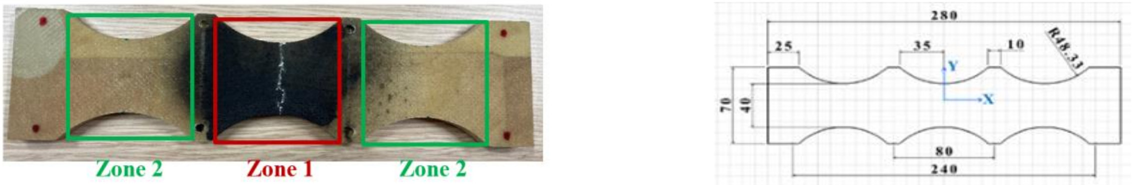
1. Introduction

In the 21st century, the increasing concerns tackling the climate change and planet protection issues drive human beings to develop some greener eco composite materials. Composite materials have been widely applied in advanced industries such as aviation and marine structures for many years, but one of the existing great challenges is to reduce the emission of greenhouse gases such as carbon dioxide or methane during their whole life cycle [1-2]. Accordingly, the partially recyclable wood cored composite sandwich materials such as Glass-Fiber-Reinforced-Polymer (GFRP)-balsa [3-4] have become more competitive due to their higher specific stiffness and strength, as well as environmentally friendly properties. Composite sandwich structures are often subjected to bending fatigue loading [5-6] during their service life, the thin skins are loaded under tension and compression, while the light thick core mainly carries shear stress. As a consequence, more than three different fatigue damage mechanisms may initiate and propagate during fatigue loading, such as core damage, skin/core debonding, and laminated skin damages [4-6]. Fatigue performance including the fatigue lifetime, fatigue limit and fatigue damage evolution could be affected by many factors such as the loading frequency, stress level, stress ratio, constituent material properties, environmental humidity and temperature etc. Particularly, 4-point bending fatigue performance of wood cored sandwich structures has not been assessed very clearly because of the complexity of the bonding of two kinds of anisotropic materials.

In this work, 4-point bending fatigue tests have been conducted to investigate the fatigue damage evolution process, stiffness degradation process and fatigue life of GFRP-balsa sandwich via our proposed bending fatigue system [5-6]. An original triple dog-bone shape [4-6] has been used to facilitate the observation of the induced skin and core damages due to the maximum stress under 4-point bending. The skin and core damage surface has been observed by microscope VHX-7000 (100X) every few thousand cycles during the whole fatigue process to investigate the fatigue damage evolution process.

2. Materials and experimental methods

GFRP-balsa sandwich specimens with the special triple dog-bone shape [4-6] (280 mm * 70 mm) were tested under 4-point bending fatigue loading, as seen in Figure 1. (a) and Figure 1. (b). The narrow width is 40 mm, as shown in Figure 1. (b). The interest of this original triple dog-bone shape is to observe more clearly the possible skin damage in the middle of pure bending zone 1, and core damage in bending and shear zone 2. Another advantage of using this special shape is to reduce the local stress concentration under the loading supports and ensure the failure in the area of interest. All GFRP skins were made of 3-layer GFRP woven balanced fabric/epoxy (Ref: Sicomin E glass fiber twill 3190 with 190 g/m^2 , with 50% fiber volume fraction), with a layup of $[0^o]_3$. The balsa wood core is supplied by BALTEK SB.100, with a density of 148 kg/m^3 [3-4]. The large cured GFRP-balsa panel was cut into small triple dog-bone specimens by water jet technique. It was proven that this technique would not cause damage to the surface of the specimen [4], so the initial surface state would not affect the fatigue damage initiation.



(a) Triple dog-bone specimen shape. (b) Dimensions (mm) of the triple dog-bone shape.

Figure 1. Triple dog-bone GFRP-balsa sandwich specimen.

The 4-point bending fatigue tests were conducted through a developed configuration including pneumatic actuators (2-6 bars) [5-6] and associated components (distributors and Zelio automation), as shown in Figure 2. Finally, the loading frequency was set to 1 Hz with a stress ratio of R=0.1. Based on our investigation in [4] in static 4-point bending tests, the fatigue tests were carried out at a maximum stress level of 50% of the failure load, that is, the max stress in center zone 1 of the compressive skin was about 120 MPa, and the initial displacement was about 5.3 mm in the first cycle. Furthermore, since GFRP-balsa sandwich has shown a linear behavior before the final rupture in static 4-point bending tests [4], in the fatigue tests, the comparator was applied to simplify the measurement of displacement of the center zone 1 during the whole fatigue process. The variation of the displacement can be used as an index of the fatigue stiffness degradation [7-8]. The support span of 4-point bending loading is 240 mm, and the loading span is 80 mm, as illustrated in Figure 2.

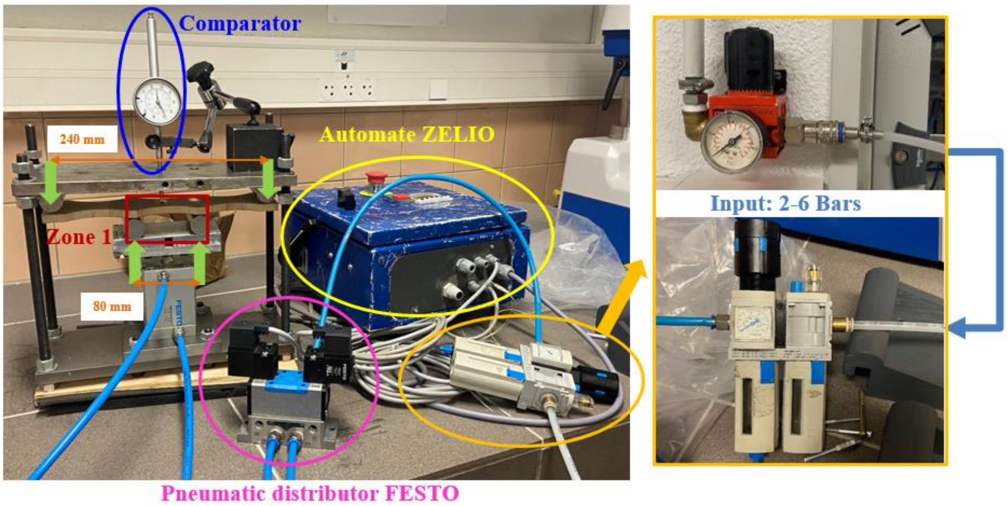


Figure 2. 4-point bending fatigue system for triple dog-bone sandwich specimens.

3. Experimental results

Figure 3 shows the normalized stiffness degradation trend of the GFRP-balsa sandwich specimen under 4-point bending fatigue loading. The final fatigue life is about $3.85*10^5$ cycles. It is obvious that the stiffness degradation process can be divided into three stages. These three stages are similar to those observed in fatigue tests on thin composite laminates [7-8]. It is because that the compressive skin damages (see Figure 1) in the center zone 1 of triple dog-bone sandwich specimens are the predominant failure modes under 4-point bending fatigue loading. According to our observations in static tests in [4] and fatigue damages of laminates in [7-8], the 4-point bending fatigue damage sequence of GFRP-balsa sandwich could be firstly matrix cracking, fiber/matrix debonding, delamination, fiber breakage, skin/core debonding and core damage in center zone 1. This damage evolution process has been demonstrated by microscopic observations in Figure 4-Figure 7.

Referred to literatures on fatigue damage evolution of laminates in [7-8], the three stages in this work can be concluded as following:

- **Stage 1:** initial rapid stiffness degradation. It occupies about 8% of the whole fatigue lifetime. Microscopic matrix cracking in the compressive GFRP skin should be the main damage source in this stage, as shown in Figure 4 (point A). No skin/core debonding and core damage can be observed in this stage.
- **Stage 2:** almost stable stiffness period. It takes up about 89% of the whole fatigue lifetime. Microscopic matrix cracking, fiber/matrix debonding and delamination in the GFRP do not progress significantly at this stage, as shown in Figure 5 (point B) and Figure 6 (point C). No skin/core debonding and core damage can be observed in this stage.
- **Stage 3:** very sudden stiffness degradation period. It occupies only 3% of the whole fatigue lifetime. Fiber breakage should be the dominant damage mode at this stage, followed by the skin/core debonding (with a 4.3 mm crack) and balsa core crack propagation, as shown in Figure 7 (point D).

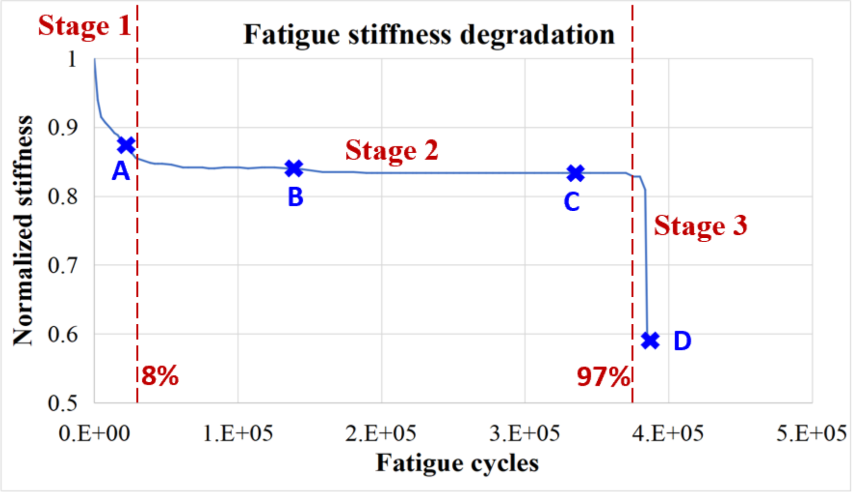
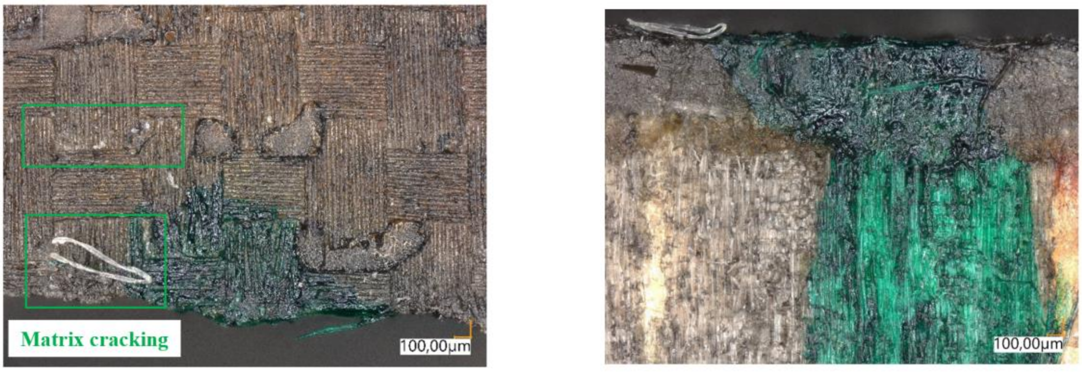
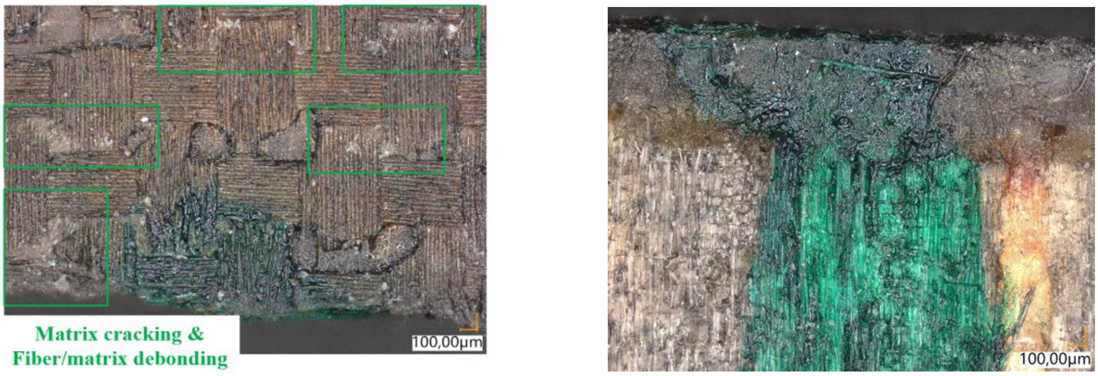


Figure 3. Stiffness degradation trend of GFRP-balsa sandwich under 4-point bending fatigue loading.



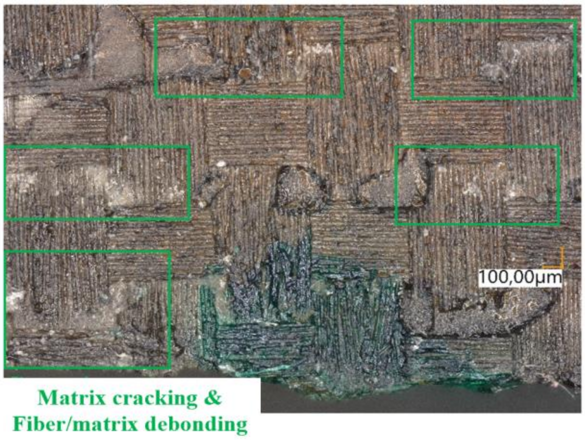
(a) Compressive skin surface. (b) Skin/core interface.

Figure 4. Microscopic images of compressive skin and skin/core interface in center zone 1 of GFRP-balsa sandwich at point A of stiffness degradation curve.

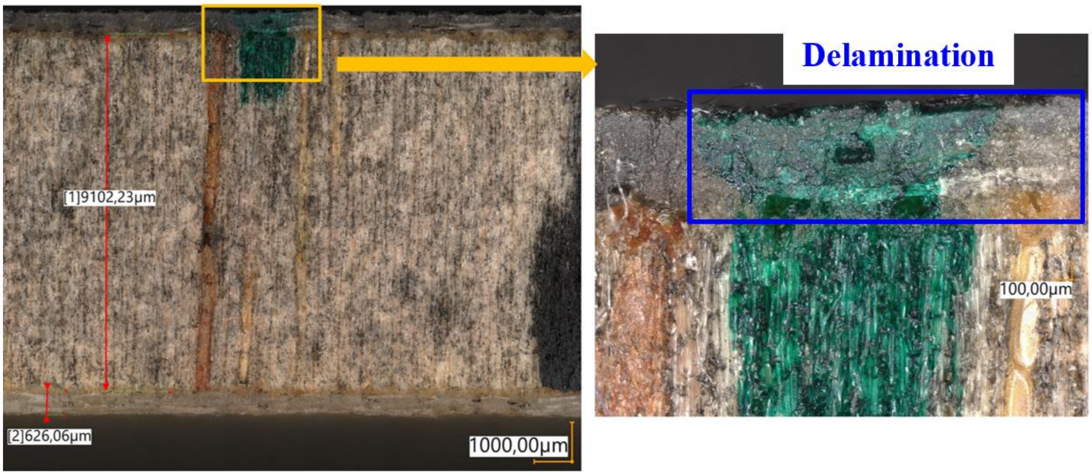


(a) Compressive skin surface. (b) Skin/core interface.

Figure 5. Microscopic images of compressive skin and skin/core interface in center zone 1 of GFRP-balsa sandwich at point B of stiffness degradation curve.



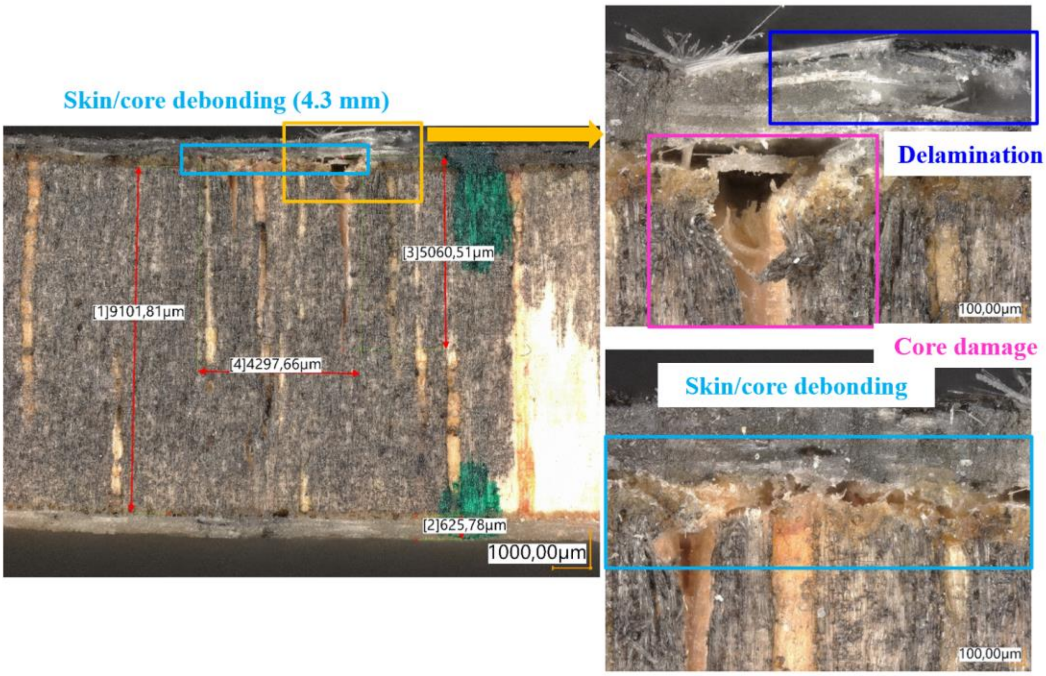
(a) Compressive skin surface.



(b) Skin/core interface.

Figure 6. Microscopic images of compressive skin and skin/core interface in center zone 1 of GFRP-balsa sandwich at point C of stiffness degradation curve.

(a) Compressive skin surface.



(b) Skin/core interface.

Figure 7. Microscopic images of compressive skin and skin/core interface in center zone 1 of GFRP-balsa sandwich at final fracture point D of stiffness degradation curve.

4. Conclusions

This work has characterized the three obvious different stages in the fatigue damage evolution and stiffness degradation process of environmentally friendly GFRP-balsa composite sandwich structure under 4-point bending fatigue loading. It has pointed out that the fatigue life is about $3.85*10^5$ cycles at a stress level of 50% of the ultimate strength in static tests.

However, more future work should be done to further study fatigue behavior of these special triple dog-bone sandwich specimens. For example, fatigue tests [5-6] at different stress levels including 60%, 70%, 80% and 90% of the ultimate strength should be conducted to obtain the S-N curve of this relatively less studied eco composite material. At the same time, the fatigue damage evolution process will be monitored by InfraRed Thermography to observe the self-heating temperature increase [1] in the damage zone to correlate thermal and mechanical fields to predict the fatigue limit and fatigue life of this balsa cored sandwich material.

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