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RESEARCH

Compressive behavior of yellow bamboo stalks (*Phyllostachys aurea* species) and their composites when filled with epoxy resin

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Abstract
This research explores the properties of yellow bamboo (*Phyllostachys aurea* species) stalks and its composite from Colombia under compression loads. The bamboo pipes were filled with epoxy resin aiming structural applications. Samples included untreated, peroxide-treated, and hypochlorite-treated bamboo, both with and without nodes. For each of these conditions, up to 20 samples were evaluated via Weibull distribution; this is to determine the variability of the compressive properties. For the characterization, scanning electron microscopy was used to analyze the microstructure, while finite element analysis was included for the bamboo stalks to better understanding of the stress–strain relations. Results showed that compressive strength was from 60 to 130 MPa, with nearly 3 times more variability for samples with node than without node, which was accounted for the Weibull modulus. Also, it was seen that bamboo stalks without node showed higher strength than samples with node, in which the node acts as stress concentrator, lowering the strength of the bamboo pipe. For bamboo stalks filled with epoxy resin was found that the resin did not contribute much to reinforce the composite, but increased the elongation at break, a very important property related to ductility and toughness. The resin also was found to increase the Weibull modulus upon the compression loads, which reduced the property variability, a known limitation of natural fiber composites. It was also observed that in both the bamboo stalks and the composites, the failure presents buckling deformation, with cracks along the longitudinal direction, parallel to the pipe axis, although with less damage for those with nodes, since the node can limit the crack growth. The composite bamboo resin could be used in construction or impact applications.

Keywords Bamboo · Compression testing · Finite element · Weibull analysis

HighlightsA new composite of yellow bamboo (*Phyllostachys aurea* species) with epoxy resin was made.

Treated samples with peroxide and hypochlorite showed a reduction in property variability studied via Weibull statistics.

The composite bamboo resin could be used impact absorption, such as bicycles, poles on roads, or crash barriers for cars, or as a solution to reducing pollution from the plastic industry.

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1 Introduction

Bamboo is an amazing material used for centuries in many countries in construction and other daily life applications, particularly extensively used in China [1]. It is a strong, tough, and elastic material used in bridges and other structural applications, which always attracted attention due to the low cost, fast growth, and because the plants not only require minimum maintenance, but also are a solution for restoring deforestation [2]. Moreover, in some countries, there are modern luxury constructions made of bamboo, which is attracting more people towards sustainable architecture [3].

There is an increasing need to reduce the pollution of construction materials, to be more environmentally friendly with strategies such as increasing the material circularity by recycling [4], using low carbon footprint materials [5], or others like combining natural materials with traditional structural materials [6]. Particularly, using polymer or cement binders combined with natural fibers from organic waste, such as rice husk [7], banana [8], coir [9], cashew shells [10], hemp [11], and many others, is an increasing trend in the manufacturing industry.

Bamboo plants (subfamily Bambusoideae) are widely distributed throughout many countries. They are classified in 12 subfamilies of the grass family (Poaceae), and with about 1500 species classified in three groups: Arundinarieae (546 species of temperate woody bamboos), Bambuseae (812 species of tropical woody bamboos), and Olyreae (124 species of herbaceous bamboos) [12]. Bamboo is distributed from 47° S to 50° 30′ N, at altitudes from sea level to 4300 m [13], and therefore mainly in Asia, America, and Africa. This plant is more abundant in tropical and subtropical areas, and its species and properties depend on the type of soil, climate, and altitude.

Bamboo is one of the most important non-timbers in the world for several reasons such as that 2.5 billion people depend economically from it; it contributes with a significant trade value of more than 2.5 billion USD per year from data reported in 2013 [14], and it has a very rapid growth rate, since typically, a large number of bamboo species can reach a height between 15 and 30 m in 2 to 4 months, thus reaching a full maturity between 3 and 8 years [14]. A more recent report informed a bamboo US market for 2021 of 3.34 billion USD, and for China for the same year for 24.1 billion USD [15]. These numbers show an increasing trend, projected up to the next decade, which shows the importance of the sector from the economical point of view and represents a unique opportunity to transform part of the buildings into a more environmentally sustainable alternative that mitigates part of the pollution from the building industry.

Bamboo is a plant that can contribute a lot to decrease atmospheric pollution. It has been estimated that bamboo building is an effective method for prolonged carbon storage, as 1 ton of laminated bamboo lumber stores about 140 kg more carbon than timber [16]. This advantage can be combined with the finding that some species of woody tropical bamboo from the Brazilian Atlantic Forest significantly increase the photosynthesis and growth in a CO_2-rich atmospheric environment [17], which could be a way to mitigate the environmental global problem. Bamboo is also known to be a resilient plant from wildfire studies in the Amazon rainforest [18] due to its fast growth after the fire disturbance. It also can be a solution to combine with other fire-resistant plants that can preserve freshwater sources and recover better and faster, or even survive to wildfires [19]. However, this fast recovery and expansion of bamboo can be detrimental as well for native species of flora and fauna [20].

Bamboo has been used extensively in many applications. One of the most extended in many countries has been civil construction, particularly in houses combining soil or other ceramic-building materials [21] with adequate seismic performance [22], with modern architecture [23], and even used in bridges [24]. A more sophisticated derived product is the laminated bamboo lumber [25], which has more controlled mechanical properties and very good finishing, enabling bamboo for many other objects. Bamboo has been also used in many projects in combination with concrete [26].

The bamboo properties have been investigated extensively. The tensile properties of Cizhu bamboo (*Neosinocalamus affinis*) from China, corresponding to strips inner and outer layers, have been reported as 18.5 and 25.5 GPa, respectively, values obtained over carefully machined dog-bone-shaped thin samples; while for mechanically retted single bamboo fibers, the tensile strength, elastic modulus, and elongation were 0.93 GPa, 34.6 GPa, and 4.3%, respectively [27]. Other authors report strength between 503 and 341 MPa, while the modulus was 19.7 GPa [28]. Although these values are very high, the bamboo species is not mentioned. Other research in larger scales samples and testing the whole culm over *Phyllostachys* bamboo [29] found a longitudinal tensile strength of 144.8 MPa, tensile elastic modulus of 16.6 GPa, and transverse tensile strength of 4.7 MPa.

Besides bamboo is an excellent structural material for structural applications, it has a high hydrophilicity, which can decrease its mechanical properties and increase its susceptibility to fungal diseases. It has been found that if treated with wood wax oil at 180 °C, it resulted in a very significant increase in the hydrophobic angle (up to 120°) due to the high absorption of the wax [30], with an associated enhancement in the tensile strength of about 30%. The compression strength of bamboo culms of different species was reported before [31], as follows: *Dendrocalamus asper* between 68 and 60 MPa, *Bambusa vulgaris* between 76.5 and 60.3 MPa, *Gigantochloa scortechinii* between 69 and 57 MPa, and *Schizostachyum grande* between 30.4 and 27 MPa.

Bamboo fibers have been also combined with other materials after being separated from the stalks, allowing polymer matrix composites with applications such as civil construction materials [32], impact or personal armor protection [33], and cement-based composites with improved ductility provided by the fibers [34]. Bamboo charcoal has been used as reinforcing filler of wood-plastic composites of low-density polyethylene (LDPE) [35], finding that flexural and tensile strength were reduced, while the impact strength was increased upon a water treatment.

Bamboo culms of *Dendrocalamus strictus* species have been processed into thin laminas and then cold pressed using epoxy resin to produce composite laminates [36], with values of tensile strength between 169 and 205 MPa, compressive strength between 55 and 88 MPa, and flexural strength between 68 and 128 MPa.

Bamboo has been functionalized or surface treated by different chemical reagents. Bamboo surfaces were pretreated with the alkali hydrogen peroxide (H_2O_2), [37], leading to less lignin and more carbohydrate, which produced a bigger pore and surface area, very significant to enhance adhesion with other materials. Another study [38] used hydrogen peroxide with solutions of various pH between 4 and 9, using the bamboo species *Dendrocalamus latiflorus* Munro with films of nitrocellulose lacquer films. It was shown that upon the use of hydrogen peroxide at pH 7, the better adhesion occurred. Another chemical substance used is hypochlorite (NaClO), [39], used for treatments and even for bamboo fiber separation. Other common treatments use sodium hydroxide (NaOH), [40], an effective treatment to remove lignin and to improve the chemical bonding not only in bamboo but in other natural fibers with polymeric resins [41]. A functionalized bamboo surface with cellulose-based adhesive to bind with epoxy resin has also been investigated [42], given good bonding strength and water resistance, where the lap shear strength was 39% better when compared with the untreated bamboo. For the yellow bamboo (*Phyllostachys* species), the tensile strength of dog-bone-shaped specimens was investigated [43], giving values of maximum 20 GPa for the elastic modulus, and a single value of strength of about 140 MPa. Other research reported values of tensile strength and elastic modulus over the species *Phyllostachys pubescens* of about 180 MPa and 12 GPa, respectively, but over machined bamboo strips [44] and after being exposed to different thermal treatments, from 100 to 220 °C, finding the maximum strength at 120 °C in about 120 MPa and the elastic modulus at 140 °C in about 13 GPa.

As shown above, bamboo is quite an interesting material to be used in construction for its properties, availability, costs, and as a sustainable construction material. Because it is preserving the resources for future generations, and it is economically feasible, it is considered now an emerging material for the construction sector [45], not only used directly as timber, in which durability is now under research for improvement [46], but also combined with other important emerging construction materials. This is the case of geopolymer-bamboo composites [47], an alternative cement material that, unlike Portland, does not involve the very high temperatures and CO_2 released during manufacturing [48]. Bamboo fibers and strips make these cements cheaper, greener, and lighter. When bamboo is combined with polymeric resins, the resultant composite is also a feasible alternative construction material, validated as a building material with up to 25% of bamboo fibers [49], which means a reduction of the same weight in resin. All these studies reviewed above never used bamboo stalks with filling resin, so the compressive and other mechanical properties are not known, which is one of the main goals to investigate in this research.

The following research investigates yellow bamboo stalks under compression loads with epoxy resin aiming structural applications under compression stresses and potentially parts under dynamic loading. The variability of the strength has been studied via Weibull statistics.

2 Materials and experiments

Yellow bamboo from *Phyllostachys aurea* species was acquired from a local supplier at Medellin, Colombia. Samples were cut with 40 mm length and selected to have approximately a diameter of 20 mm, with a variable wall thickness ranging between 2 mm and about 4 mm (see Fig. 1). The samples of bamboo stems are dried by local farmers with low heat with wood smoke; they found this simple process stabilizes the bamboo, avoiding rotting, decomposing, or deteriorating under the environmental conditions. Bamboo samples had an average density of 0.70 g/cm^3. The pipe bamboo stalks samples were samples without node (No Node samples) and with node (Node samples).

A total of 40 specimens of bamboo stalks were tested as received (Untreated), which were divided into 2 types with node (20 samples: No Node) and without node (20 samples: Node).

For the determination of the cross-sectional area of these specimens, a caliper was used to measure the diameter and thickness of each specimen, and with this information, the following equation was used to determine the cross-sectional area of these specimens where D is the external diameter, and d is the internal diameter:

$$A_0 = \frac{\pi}{4} * (D^2 - d^2) \tag{1}$$

Also, 40 samples were prepared per surface treatment; this was to test the surface treatment effectiveness, via Weibull analysis, on the adhesion bamboo-epoxy resin, 20 for No Node, and 20 for Node. The Weibull statistics is based on the Weibull cumulative failure probability P_f, summarized as:

$$P_f = 1 - exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \tag{2}$$

where σ_0 is a normalizing parameter, and m is referred to as Weibull modulus, which indicates the level of dispersion in the data being analyzed.

The average dimensions for the No Node sample were D, 32 ± 2 mm; d, 28 ± 2 mm; and H, 32 ± 2 mm, while the average dimensions for the Node sample were D, 30 ± 3 mm; d, 26 ± 3 mm; and H, 30 ± 3 mm. All samples were tested under compression loads using a Shimadzu AGX-Plus universal testing machine at a crosshead speed of 1 mm/min, according to the standard ISO22157 for bamboo, corresponding to approximately to a strain rate of 1.0×10^{-2}/min for all

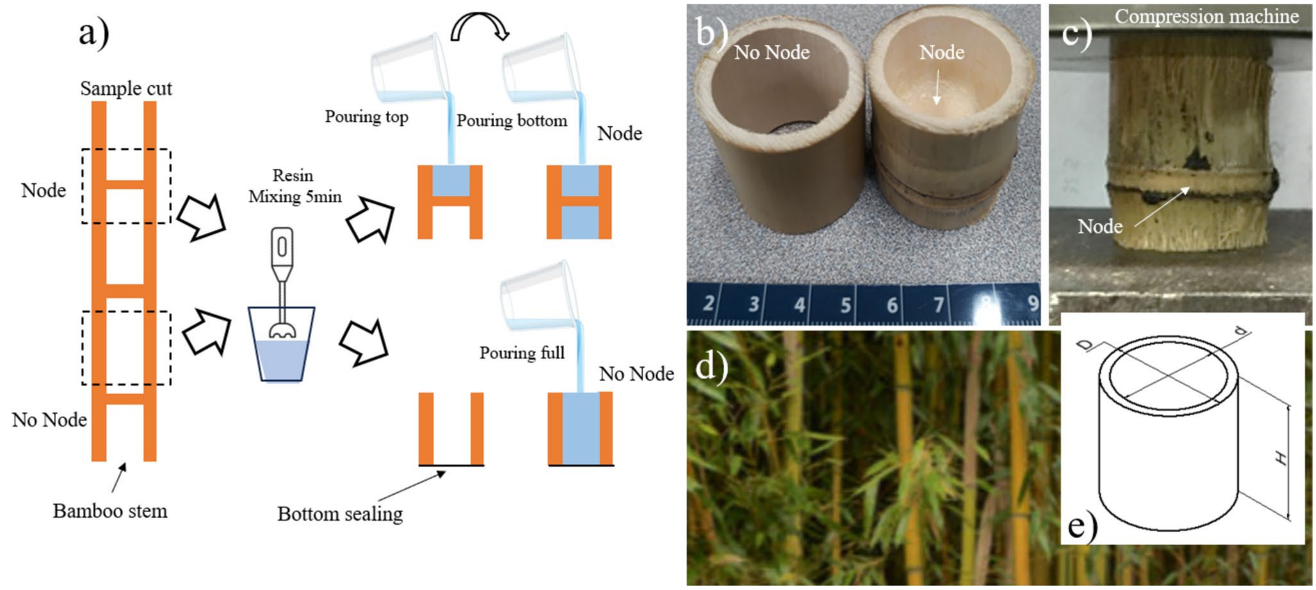

Fig. 1 **a** Bamboo sample preparation process describing the main steps from cutting the samples to filling with resin, **b** typical samples, **c** a typical sample during the compression test, **d** yellow bamboo plant, **e** samples parameters used in the calculations

samples. All samples were polished with two parallel surfaces for the compression tests.

For the composite bamboo-epoxy resin samples, epoxy resin was used and prepared by mixing mechanically for 5 min the resin and the hardener in a proportion of 100 to 1 parts of resin to hardener. Three conditions were made for the internal surface of the bamboo pipes before adding epoxy resin to see the probably interfacial adhesion: untreated (as received bamboo), surface cleaned with hydrogen peroxide (H_2O_2), and surface cleaned with sodium hypochlorite (NaClO), obtained from a local provider in Medellin, Colombia. Both hydrogen peroxide and sodium hypochlorite were used in 3% concentration in water, first used to clean the internal surfaces to remove possible dirty with a cloth humidified in the solution, and then applied with a brush, but only on the internal surface of the cylinders (to avoid structural damage of the bamboo), let it dry in open air, and tested after 1 week.

A set of other 40 samples distributed in the same way, 20 No Node and 20 Node, were tested per each surface condition, thereby giving 120 compression tests over the composites. The treatments with peroxide or hypochlorite can be seen as a cleaning process for the internal surface with these agents. The morphological analysis of the yellow bamboo used was performed using scanning electron microscopy (SEM). The samples were sputtered with gold before the observation.

All the process of sample preparation is shown in Fig. 1a. From a bamboo stem, two types of samples were obtained: samples with node (Node samples) and without node (No Node samples). The epoxy resin was prepared by mixing mechanically for 5 min the resin and the hardener. Then, this one was poured into the bamboo stalk samples. For the Node samples, first, it was poured on one side (top in the image), and after 2 h, it was poured on the other side (bottom). For No Node samples, plastic tape was used to seal the bottom to avoid the leaking of the resin, and the filled. Samples were tested after 24 h of preparation.

Figure 1b shows bamboo samples without node (No node) and with node (Node) before the compression tests, and during the compression tests in Fig. 1c. Figure 1d shows the yellow bamboo plant used in this research, the species *Phyllostachys aurea*. Figure 1e shows the cylindrical parameters of the bamboo sample (internal diameter, d; external diameter, D; and height, H) used for the property calculation. The species *Phyllostachys aurea* is also known as the "golden bamboo" due to its yellow color characteristics, and it is a bamboo species originally from China and Vietnam but spread now in many countries, with even significant differences in properties depending on the region in China, mostly associated with differences in its water and nutrient components [50]. In Colombia, this species is cultivated typically between 800 and 1500 m.a.s.l. in the Andes mountains regions.

3 Results and analysis

Figure 2 shows the microstructure of the yellow bamboo used in this research, taken with a scanning electron microscopy (SEM). The internal part side view of the bamboo reveals a cellular-like structure (see Fig. 2a)

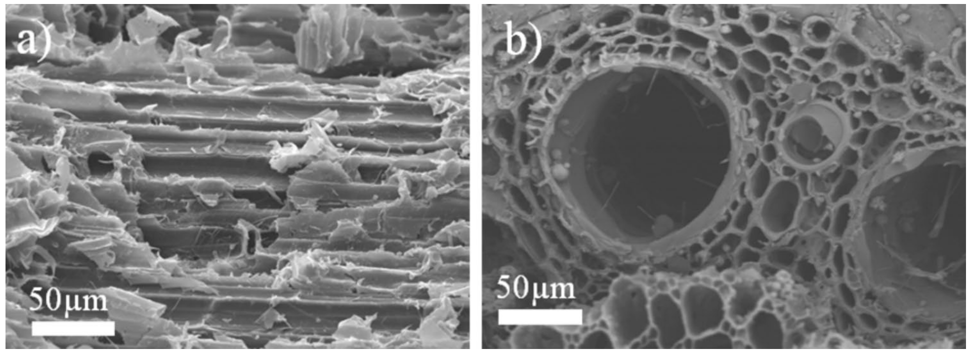

Fig. 2 SEM microstructure for bamboo samples, **a** longitudinal view, **b** cross-section view

whose cross-section view shows a series of tubes in charge of transport the fluids inside the plant (Fig. 2b). The hollow structure makes the material very light and tough, ideal for construction and impact applications [33].

The compression stress tests of the samples are summarized in Fig. 3, where parts a and b show typical stress–strain curves for samples without node (No Node) and with node (Node) samples, respectively. From these tests is observed that the nodes weaken the bamboo pipe, acting as a stress concentrator. It has been reported [51] in bamboo (*Phyllostachys edulis* species) that the tensile strength of bamboo culm with nodes (Node) has 47% less strength than without nodes (No Node), while the stiffness is improved by 123%. In our experiments, Fig. 3c (force shown for reference) and d (for strength), with the yellow bamboo from Colombia, the compressive strength was 115.8 MPa for No Node and 95.9 MPa for Node samples respectively, corresponding to a decrease of 17.2%, which is still quite significant.

Figure 4 shows the bamboo culm samples after the compression tests, and for No Node samples, side and top view (see Fig. 4a and b), respectively. These bamboo pipes show all catastrophic and generalized buckling and splitting failure along the longitudinal direction of the pipe, parallel to the fibers along the cylindrical axis of bamboo, like previous research reports [51]. Figure 4 c shows a detail of the tube base squashed from extreme damage loading. For Node samples, the damage is more contained from the deformation perspective, as the node limits the splitting of the pipes, see Fig. 4d and e for side and top view of the Node samples. Figure 4f shows a similar squashed end due to the extended damage. In all cases, even with the extension of the deformation, samples kept all their parts,

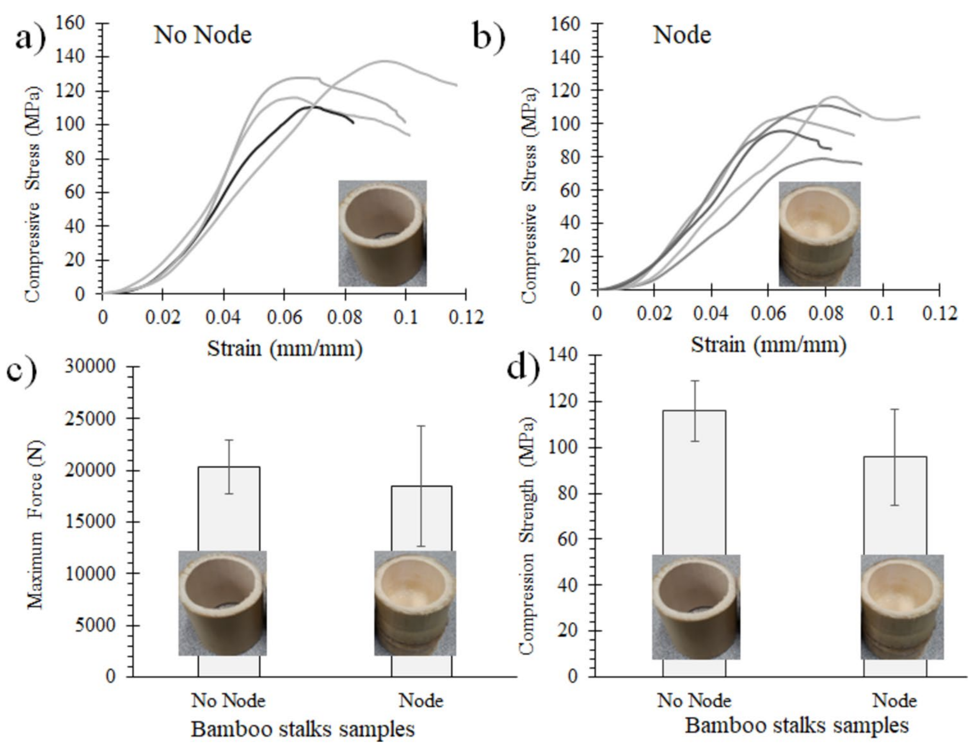

Fig. 3 Typical stress–strain curves for samples with (**a**) No Node, **b** Node, **c** summary of force–displacement results, and (**d**) summary of compressive strength results. All tests were done under compression loads using a crosshead speed of 1 mm/min

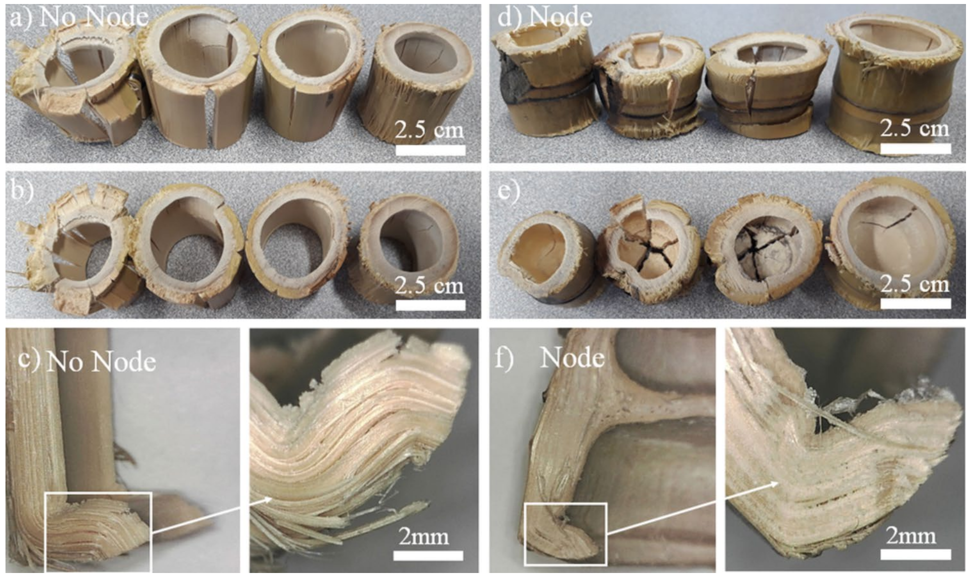

Fig. 4 Bamboo samples after compression tests showing the damage failures: **a** No Node samples side view, **b** No Node top view, **c** details of failure; **d** Node samples side view, **e** Node top view, **f** details of failure

which shows a very tough material under low speeds and low strain rates, 1 mm/min and 1.0×10^{-2}/min, opposite when the speed of tests is increased which can cause the samples broken into many parts [33].

The elongation at break is presented in Fig. 5 for both No Node and Node samples, with very similar values in both cases, and consistent with FEA simulations. In both cases, the maximum deformation is shown at the middle of

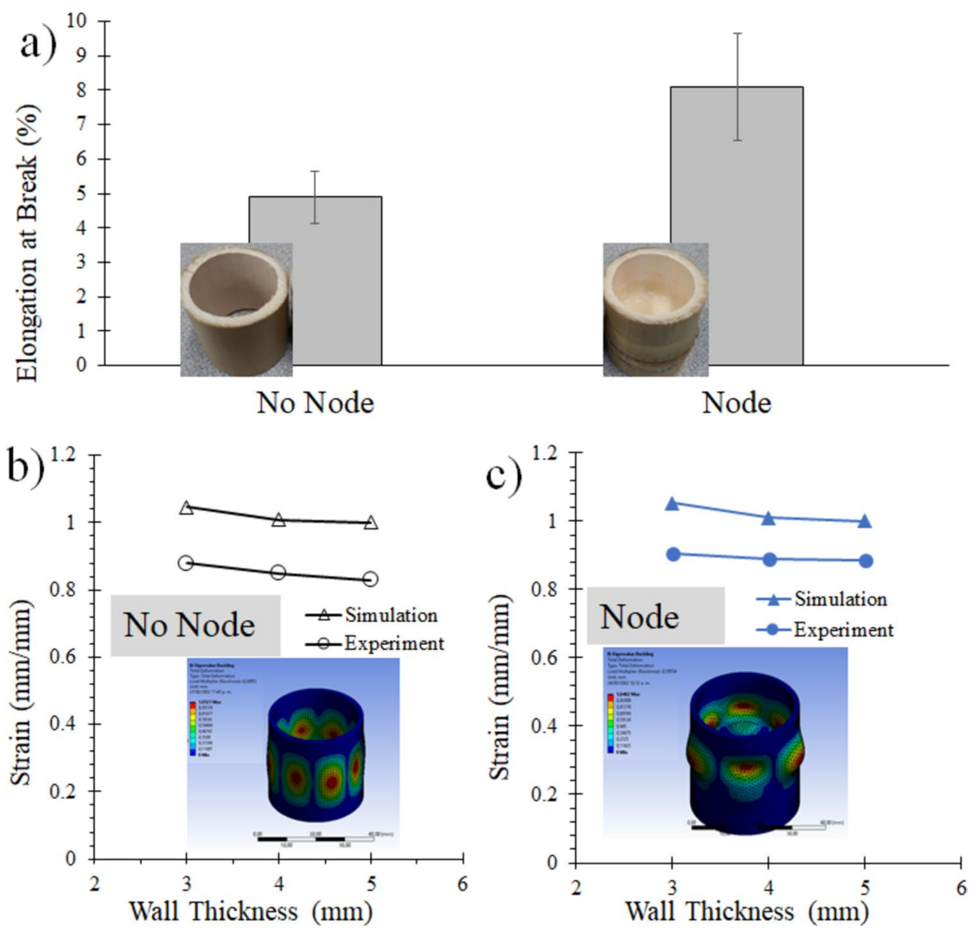

Fig. 5 **a** Elongation at break for bamboo stalks, for No Node and Node samples, **b** FEA and experimental data for No Node samples, **c** FEA and experimental for Node samples. The maximum strain was obtained at the center of the samples, which is confirmed by the buckling-like failure

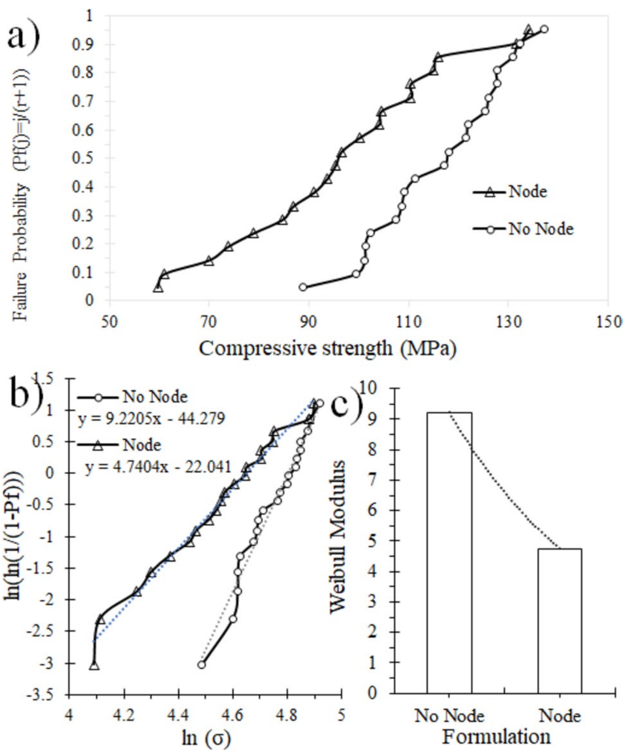

Fig. 6 **a** Weibull analysis in bamboo stalks, **a** failure probability, **b** curve fit, **c** Weibull modulus. The Node samples are stronger in compression and less variable as well (higher Weibull modulus)

the pipe, which causes the buckling and then splitting failure along the longitudinal fibers. More details about these results are presented in the supplementary Fig. S1, with data for different sample thicknesses and for Node and No Node samples.

To account for the variability of the compressive strength values on the No Node and Node samples of the tested yellow bamboo culms, a Weibull statistics analysis was conducted (see Fig. 6). It is observed that both samples have almost the same maximum values, although the No Node samples showed a mean strength of 115.8 MPa, in comparison to 95.9 MPa for Node samples, which put it as the stronger (see Fig. 6a). But not only that, the No Node samples showed a lower standard deviation, 13.3 vs 20.9 MPa for Node samples, which is clearly reflected in the Weibull modulus from Fig. 6. Thus, by processing the data in Fig. 6b, Fig. 6c shows a superior value for the No Node sample of 9.2, while for Node sample was 4.7. This is clearly due to the node increasing the variability of the property, since not only acts as stress concentrator, but also the nodes themselves vary a lot in size and internal structure [51].

Figure 7 shows bamboo pipe samples filled with epoxy resin. Figures 7a and b show No Node and Node samples with epoxy resin, while Figs. 7c and d show details of the resin binding the bamboo, while Figs. 7e and f show samples with poor adhesion between these two materials, mainly due to non-proper cleaning of the internal surface of bamboo.

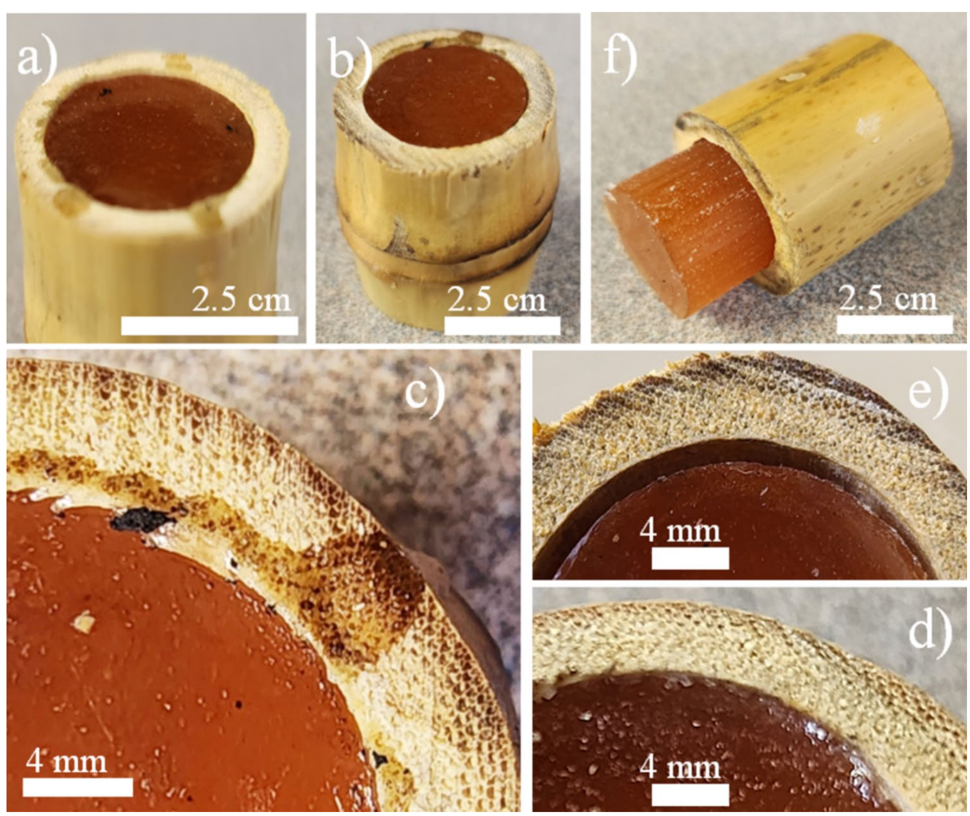

Fig. 7 Composites bamboo-epoxy resin: **a**, **b**, **c**, and **d** samples with good adhesion; **e** and (**f**) samples without adhesion resin to bamboo, as some samples show debonding resin-bamboo

The adhesion of bamboo resin is difficult because these two materials are quite different and have less surface roughness when compared to other fibers; therefore, suggesting a more complex preparation is needed, such as mechanical grooving, functionalization by a chemical agent, or even thermal treatment [52].

The composite samples of bamboo culms filled with epoxy resin after the compression tests are shown in Fig. 8. The samples made with the bamboo culms as received are shown in Fig. 8a, while samples with the internal bamboo culms treated with peroxide and hypochlorite are shown in Figs. 8b and c, respectively. The failures of the bamboo with resin look very alike to those in the bamboo pipes itself (see Fig. 8), for both No Node and Node samples, which can be confirmed in the details shown in Fig. 8d and e. What happened is that the high stresses cause that the materials at some point detach, because the resin can be compressed much more without catastrophic failure than bamboo, and because the buckling deformation is more destructive in the culm than in the cylinder. Moreover, in most images is seen the resin higher than the failed culm, which means a higher recovery from the stresses, confirming two very different mechanical behaviors per material under the compression loading.

Figure 9 shows typical compressive stress–strain curves for the composite bamboo culms samples filled with epoxy resin. As expected, the No Node samples can show higher values (although not significantly different in the collected data) than Node samples (see Fig. 9a and b, respectively), which is also associated with the nodes weakening the bamboo pipes due to stress concentration and inhomogeneities effects. The deformation in both cases No Node and Node samples is quite alike. Figures 9c and d account for the force (shown as reference) and strength of these composites, revealing not a significant effect of the surface treatment on the compression tests. However, Fig. 10 shows important results regarding the deformation of the samples, and even more notorious when the composites are compared with just the bamboo culms. It was found in general that first the composite and then the treatment (both peroxide and hypochlorite) can improve the strain at break, which is important for some applications involving pieces potentially exposed to catastrophic, impact, or dynamic damages.

The Weibull statistics were also conducted for the composite samples (see Fig. 11), again, to account for the variability of the compressive strength values on the No Node and Node composite samples. In all cases (Fig. 11a and b for untreated bamboo, Fig. 11c and d for peroxide treated, and Fig. 11e and f for hypochlorite-treated samples), the Node samples give lower compressive strength values when compared with No Node samples, and also, the variability, summarized by the Weibull modulus, was lower for Node samples, which mean a higher modulus value, explained by the fact that the node increases the stress concentration and also variability by the node changing structure parameters (thickness, position, inclination, microstructure, etc.) itself from sample to sample. It is also worth noting that the treatment in general improves the Weibull modulus with respect to the Untreated samples, which is important as the high property variability is one of the bigger drawbacks of the natural fibers when compared with the ceramic counterparts, which can be related to reduce dirt and lignin from the internal bamboo samples, producing a more reliable chemical bonding between the bamboo and the epoxy resin.

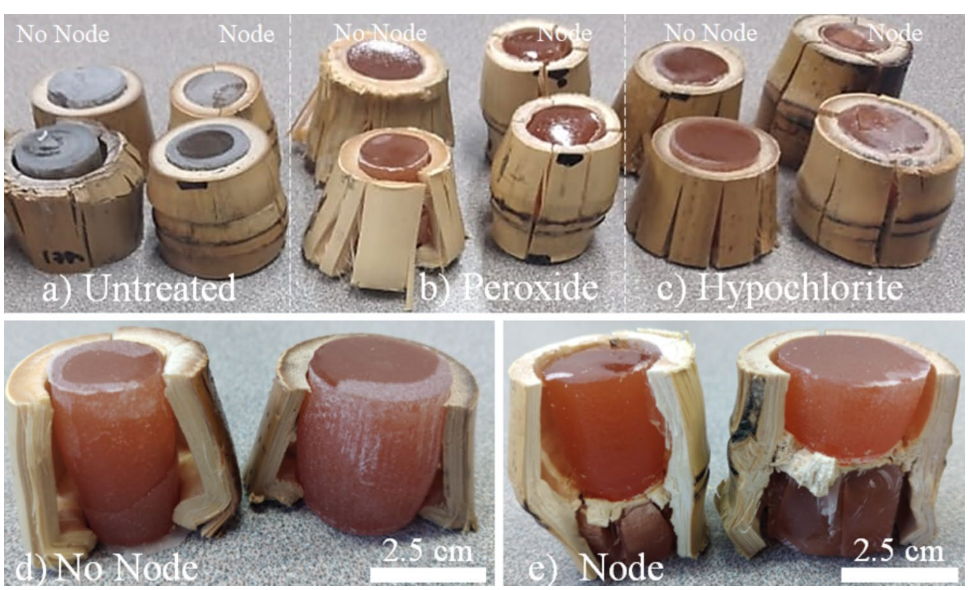

Fig. 8 Composite samples after compression tests: **a** Untreated bamboo, **b** peroxide-treated bamboo, **c** hypochlorite-treated bamboo, **d** details of No Node samples, **e** details of Node samples. Almost all samples show a similar failure mode, with cracks in the longitudinal direction and buckling

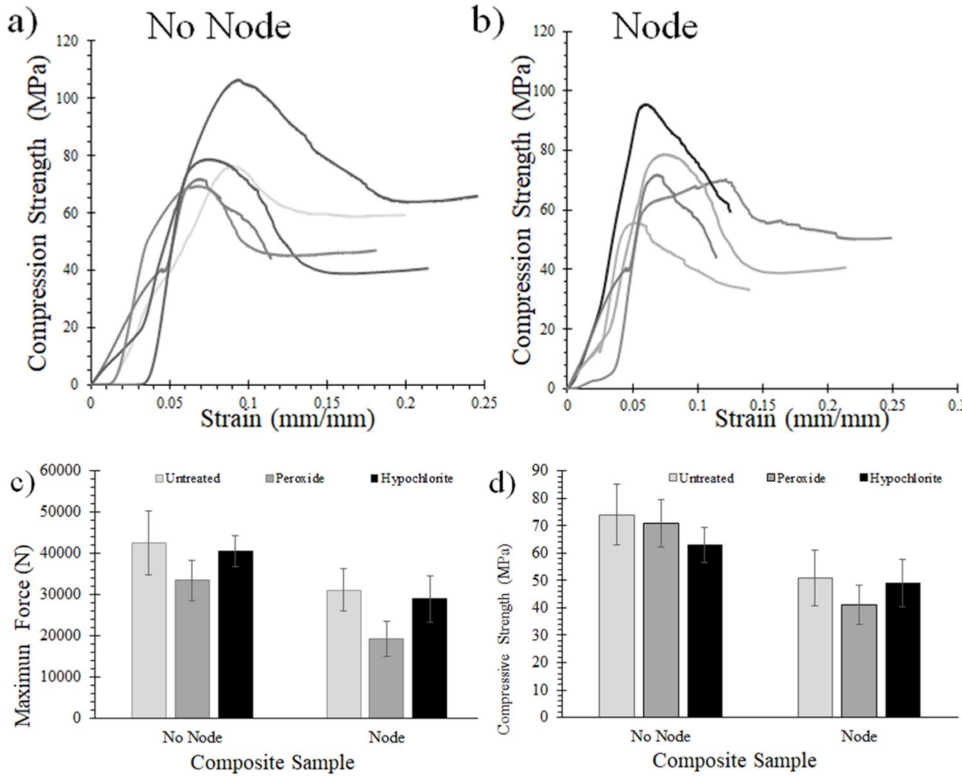

Fig. 9 Compression tests for the composites: typical stress–strain curves for the untreated samples, **a** No Node samples, **b** Node samples; **c** summary of force–displacement results; **d** summary of compression strength. In general, the No Node samples have higher mean compression strength values

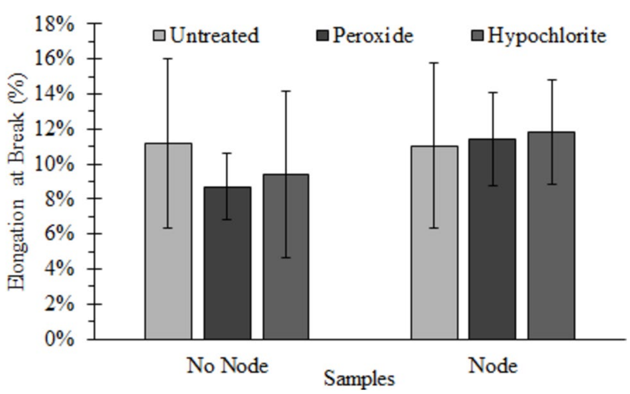

Fig. 10 Elongation at break for bamboo with epoxy resin untreated, treated with peroxide, and treated with hypochlorite. Although values were better for Node samples, the improvement is not significant

4 Discussion

This research has shown bamboo stalks have a very good mechanical performance under compression loads, with strength over 100 MPa in almost all cases (corresponding to over 2 tons), while in the composite was over 50 MPa in almost all cases (corresponding to over 3 tons), a reduction due to the dissimilar materials, in the amazing nature microstructure of bamboo, and in the hollow structure consideration in the calculation of the properties, opposite to the filled composite cylindrical samples. However, the resin showed a good contribution in the force that the structure can support, and also in strain-related properties, specifically in the elongation at break. These results can be extrapolated to ductility and toughness, which can correspond to a higher impact response. These results open possibilities not only in the construction sector to use bamboo directly as a reinforcing beam of column, but also in applications that include impact absorption, such as bicycles, poles on roads, or crash barriers for cars, among other possibilities.

The compression strength for bamboo culms of different species as mentioned before [31] was between 68 and 60 MPa for *Dendrocalamus asper* species, between 76.5 and 60.3 MPa for *Bambusa vulgaris*, between 69 and 57 MPa for *Gigantochloa scortechinii*, and between 30.4 and 27 MPa for *Schizostachyum grande* species. The compressive strength for bamboo, the *Phyllostachys aurea* species investigated in the current research for No Node samples showed a mean strength of 115.8 MPa, while for Node samples was 95.9 MPa, which is clearly higher. This can be explained not only for local species properties, but also for the farmers' stabilization to the bamboo stems, which are locally dried with low heat with wood smoke, said by them, avoiding rotting, decomposing, or deteriorating. Carbonization is known in wood [53] and significantly increases the strength, more than 28%, which can contribute to these properties. The bamboo (*Phyllostachys aurea*

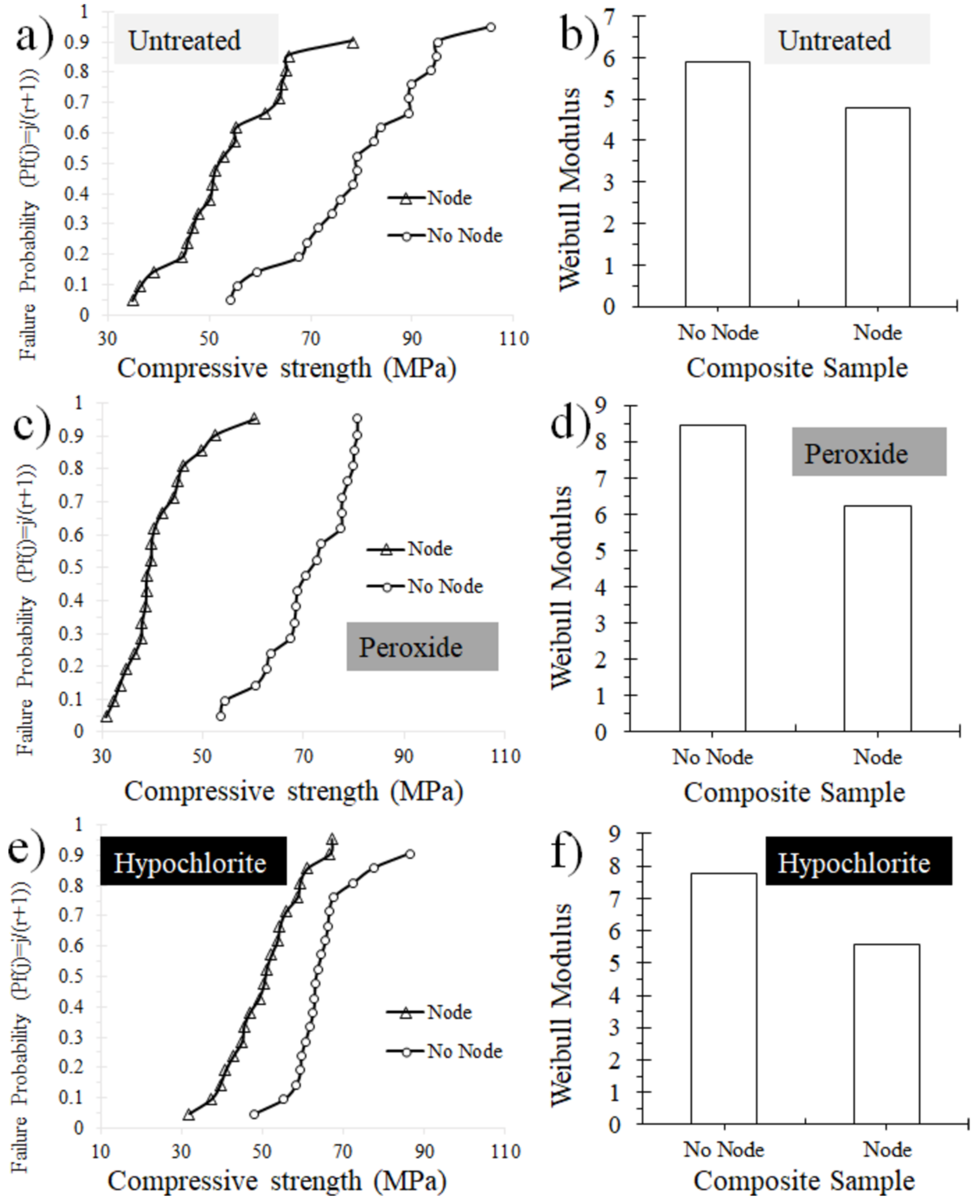

Fig. 11 Weibull analysis showing failure probability and modulus in bamboo-resin composites: **a** and (**b**) untreated bamboo; **c** and (**d**) peroxide treated; **e** and (**f**) hypochlorite treated. In all cases, the No Node samples showed a higher Weibull modulus, which means less variability in the compression data

species) filled with epoxy resin is a new material with not found previous examples, which showed effectively less compression strength than the bamboo alone, although with better deformation properties when considering ductility and toughness.

In terms of the adhesion resin to bamboo, it can be recommended to use more intense approaches, such as mechanical grooving or stronger chemical agents that produce not only strong chemical bonds, but also a rough surface to increase surface area and mechanical anchorage. The proposed composite then can be used in structural application as the strength is good enough for housing; however, the resin can also be replaced by commodity plastics, such as polyethylene, polypropylene, and ABS, among others. Moreover, this can be from a recycling process, which will add to the new material the benefit of reducing plastic pollution, a global threat that requires multiple solutions [54].

The failure found in these samples has been reported before for other bamboo types [51], although not for this yellow bamboo and neither up to the extended damage found in this research. One possibility to decrease such generalized buckling and splitting failure could be adding an external reinforcement, such as polymeric resin or plastic that can even be reinforced with the natural fibers, such as the Colombian fique fiber [55], very strong and tough, which is produced in large scale as ties and ropes able to be used as external reinforced.

The values of compressive strength found in this research are like those found in the bamboo culms of other species [31], although when compared to some of them, such as

Bambusa vulgaris between 76.5 and 60.3 MPa, values are considerably much better. In addition to the above reasons, another factor for this is that the species tested in this research was smaller in diameter, having the known results for many materials, the smallest the strongest. The mechanisms of the samples tested in compression found in this research are summarized in Fig. 12. For No Node samples (Fig. 12a), the failure appears after significant buckling deformation, which produces cracks that grow along the longitudinal direction, which is parallel to the fibers [56].

Almost all cracks grow along the full length of the pipe. In all failed samples, stunting is seen at the edges, which can be internal, external, or in both directions of the bamboo radius. For Node samples (Fig. 12b), the node restricts a lot of the buckling deformation, which can even stop some of the cracks from growing up to the end of the sample's length. This is mainly due to the mechanical mooring between the longitudinal and transversal fibers. The damage due to crack growth affects the structure of the node as well, showing the longitudinal cracks growing in the node as well. As shown, stunting is seen at the edges as well.

The combination of bamboo with epoxy resin can reduce its water absorption, and thus, its susceptibility to fungal diseases [30], which can increase the bamboo durability, a very important property for building and for many places with materials exposed to humid conditions. The durability of these composites can be significantly improved if external wax or even resin is used as a thin film to increase hydrophobicity. The feasibility of bamboo composites particularly using the chemical treatments of hydrogen peroxide (H_2O_2) and sodium hypochlorite (NaClO) is high as they are inexpensive, nontoxic, and available elsewhere. The epoxy resin can be replaced with other plastics more abundant and recyclable, such as thermoplastics polyethylene (PE), polypropylene (PP), acrylonitrile butadiene styrene (ABS), or polylactic acid or polylactide (PLA). These plastics are not only cheaper but also recognized as highly pollutants of nature, and thus, their use will be not only economically but environmentally sustainable. The composites developed here are easily recyclable, as the bamboo culms can be easily removed mechanically, and thus the separated materials (bamboo and epoxy) can be used in other circular

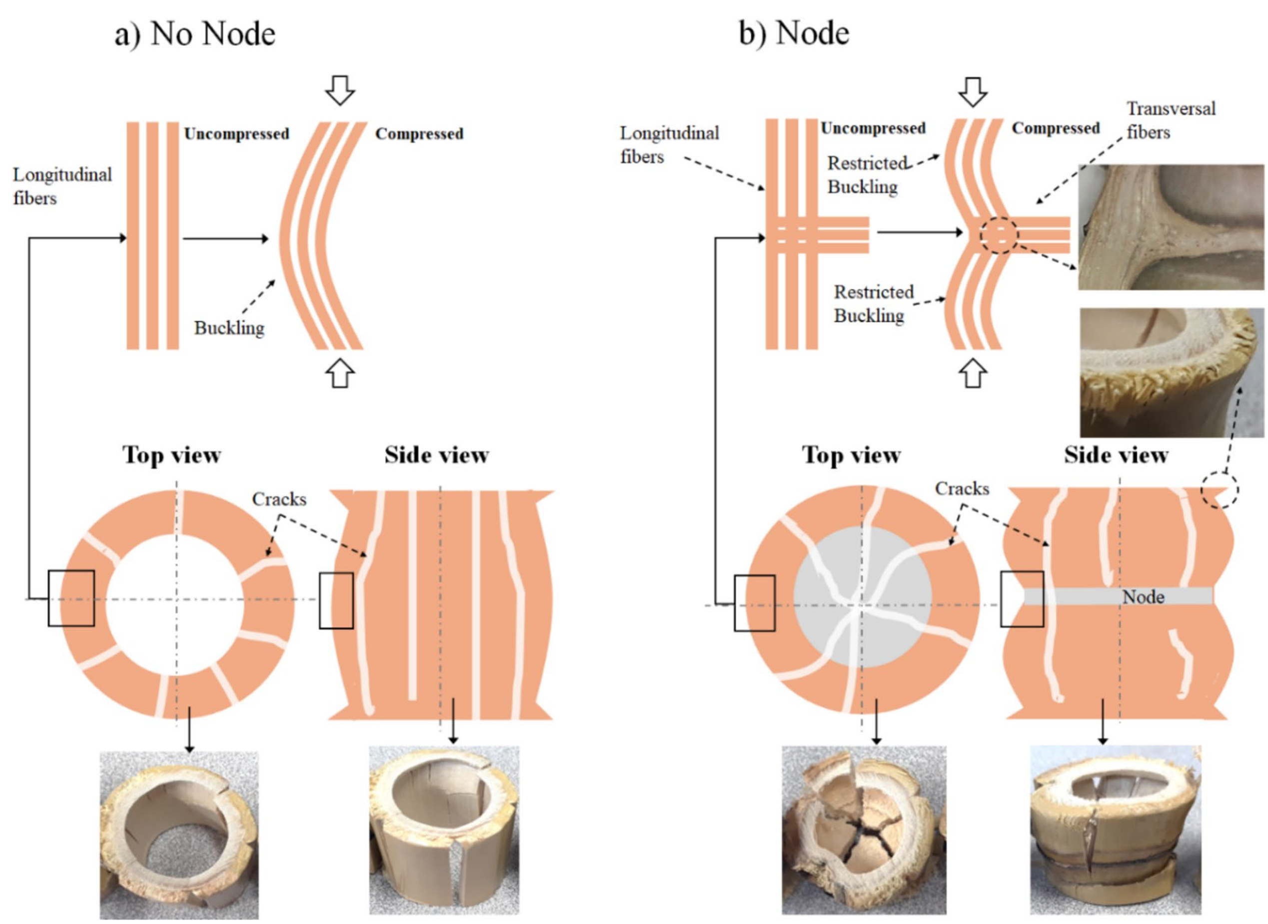

Fig. 12 Representation of the failure for (**a**) No Node and (**b**) Node samples. In general, the failure modes were similar for Node and No Node samples showing longitudinal cracks and buckling

applications, such as in soil enrichment for agriculture of bamboo itself, or polymeric composites for the resin.

Finally, the research opens new questions that could bring new applications regarding the thermal treatments for bamboo *Phyllostachys aurea* species investigated, and new ways to improve adhesion, such as machining or slotted surfaces, and dynamic tests over the composites, such as Charpy or drop tests.

5 Conclusions

The following conclusions can be drawn from the compression tests over the yellow bamboo culms with node (Node) and without node (No Node):

- The yellow bamboo culms with epoxy resin have been developed for the first time, showing composites could be applied not only in the construction sector, to use bamboo directly as a reinforcing beam of column, but also in applications that include impact absorption, such as bicycles, poles on roads, or crash barriers for cars, among other possibilities. This method can be a solution to make bamboo combined with plastic waste, therefore reducing pollution from the plastic industry.
- It was proved that the node reduced the compressive strength by about 17.2%, with a mean strength of 115.8 MPa for No Node and 95.9 MPa for Node samples, respectively. The failure of these samples was a generalized buckling and splitting failure, parallel to the fibers along the cylindrical axis of bamboo, along the longitudinal direction of the pipe. These values are very high compared to other bamboo species, which can be explained not only for local species properties, but also for the farmers' stabilization to the bamboo stems with low heat with wood smoke, a local procedure that must be investigated.
- It was shown that the stronger bamboo stalks in compression were the pipes without node (No Node samples), while the samples with node (Node samples) were more ductile, as the elongation at break revealed. Thus, the node not only weakens the tube acting as stress concentrator, but also provides a much more stable and better deformation when compared to No Node samples. Moreover, the No Node samples have a much less Weibull modulus, this is 9.4 against 4.7 for Node samples, which means that the nodes introduce a high property variation in the samples.
- The bamboo-epoxy resin behavior was quite interesting. First of all, it is also confirmed that the No Node samples were stronger in compression than the Node samples; however, the treatment as simple as was done of just cleaning the internal surface of the bamboo pipes (with hydrogen peroxide and sodium hypochlorite) could cause a more smother surface and a weaker chemical bonding resin-bamboo after lignin is removed. In addition, but also supporting this finding, the elongation at break was improved with the treatment, which is important in dynamic and impact applications, where ductility is very important. Also, the adhesion of these two dissimilar materials is quite challenging as the resin in some samples was easily detached, which suggests a more aggressive surface modification such as mechanical grooved must be convenient to increase the resin attachment, and perhaps a stronger chemical treatment.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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