Interaction of Low Cycle Fatigue and Creep in Biomass-filled Plastic Composites

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Most research on biomass-filled plastic composites (BFPCs) mainly focuses on their formulation and physical/mechanical properties, but studies on the connection performance of BFPCs are very rare. However, such performance is vital in the quality assessment of BFPCs products and plays an important role in improving product quality and promoting its application in the field of architecture and furniture. Therefore, the behavior of L-type BFPCs structure under the interaction of fatigue-creep was investigated. Results suggested that the fatigue-creep curve is a typically three-region curve at 80% and 60% failure load, and only first two stages at 40% failure load. But the damage caused by fatigue-creep interaction was not a simple superposition. Fatigue damage dominated when the holding time was short, and creep damage occupied a dominant position gradually when the holding time was longer. In addition, the lifespan of the BFPC component increased initially and then decreased as holding time increased. The component joint exhibited the least integrated damage when the holding time was 60 s and the lifespan was longer.

Keywords: Low cycle fatigue; Creep; Biomass-filled plastic composite; L-type components

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INTRODUCTION

Biomass-filled plastic composites (BFPCs) are a very promising and sustainable green material for application in high-performance and high value-added products. The term BFPCs refers to any composites that contain biomass (including animal and plant fibers, agriculture and forest residues) and thermosets or thermoplastics, which are produced by adding biomass as filler in a polymer matrix and homogeneous mixing, then subjected to hot pressing, extrusion, or injection molding under the action of temperature and pressure (Ashori 2008; Khalid *et al.* 2018). BFPCs have the advantages of wide raw materials source, convenient treatment, green and eco-friendly character, excellent process-ability, and guaranteed strength. One of the most important uses of BFPCs is the replacement of solid wood in various fields, especially in the furniture and construction industries (Chaharmahali *et al.* 2008).

However, in practical applications, the rise and fall of an emerging material is determined by many factors, including economy, mechanical processing ability, strength, dimensional stability, safety, and durability. Just as fiberboards and particleboards, BFPCs are used in furniture, so there is a need for tests of mechanical strength, nail holding power, connectivity, durability, and decorativeness. BFPCs also need to undergo these tests to meet the standards of use. Currently, the research on BFPCs mostly focuses on their formulation (Naldony *et al.* 2016; Torres-Tello *et al.* 2017; Yáñez-Pacios and Martín-Martínez 2017), interfacial compatibility (Beg 2007; Bera *et al.* 2010), and physical and mechanical properties (Herrera-Franco and Valadez-Gonzalez 2005; Graupner and Müssig 2011; Dikobe and Luyt 2017; Khalid *et al.* 2018). As the study of the connection properties of BFPCs, only the effects of screw type, pilot hole, and material thickness on the strength of the joint have been considered (Özçifçi 2009; Haftkhani *et al.* 2011), whereas research on their fatigue and creep characteristics is scarce. However, the fatigue and creep properties are important indicators for evaluating the durability and safety of furniture and construction products. Furthermore, the mechanical behavior of furniture and construction products (such as seats, floors, beams, and partitions) is a practical application of fatigue-creep (Song *et al.* 2002). Therefore, in order to promote the use of BFPCs, the influences of fatigue-creep interaction on the connectivity of BFPCs were studied.

But seriously, there are many factors affecting the creep and fatigue properties of BFPCs that need to be considered. As reported in the literature, the fatigue behaviors of polymers and polymer-matrix composites have been evaluated with respect to the effects of loading modes, time, temperature, mean stress, stress concentration, frequency, aging, anisotropy, and environmental effects (Mortazavian and Fatemi 2015a; Mortazavian and Fatemi 2015b; Shojaei and Wedgewood 2017). The creep of the composites increased as time, temperature, and stress increased (Homkhiew *et al.* 2014), and high correlations between fatigue strength and tensile strength were obtained. In one study, the creep resistance values of composites with heat-treated wood particles were greater than those with untreated wood particles due to the hydrophobic quality of the treated wood particles and the improved interfacial compatibility between the wood particles and polymer matrix (Yang *et al.* 2017). Furthermore, the incorporation of wood flour reduced the short-term creep response of the HDPE matrix, and the presence of Nylon-6 microfibrils further contributed to creep reduction (Liu *et al.* 2010). In addition, the flexural strength and modulus initially increased with increasing nanoclay content, yet later decreased. The fractional deflection and relative creep decreased with increasing nanoclay content (Kord *et al.* 2016).

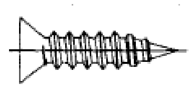
Research on the interaction of fatigue-creep suggested that the temperature, frequency, load level, and hold-stress position has an effect on creep-fatigue interaction behavior (Eftekhari and Fatemi 2016). It is a non-linear creep-fatigue interaction behavior for the composites, and the non-linearity of the interaction decreased with increasing stress level. However, frequency and position of hold-time stress did not affect the creep-fatigue interaction curve. In addition, the effects of cross-sectional design, load direction, load levels, loading waveform, and plastic type on the creep and fatigue properties of BFPCs were also investigated (Sain *et al.* 2000; Najafi and Najafi 2009; Pulngern *et al.* 2010; Zhou and Li 2009; Zhu *et al.* 2013). These results suggest that it is vital to study the damage behavior of BFPC components under fatigue-creep interaction. In this paper, the influence of low-cycle fatigue and creep interaction on the durability of BFPC components was studied by using self-tapping screws as fastenings, which were expected to provide theoretical support for the promotion of BFPCs.

EXPERIMENTAL

Materials

The BFPCs used in the experiments were supplied by Nanjing Jufeng Advanced Materials Co., Ltd (Nanjing, China) with the section size of 40 mm × 30 mm. The main components of the composite were recycled high-density polyethylene (HDPE, the density is 0.94 g/cm^3 the melt flow index (MFI) is 0.45-0.57 g/10min) and rice husk powder with a mixing ratio of 1:1, respectively. In addition, the sheets used in this study were obtained by an extrusion process in the same batch, with the temperature profiles 150 to 180 °C for each temperature zones and a screw rotation speed of 600 mm/min. The density was 1.18 g/cm^3, the flexural strength was 19.1 MPa, and the modulus was 2.8 GPa. The self-tapping screws (ST4.8, GB846-85) used in this study were provided by Xinghua Pingfan Stainless Steel Standard Fastener Factory (Xinghua, China), and the parameters of the screws used in this study are shown in Table 1.

Table 1. Self- Tapping Screw Parameters

Screw	Schematic	Outer Diameter (mm)	Inner Diameter (mm)	Length (mm)	Pitch (mm)
Self-tapping screw		4.8	3.3	70	1.6

Methods

Preparation of samples

The specimen was a coplanar joint with an arm length of 150 mm. The guide holes were drilled before installation and had a hole diameter of 4.5 mm and a hole depth of 60 mm. The connection form and the guide hole position of the BFPC component are shown in Fig. 1. A total of 42 specimens were used for testing.

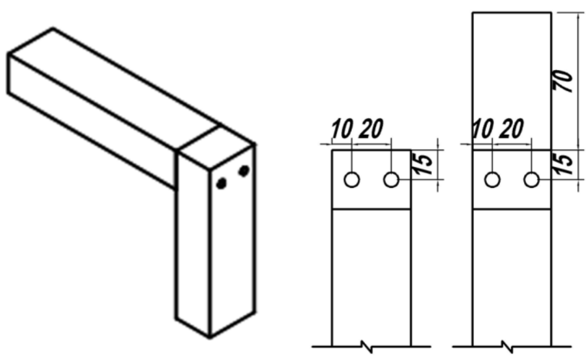


Fig. 1. The connection form and the guide hole position of the BFPC component. Measurements are given in mm.

Testing

The mutual action of the bending fatigue-creep test for the BFPC component was carried out on an electronic universal testing machine (Shimadzu AG-10TA, Kyoto, Japan), which has a loading accuracy of 0.25% and a time accuracy within 1 s. Furthermore, the experiments used inward bending to apply loads, and the specimen jamb was vertically fixed to the test bench. The cyclic loading test was carried out by applying a load on a cross arm, which was 150 mm from the side shaft. The displacement (d) was measured at a distance of 50 mm from the joint surface (as illustrated in Fig. 2). The displacement angle (θ) of the joint was calculated using Eq. 1.

$$\theta(\text{radian}) = d / 50 \tag{1}$$

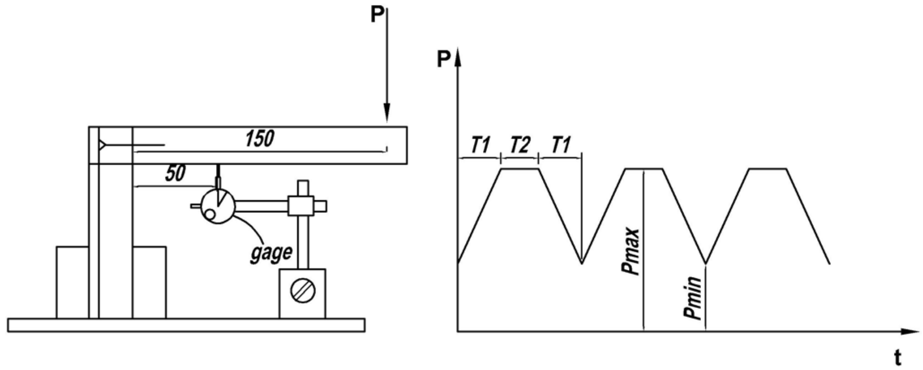


Fig. 2. Diagram of the loading applied to the BFPC component for the test (T1: load or unload time; T2: maximum load hold time; Pmax: maximum load; and Pmin: minimum load)

The loading waveform was a trapezoidal wave (Fig. 2) that was the well-known "between place cut in" load diagram (Zhu and Huang 2010). To ensure that in each cycle the BFPC components were both subject to fatigue damage and creep damage during the maintenance, the holding time (T2) was added to the maximum value of the alternating load during the bending fatigue cycle. The holding times (T2) were 0 s, 60 s, and 120 s, respectively. In addition, no holding time was applied to the minimum alternating load. The speed of loading and unloading was 20 mm/min, and T1 was determined by loading or unloading speed and displacement.

The fatigue alternating stress ratio was R = 0.3 and the maximum value of alternating load consisted of three values: one value was 80% of the maximum failure load of the BFPC components. Under the action of this load, the BFPC component will access plastically deforming phase and destroyed in a short time. The second value was 60% of the failure load, which was near the conditional yield limit of the component, and the third value was 40% of the failure load, which was within the elastic range of the BFPC component (Yan-Qing *et al.* 2007). To determine the maximum value of the alternating load, the L-type components were made from the same batch of BFPCs, and six of the optional specimens were tested for static bending failure. The mean value of the failure load was 483.1 N, the standard deviation was 42.76 N, and the correlation coefficient (v) was 0.071. Therefore, the maximum values of the alternating load were 386.5 N, 289.9 N and 193.2 N, respectively.

RESULTS AND DISCUSSION

Fatigue-Creep Failure Curve

Figure 3 illustrates the variations of the displacement angle (θ) with the cycle number for the BFPC component under the interaction of fatigue-creep. The test was carried out under different holding times, and the loads were 80%, 60%, and 40% of the maximum failure load, respectively. Figures 3(a) and 3(b) show that the fatigue-creep curve was divided into three stages (Song *et al.* 2002). The first was the rapid small deformation stage, in which the stress was proportional to the variation of the displacement angle (θ); the displacement angle increased as stress was increased, which represents instantaneous elastic deformation (reversible deformation). The second stage was the strain platform stage, in which the angle change slightly increased as time increased, and the angle change was almost constant, representing delayed elastic deformation. The third stage was the accelerated failure stage, in which the angle change was very rapid until the damage occurred. The fatigue-creep curve in Fig. 3(c) had only two stages, which were the same as the first two stages described above. This was because the load strength was within the elastic range of the component connection. Furthermore, the test machine had to complete 1200 cycles to stop running, and the components did not fracture or fail.

In the rapid small deformation stage, the rates of increasing angles of all the curves were almost identical (Figs. 3(a) and 3(b)), which suggests that the different holding time has a slight effect on the rate of displacement angle change. In the strain platform stage, the change rate of the displacement angle increased as holding time increased, and the displacement angle continued to increase. Furthermore, the strain platform stage ended rapidly and quickly entered the accelerating deformation stage. In the initial stage of the experiment, the time of fatigue-creep was short and the BFPC components were still in the elastic deformation stage. As such, the change rate of the displacement angle at the same stress level was the same. However, the fatigue-creep interaction began to appear when the test reached the intermediate and final stages. With increased holding time, the proportion of creep load increased, and the proportion of fatigue load decreased. The creep accelerating the plastic deformation of the BFPC component, and increased the growth rate of the platform strain and the increments of the displacement angle. As a result, the displacement angle in the BFPC components joint grew quickly in a short period, eventually leading to breakage.

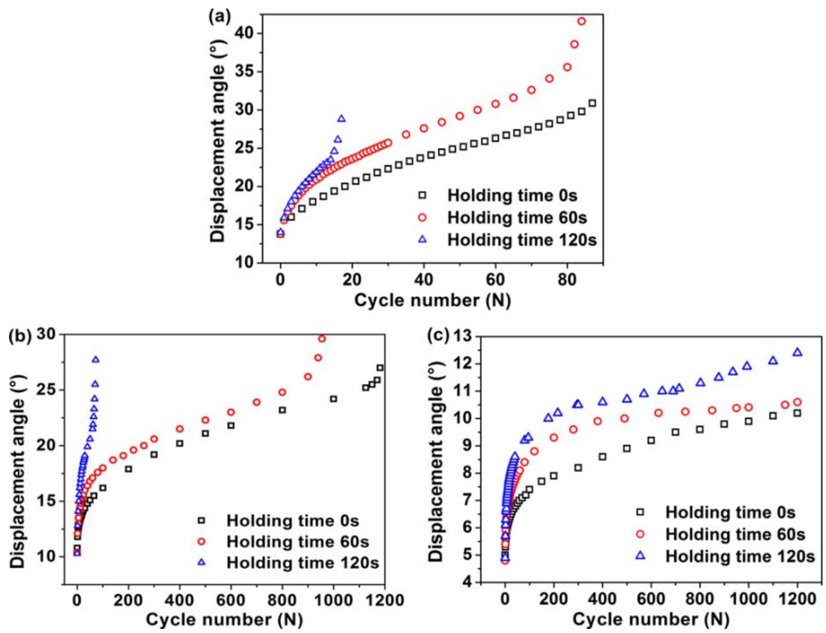


Fig. 3. Variations of displacement angle (θ) with the cycle number for the BFPC component; (a), (b), and (c) represent the conditions of 80%, 60%, and 40% maximum failure load, respectively.

In addition, the shorter holding time produced a smaller slope in the elastic strain stage and an earlier transition into the strain platform stage. Furthermore, the delayed elastic deformation was smaller. A decrease in holding time means that the frequency of loading and unloading increases. Frequent alternation of fatigue results in an increase in the plastic strain of the component joint, thereby accelerating the end of the strain platform stage (Yan-Qing *et al.* 2007). Under the same cycle number, the displacement angle of the component joint increased as holding time increased, indicating that the destruction of the components has increased. The displacement angle of the component joint was not equal when final breakage occurred. In contrast, it was significantly larger than the other two cases when the load time was 60 s. This was mainly due to the slight integrated damage of the component joint at 60 s, such that the lifespan of the component was longer (Fig. 4(a)). The screws were heated under sustained load, and the brittleness of the BFPC components was reduced. Therefore, a large enough displacement angle is required to break the connection between the components (Fig. 3 (a), (b)).

Variations of the Life Span with the Holding Time for BFPC Component

The time corresponding to the cycles can be calculated based on the holding time of T2 and the loading and unloading time of T1. Figure 4(a) illustrates the variations of life span with the holding time for the BFPC component under 80% and 60% of the maximum failure load, respectively. It can be seen that the life span was low at high loading. In addition, with increasing holding time, the fatigue life of the BFPC components initially increased and then decreased rapidly. In contrast, under the interaction of fatigue-creep, the life of BFPC components decreased with increasing holding time. In fact, the component joint was only affected by fatigue when the holding time was 0 s. Under the same displacement angle, the cycle number was much greater than that of a holding time is 60 s (Fig. 3), and the component was subjected to greater fatigue damage. Increasing the holding time is equivalent to reducing the fatigue damage. However, as holding time continued to increase, the displacement was increased fast, and creep played an important role in the accelerated damage of BFPC components. Therefore, the integrated damage of the component was smaller at the holding time of 60 s, and the lifespan of the component was greater.

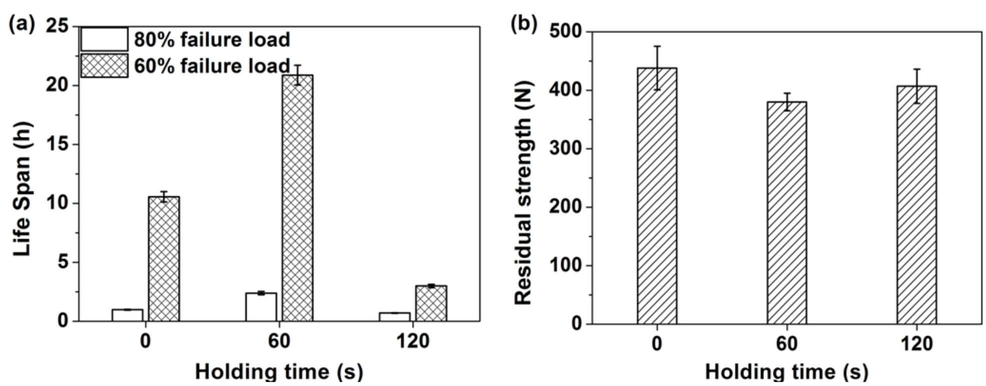


Fig. 4. Variations of (a) life span and (b) residual strength (at the condition of 40% maximum failure load) with the holding time for the BFPC component

In addition, Fig. 4(b) presents the variations of residual strength with the holding time for the BFPC component after the interaction of a 1200 cycle load, in which the loading was 40% of the failure load. It can be seen that the strength of the component was reduced to a lesser degree at different holding time. This result can be attributed mainly to the fact that the deformation of the component remains within the elastic range, leading to less damage to components (as discussed in Fig. 3(c)). However, the strength of the components will also decrease in a small range under the frequent interaction between fatigue and creep.

CONCLUSIONS

1. The fatigue-creep curves of the BFPC component are typically three-region curves at 80% and 60% failure load, including rapid small deformation stage, strain platform stage, and accelerated failure stage (The fatigue-creep curve have the first two stages at 40% failure load). But the fatigue-creep interaction is not a simple superposition relationship. The fatigue damage dominated in short holding times and the role of creep damage gradually increased as holding time increased.
2. The displacement angle increased with increasing holding time and increasing load, and the component will accelerate destruction under high load. The shorter the holding time, the earlier to access the delayed elastic deformation stage and the delayed elastic deformation is small.
3. As the holding time increased, the integrated damage of fatigue-creep interaction on BFPC component joint initially decreased and then increased. So the life of the BFPC component initially increased and then consequently decreased with increasing holding time.
4. The damage of the fatigue-creep interaction was small at a moderate holding time and the life of the BFPC components was longer. But the longer interaction increased the frictional heat between the screw and the materials, and the higher temperature reduced the brittleness of the BFPC. Therefore, the displacement angle increased when the components were broken.

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