LISTEN TO THE WATER CONCERTO DURING THE FRACTURE PROCESS OF CELLULAR FIBROUS BAMBOO

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ABSTRACT

Bamboo, as a kind of environmental friendly natural biomaterials, is world-widely distributed and applied. Their mechanical properties have drawn numerous studies, but the dynamic fracture behaviours were still unclear. Fibres and parenchyma cells form the majority of the bamboo stalk in terms of volume fraction. Tensile performances of bamboo samples with different water weight contents (0 %, 6 % and 17 %) were investigated, while the dynamical tensile fracture process was synchronously recorded and analyzed by acoustic emission (AE). The primitive and fractured microstructures of the cellular fibrous bamboo were observed and analyzed, and the underlying dynamic mechanical behaviours were discussed. Samples with different water contents showed obviously different tensile properties in both of strength and toughness. There were three kinds of fracture behaviours during the fracture process of the bamboo samples, which were parenchyma cells breakage, interfacial dissociation and fibre breakage, when the three fracture types were decorated as accompaniment instruments, and water played as the main theme. Considering of the varied components in the bamboo fibres and parenchyma cells, the molecular toughening origins were lying in the hydrogen bond and the ring structural molecules. Water played the leading role in this enchanting and wonderful concerto, where the water molecules and the cellulose-hemicellulose-lignin complexes were collaboratively working together, ensuring the high strength and toughness of bamboo.

1 INTRODUCTION

Bamboo, as a kind of environmental friendly natural biomaterials, is world-widely distributed, and they have been extensively used in architectures, bridges, furniture, cars and many daily necessities [1, 2]. With excellent mechanical properties (e.g. strength and toughness), bamboo have been used as engineering materials. However, the underlying dynamic fracture behaviours were seldom reported.

Acoustic emission (AE) was generally used in the non-destructive detect of varied kinds of engineering materials [3-5], and the dynamic fracture behaviours [6] could be recorded and analyzed during the deformation and fracture processes. According to the typical features of the AE signals, there are mainly three kinds of fracture types within the artificial fibre reinforced composites, including matrix breakage, fibre debonding and fibre breakage [4, 5]. Bamboo, as a typical kind of natural fibre reinforced bio-composite materials, might have the similar fracture behaviours during the dynamic fracture process. However, the fracture behaviours within the cellular fibrous bamboo would be affected by the water content, as water molecules were filled in the porosity, which might make great influences on the cellulose-hemicellulose-lignin complexes [7].

Here, with water as the bridging medium, the dynamic fracture process and behaviours of cellulose fibrous bamboo are proposed for the first time by AE method, as far as the current knowledge. The influences of water content on the mechanical properties and the dynamic fracture behaviours were investigated. This work may contribute some inspirations and enlighten the lateral researches on the preparation and mechanical researches of bio-mimetic materials.

2 MATERIALS AND METHODS

The Moso bamboos *(Phyllostachys heterocycla (Carr.) Mitford cv. Pubescens)*, collected and bought from a plantation located in Hengyang in the central Hunan province, China, was selected as raw materials. They were all mature (5 years old), sectioned from the stalks ~1.5 m high from bottom, and kept at room temperature of ~22 ^{o}C and relative humidity of ~45 % -65 %. The hierarchy structures and chemical compositions of bamboo are displayed in Fig. 1. By a carefully precise dehydration in a temperature-controlled oven (102 ^{o}C, 7.5 hr), absolutely dry samples (water weight content of 0 %) were obtained. One third of these dry samples were sealed and stored with strong desiccant, while another third were exposed in the ambient air for 2 days with an average water content of 6 % after though. The last third were soaked into the calm distilled water for 6 hr, making the water content up to 17 %. Samples with different water content (0 %, 6 % and 17 %) were obtained and for each at least 5 samples were selected for the later tests. The fractured surfaces were observed by scanning electron microscope (SEM, CamScan-3400, CamScan Corp., UK), with accelerating voltages of 15 -25 kV. The wet samples were treated by a slow moderate dehydration for the lateral morphological observation in SEM.

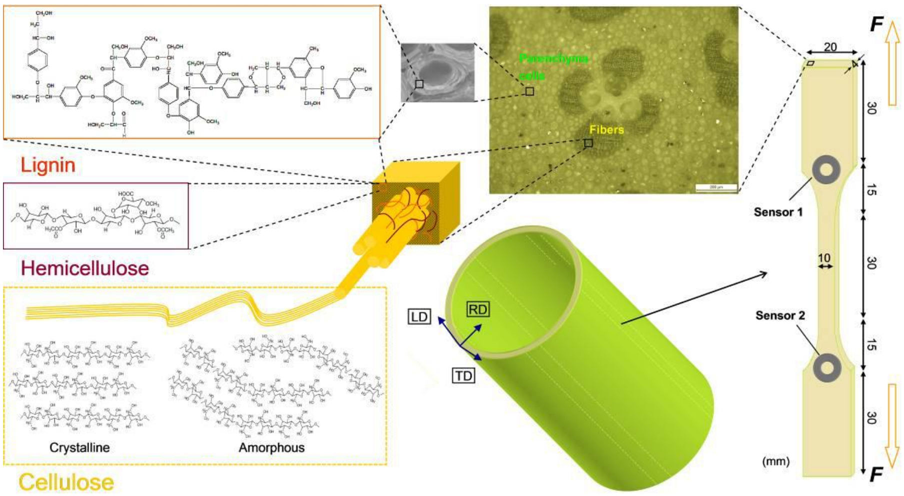

Figure 1: Tensile-acoustic emission test diagram and the chemical compositions [1, 7] of bamboo.

To evaluate the dynamic facture behaviours of bamboo, samples with the same fibre and cell volume fraction (cut from the five centrosymmetric positions of the stalk, Fig. 1) were prepared for the tensile-acoustic emission (T-AE) tests. The T-AE tests were performed on a mechanical test machine (SANSI, MTS Industrial System Co. Ltd., China) at a strain rate of 1.4×10-4 s^{-1}. Two piezoelectric sensors (Nano-30) with a resonant frequency of 140 kHz, a preamplifier with 40 dB gain and a compatible filter (10 kHz–2 MHz) were used to capture the AE signals (Fig. 1). Signals were recorded and analyzed by a digital signal processor with an AEwin v2.19 AE system (Physical Acoustic Corporation, USA). Vaseline was used at the interface between the sensors and the specimen surface to improve the signal transmission. To eliminate the noise from the external environment, an amplitude threshold of 35 dB and a frequency threshold of 20 kHz were used in the experiment.

3 RESULTS AND DISCUSSIONS

3.1 Mechanical performance of bamboo with different water content

Bamboo samples with different moisture content have great difference on tensile performance (Fig. 2). The dry samples were brittle, with the lowest fracture strength (134.7 MPa) but the highest tensile modulus (~2.69 GPa) in average. Samples with a water content of 6 % have a better performance in strength (141 MPa) and a more advance in strain, which had almost a half increase than the absolutely dry samples. As the moisture content went up to 17 %, the tensile performance was greatly improved, both in strength and toughness. As displayed in Fig. 2, the samples with the highest water content have an average tensile strength of 178 MPa, and a strain getting close to 0.14, which is almost the twice of the 6 % samples, and triple of the dry samples.

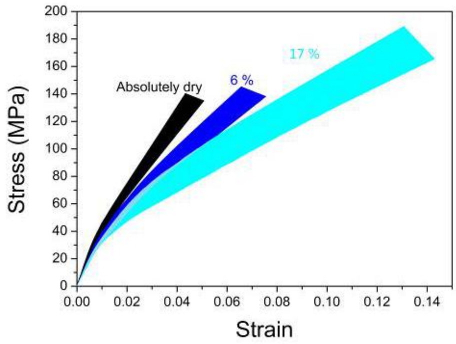

Figure 2: Tensile performance of bamboo samples with different water content.
For each content at least five samples were tested.

3.2 Fracture morphologies of bamboo with different water content

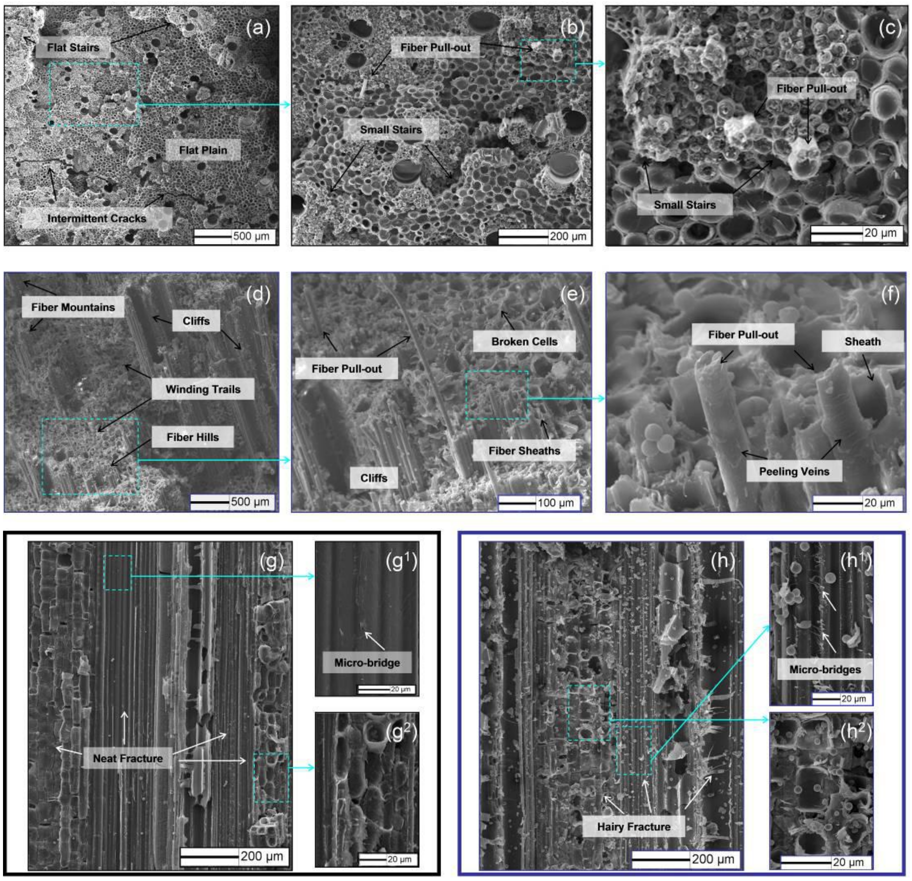

Figure 3: Tensile fracture sections of the dry and wet (17 %) samples. Cross section of the dry (a, b, c); and wet (d, e, f) samples in different magnifications; Longitudinal sections of the dry (g); and wet (h) samples in different magnifications.

The fractured surfaces of dry and wet samples showed quite different morphologies, which were typical brittle and tough fractures, respectively (Fig. 3). The tensile fractured dry bamboos showed neat morphologies on both of the cross and longitudinal sections (Figs. 3a and g). Flat stairs and plain can be seen on Fig. 3(a), the cross section of the dry samples, where the step-like stairs and plain were just like highlands and basins on earth. There were also intermittent cracks lying on the plain, like rivers flowing past, which will be discussed in the next chapter. Take a close look at the plain (Figs. 3b and c), small stairs were observed at the fibre-parenchyma cell junctions, due to the difference on tensile properties. These small stairs were consisted of varying numbers of fibres or parenchyma cells, caused by collective fracture processes. A few pulled-out fibres can be seen stretching out of the fibre bundles, showing a less obvious fibre-bridging process during the fracture of the dry samples. Additionally, the outstretched fibres also have flat cross sections, as the Fig. 3(c) shows, supposed to be the smallest stairs on the fracture sections of dry bamboos.

The longitudinal sections of the dry samples showed clear outlines of fibre bundles and parenchyma cells (Fig. 3g). Step-like cross sections reasonably indicate that during the tensile fracture process, the fibres were sheared along the interfaces, where only a small amount of micro-fibres can be observed (Fig. 3g^1). It can be assumed that there were less friction and fibre-bridging taking place during the fracture process of dry bamboos. The fracture parenchyma cells in Figs. 3(g) and 3(g^2) showed neat brittle sections, which also illustrated that during the dry fracture process there were mainly dry brittle fractures among the parenchyma cells.

Compared to the dry samples, the wet bamboos had quite different fracture morphologies, where a variety of fracture forms can be observed on the cross section (Figs. 3d, e and f). The pulled-out fibres have great elevation difference with the nearby fibre bundles and broken parenchyma cells, thus the wet fracture cross section displayed a rugged morphology. If the dry fracture had cross sections consisted of highlands and plains, then the wet fracture would have sections shaped with mountains, hills, cliffs and the winding trails lingered between them, though they are just made of fibres and parenchyma cells (Fig. 3d). Broken parenchyma cells were paved as winding trails, surrounding the pulled-out fibre mountains, hills and the sheared fibre-bundle cliffs. Multi-walled fibres were peeled out from layers of bondage, and the peeling degrees decided the lengths and diameters of the pulled-out fibres, around which, correspondingly, there were also numbers of fibre sheaths. Obvious pulled-out fibres and the left sheaths can be found in Fig. 3(e), which were not observed in the dry fracture sections. Interestingly, corrugated peeling veins were observed on the out surface of the pulled-out fibres (Fig. 3f), which indicate that there might be more subtle fractures between the fibre walls.

The rugged morphology of the wet fracture cross section illustrates that the fibres and parenchyma cells must have experienced roughly deformation and fracture during the wet fracture process, which can also be reflected upon the longitudinal sections or the fibre cliffs displayed in Fig. 3(d). The longitudinal sections of the wet samples had hairy fracture morphology, as can be seen in Fig. 3(h). More micro-fibres were observed on the interface of the shearing fibres, which were pulled longer and in softer postures (Fig. 3h^1), quite different from the micro-fibres seen in Fig. 3(g^1). The fractured parenchyma cells in Fig. 3(h^2) were seriously damaged into chaos, where cell walls were peeled and tore into layered scraps. This was very alien to the dry fracture parenchyma cells displayed in Fig. 3(g^2). Additionally, there were micro-fibres exposed at the edge of the phloem and vessel tubes (Fig. 3h^2), due to the roughly toughening fractures of the wet samples.

3.3 Dynamic fracture behaviors of bamboo

All the collected waveforms were analyzed in time and frequency domains. Fast Fourier Transform (FFT) was used for the frequency domain switching, and the original and transformed waveforms are displayed in Fig. 4. The collected signals can be divided into three types, according to their shapes and frequency distributions. The waveforms were all burst signals but composited with multi-frequencies (main frequency and the other frequencies with lower amplitudes). The type 1 waveforms had a voltage fluctuation of ±0.05 V and a longer gentle attenuation, which answered a main frequency distribution from 95 to 140 kHz (Figs. 4a and d). This type of signals was proposed to be attributed to the fracture of the bamboo matrix (parenchyma cells). The second type waveforms had about ±0.08 V in the volts fluctuation, and sharp frequency distribution ranging from 230 to 275 kHz (Figs. 4b and e), corresponding to the fibre wall-wall and/or fibre-matrix interfacial dissociations. Considering the chemical components of the fibre and parenchyma cell walls, the type 2 origins were abbreviated as interfacial dissociations. The type 3 waveforms had volts fluctuation of ±0.10 V, and obvious frequency distribution from 280 to 340 kHz (Figures 4c and f), which were directed to the fibre breakage. Similar results were reported by some previous works [4, 5], where the fracture signals of the fibre reinforced composites could be divided into three frequency bands. The lowest frequency, the middle and the highest frequency represent the fracture of the matrix, fibre-matrix debonding and fracture of the fibres, respectively [4, 5]. For unveiling the secrets of the dynamic fracture behaviours of bamboo, the peak frequency was used to show the main fracture origin of every signal during the tensile process, because it's more reliable [4, 5] in the AE detect of the fibrous composites. Therefore, the AE signals indicated that there were three different accompaniment instruments (fracture types), which were parenchyma cell breakage, interfacial dissociations and fibre breakage (Fig. 4).

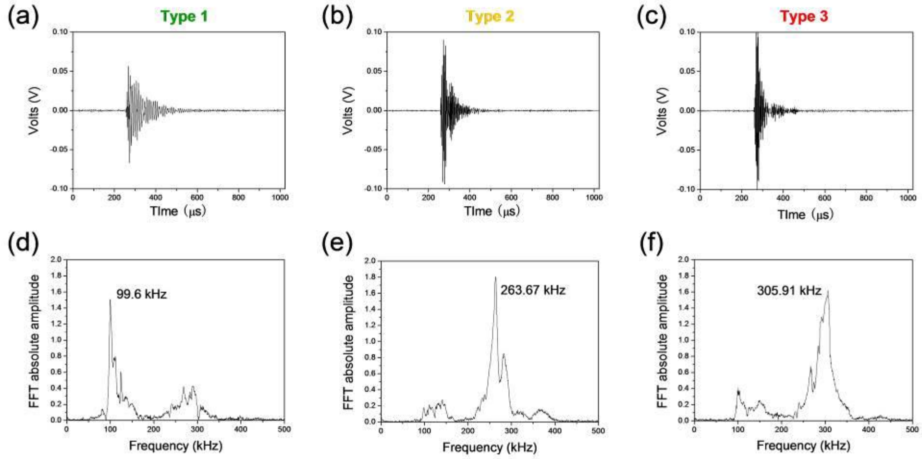

Figure 4: Three types of signal waveforms and their FFT frequency distributions.
(a, d) Type 1 waveform and the FFT frequency distribution;
(b, e) Type 2 waveform and the corresponding FFT frequency distribution;
(c, f) Type 3 waveform and its FFT frequency distribution.

3.4 Water concerto during the fracture process of bamboo

The signal distributions along the tensile process are displayed in Fig. 5. Dry samples had the least signal numbers and also the worst strain, simultaneously showing a brittle fracture process. Fibre breakages were detected and concentrated in the stage 2 and stage 3, showing a premature damage during the fracture process (Fig. 5a), while the similar signals were found just in the stage 3 of the wet samples (Figs. 5b and c). Stage 2 and stage 3 took more than half of the total strain of the dry samples, while the stages 3 only respectively took ~20 % and ~17 % of the later two wet samples. Thus, the wet samples have better tensile properties, and the fracture process could be detected by AE method.

In general, signal numbers increased along with the water content, and all types of signals could be found in the whole fracture process of all kinds of samples. But there were obvious signal distribution variations along the tensile process. The proportions of these three type signals within different samples are displayed in Table 1. Type 1 signals indicated a down flat trend, and the type 2 signals showed a rapid growth as the bamboo samples had more water inside, demonstrating a positive correlation with the tensile properties showed in Fig. 2. Type 3 signals had a stable proportion but an uptrend in signal numbers as the water percentage went up, which might play a decisive role in the high performance of wet bamboos. With water absorbed into the bamboo samples, the type 2 and type 3 signals were more sensitive to the change of water content. Correspondingly, the fibre breakage and interfacial dissociation might be the keys to the tensile strength and toughness of the bamboo samples, according to the varied signal numbers and proportions.

Though the fibres and fibre interfaces played decisive roles in the high performance of wet bamboos, which could be found in all the stages of the fracture process (Fig. 5 and Table 1), they are deeply affected and restricted by water. Dry samples had no water inside, while fibres and parenchyma cell breakage were the main themes, playing the prelude (type 1 and type 3 signals in Table 1). As more water was absorbed into the samples, the lignin and hemicellulose within the fibre/parenchyma cell walls were activated with more hydrogen bonds. Great differences may happen to their interfacial bonding strength, thus the interfacial dissociation (type 2 signals) began to play a major theme (Table 1). Additionally, the cellulose/hemicellulose/lignin complexes inside of the fibres might be swelled as more water and soluble molecules were introduced in. The long cellulose (lignin) chains would be decompressed and stretched out from the dense fibre bundles, and more binding points would be created within the swelled fibres. Ring structures and sacrificial bonds within the long chains would make great contribution to the fibres' toughness and strength [8]. To perform together with the fibres and parenchyma cells, water played the leading role in this enchanting and wonderful concerto.

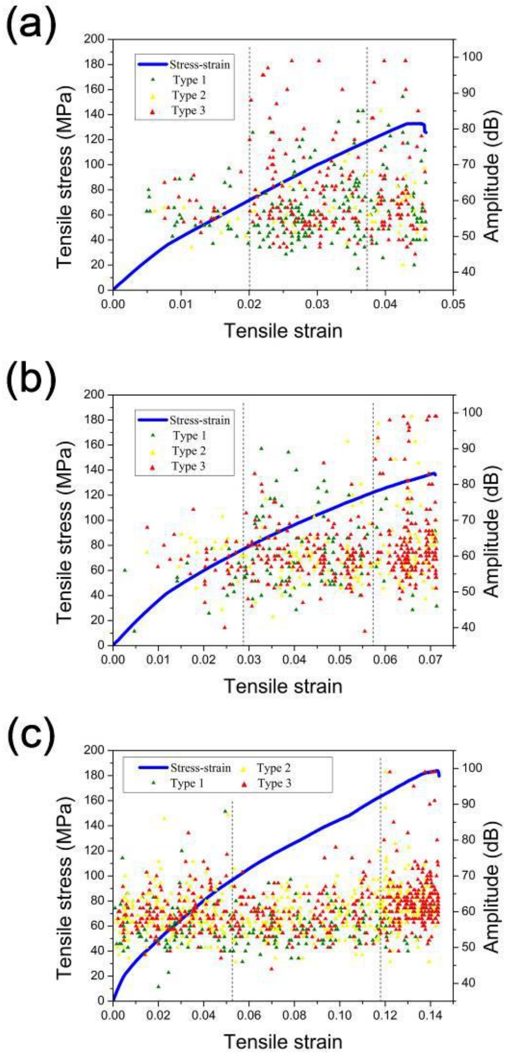

Figure 5: Signal distributions along the tensile process within different water content. (a) 0 %; (b) 6 %; (c) 17 %.

Samples (wt. %)	Type 1	Type 2	Type 3
0	26.6 %	**24 %**	49.4 %
6	18.45 %	**25.87 % ↑**	55.68 %
17	17.74 %	**38.3 % ↑**	43.96 %

Table 1: Signal proportion in the fracture process of different samples.

4 CONCLUSION

Bamboo samples with different water weight contents (0 %, 6 % and 17 %) showed obviously different tensile performance, in both of strength and toughness. The dry and wet samples' fracture surfaces showed typical brittle and ductile performances, respectively. There were three different fracture behaviours: matrix (parenchyma cells) breakage, interfacial dissociations and fibre breakage. The excellent tensile toughness of bamboo was came from the matrix breakage and interfacial dissociations, and the strength was depend on the fibre breakage and interfacial dissociations during the fracture process. To perform together with the fibres and parenchyma cells, water played the leading role in this enchanting and wonderful concerto.

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