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Strength, Fatigue Strength and Stiffness of High-Tech Bamboo/Epoxy Composites

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Abstract

A major problem in the strength data available for cellulose fibre-based materials is that the moisture content of the test specimens is rarely measured, and yet it is the dominant variable in the tests. Detailed strength and stiffness results are presented for Brazilian Dendrocalamus Giganteus bamboo at a wide range of moisture contents down to 2% and the fatigue curve is given for Chinese Moso bamboo at 4% moisture content. Techniques are described for handling the variability of these natural materials, both in design and in manufacturing quality control, for the mass production of large, high-tech composites wind turbine blades.

Keywords

Bamboo, Moisture Content, Epoxy, Dry Strength, Fatigue Strength, Quality Control, Composites Manufacturing Process, Wind Turbine Blades

1. Dry Cellulose

Cellulose is fundamentally hygroscopic at molecular level, and it weakens as it absorbs moisture. This is not at all new information. For instance in the British Standard code of practice for timber design, there are (and have always been) two tables of timber strengths, one for "green" timber (*i.e.* actively wet, and typically above 25% moisture content) and one for air dry timber, which in the UK is typically about 16% moisture content. The air dry strength figures are typically 25% better than the green strength figures, showing this is a significant effect.

In Dinwoodie's 1981 student textbook on timber [1] he outlines the reason why and has a graph showing that it gets even better if you dry it further (**Figure 1**). Cellulose molecules are essentially flat chains and they bind together in fibrils essentially as a set of flat layers held together by weak hydroxyl bonds between the layers

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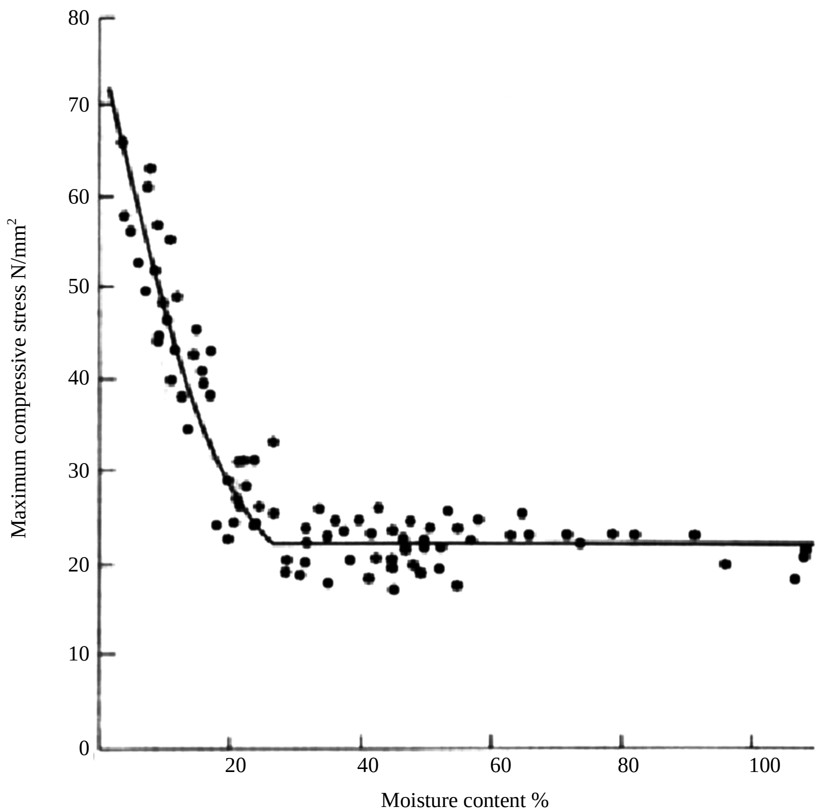

Figure 1. Effect of dryness on strength.

(**Figure 2**). With any water vapour present, H_2O molecules will readily get in and substitute for the hydroxyl bonds and as they do so, they distort the straightness of the molecules, thus reducing the strength and stiffness of the fibrils. Nature combines these fibrils in many different geometries to create the fibre structures of different plant species (**Figure 3**), with some species having predominantly longitudinal fibrils, creating stiff, strong fibres. These are then again arranged in many different geometries and packed closely or less closely, creating the vast range of timber properties available from different timbers. In bamboo, the fibrils are predominantly aligned longitudinally in the fibres and the fibres are also aligned longitudinally in the stem of the plant, so it has very attractive structural properties. But as with all timber, these properties are strongly affected by moisture content.

Recent research on Brazilian Dendrocalamus Giganteus (DG) bamboo [2] shows that, starting from being completely dry, H_2O molecules substitute for the hydroxyl bonds between the primary molecular chains of the cellulose between 0% - 5% moisture content. Above this, the H_2O molecules substitute into and distort the hemicellulose and the lignin and this distorts and weakens the way that the fibrils are bonded together and formed into the larger structure of what we would recognize as cellulose fibres, and it has an even stronger effect on the larger volume of hemicellulose and lignin forming the matrix in which the fibres are located. Between 5% - 25% moisture content, this matrix swells as it absorbs the H_2O molecules and the timber swells both radially and circumferentially, reducing its strength and stiffness but, in bamboo, interestingly, not altering its density as the dimensional swelling matches the weight increase due to the increase in moisture content. Above about 25%, this absorption process is complete (and the timber would still "feel" dry), but the strength and stiffness are reduced to the green figures, and after that you begin to get "free" water in the timber and it "feels" wet.

If you turn this on its head, what this says is that, from an engineering point of view, it is seriously beneficial to dry timber. It seriously improves the strength and stiffness properties. The question then is: how do you keep it dry? In the late 1960s and early 1970s, the Gougeon Brothers, boat builders in Bay City, Michigan, realized that epoxy is a complete vapour barrier and dry timber, sealed in epoxy, will remain dry forever [3]. And so it does. This has been very successfully used at seriously large scale in wind turbine blade technology globally for 30 years.

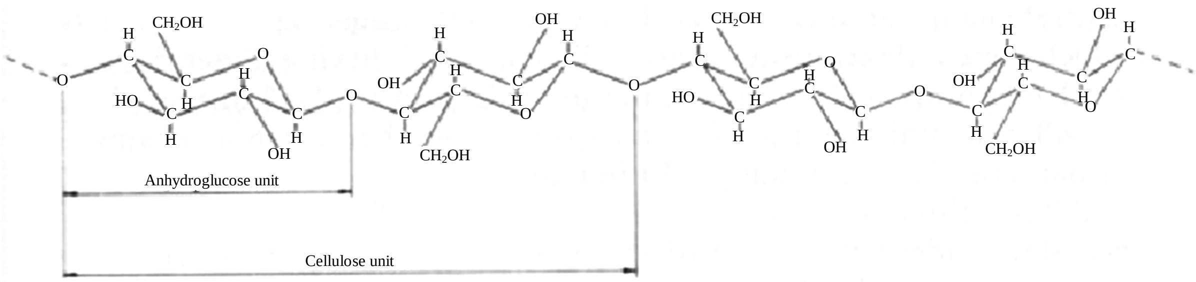

Figure 2. Cellulose molecular structure.

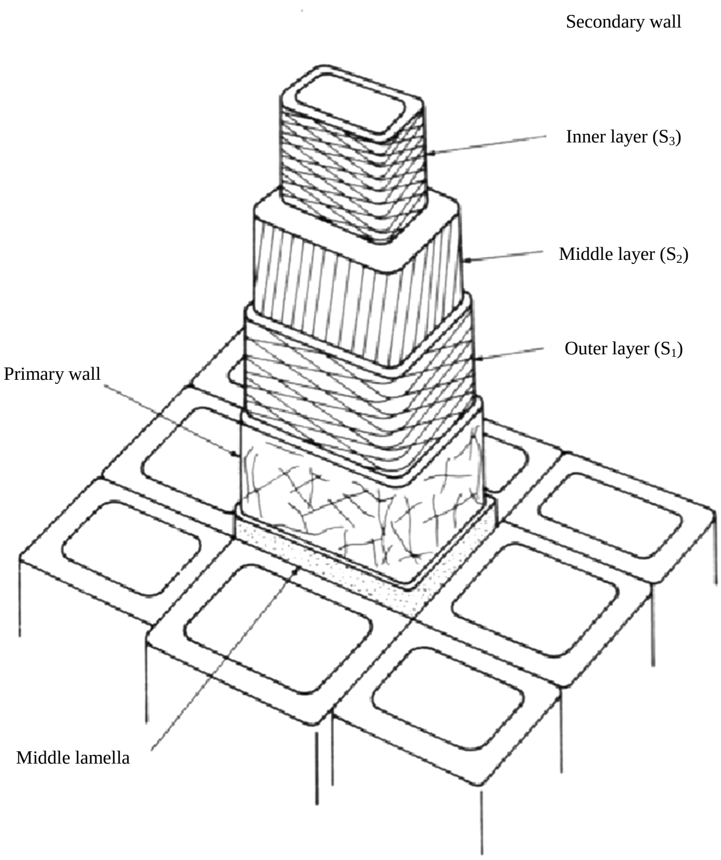

Figure 3. Fibril geometry.

2. Experimental Results and Discussion

2.1. Packed Fibres

Figure 4 shows the effect on tensile strength of changing moisture content from seriously wet down to 2%, on DG bamboo. Each moisture curve on each graph represents the average of 15 test samples. Unfortunately the rapid rise of strength from 5% - 2% had not been anticipated and there were no specimens remaining to test at zero moisture content. The three sections (a) (b) (c) of Figure 4 show the effect of fibre volume fraction, which bamboo exhibits because of its packing of the fibres towards the outer skin of the stem (Figure 5). The test specimens for sections (a) (b) and (c) are made from strips taken from the outer 2 mm "skin", the next layer in and then the third layer in, as shown in Figure 5, giving fibre volume fractions of 57.4%, 52.3% and 47.4%. The effect of moisture content above 5% is increasingly marked as the fibre volume fraction drops, showing the value of stripping off and using only the outer skin for serious technical use. Figure 6 shows the increase in final tensile strength and in tensile stiffness as the fibre volume fraction increases.

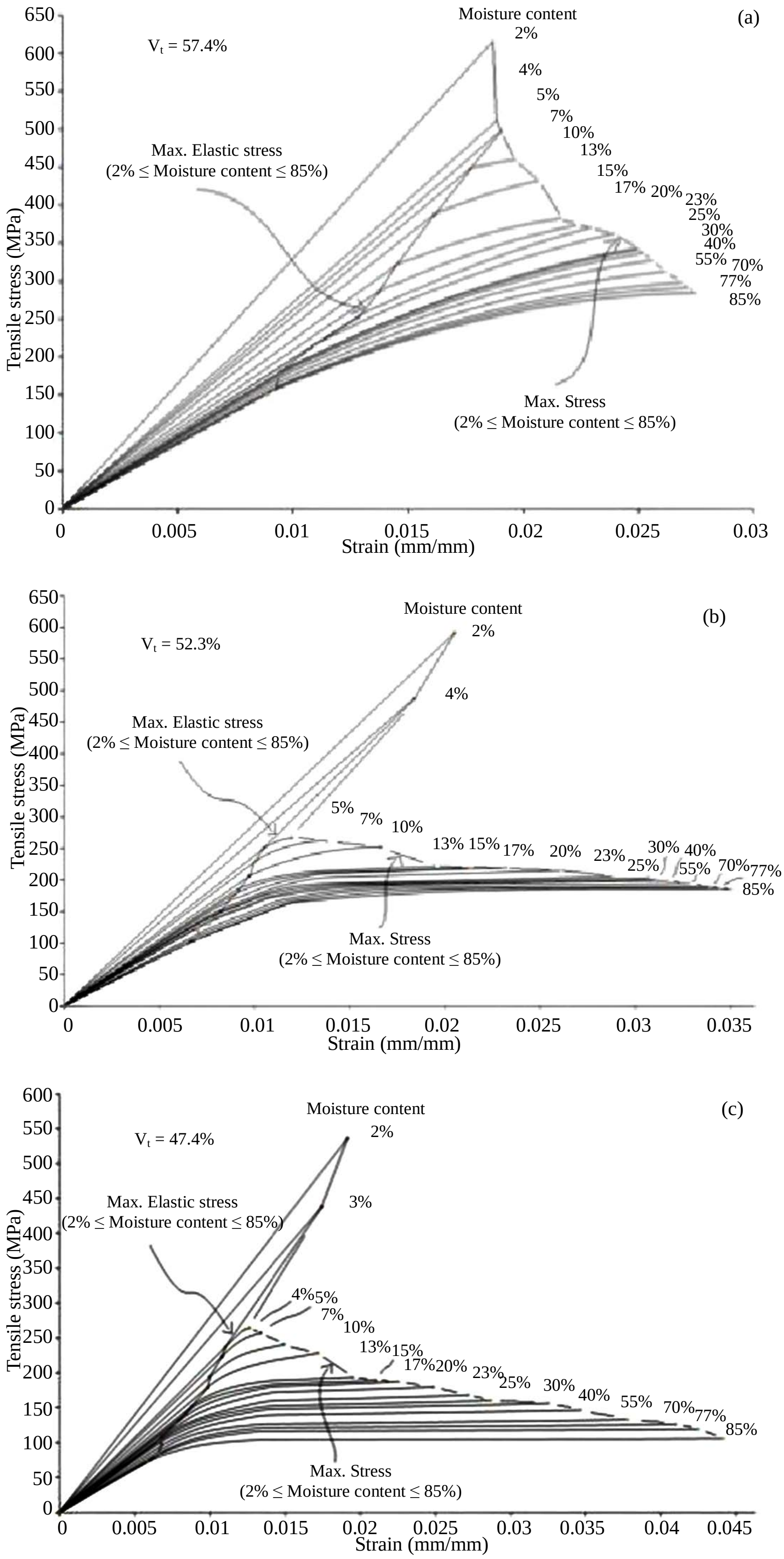

Figure 4. Moisture content effects on tensile stress-strain of DG bamboo.

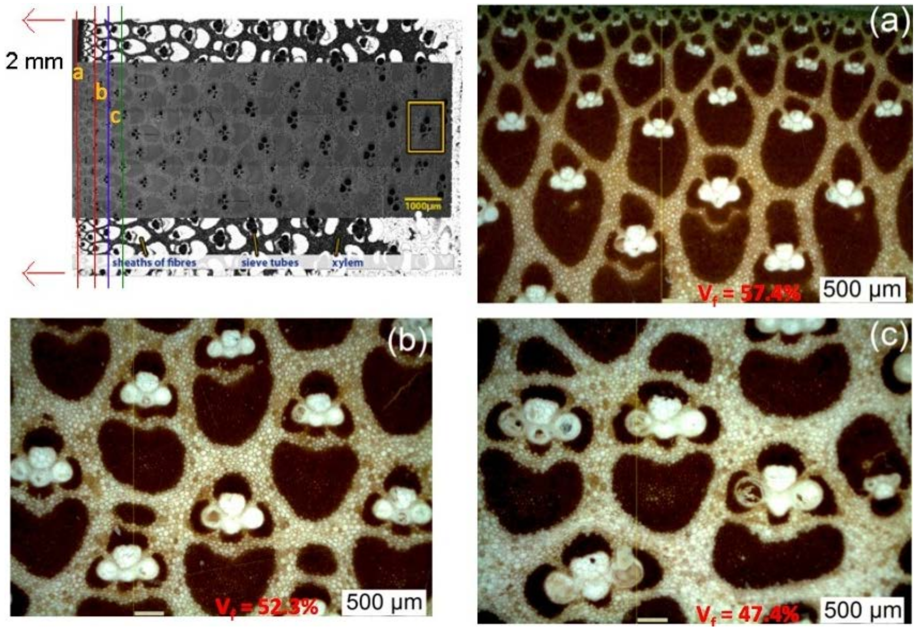

Figure 5. Outer wall fibre concentration in DG bamboo.

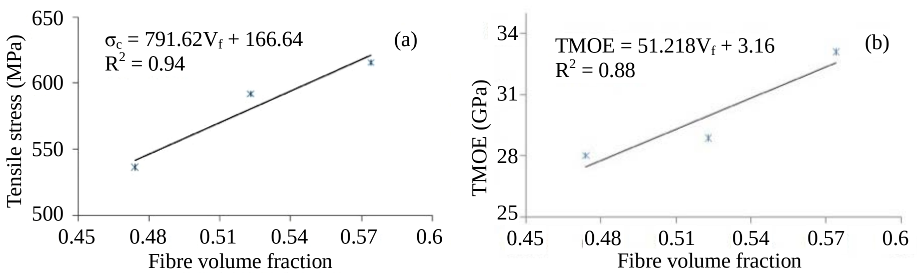

Figure 6. Tensile strength and stiffness varition with fibre volume fraction.

In DG bamboo the fibres themselves are of very large cross-section and this shows in this bamboo having relatively weak compression strength (**Figure 7**). What is interesting, and completely in contrast to experience with Chinese Moso (M) bamboo, is that in freezing conditions DG bamboo seriously loses even the low compression strength it has (**Figure 8**), particularly at low fibre volume fractions.

2.2. Taming Statistical Variations

It has already been mentioned that the test specimens discussed above were laminated from strips taken from the outer layers of the bamboo stem, and that using the outermost layer alone produced the best properties. This process is the standard process used in China for producing bamboo floor panels from Moso (M) bamboo and it is easy to produce planks laminated from just the outer layer of this bamboo, for structural use. 2 m long planks 13 mm wide and 25 mm deep laminated from 25 1 mm strips using conventional wood glue have been used in wind turbine blade development in China. The laminating of so many strips into one plank does two things. Firstly it averages the properties of the 25 strips. But secondly, each strip has positions along it where there was a ring round the bamboo and so the fibres lose their straightness for a few mm. Laminating up these strips randomly distributes these low stiffness points in the material, again producing an averaging effect. Finally, many planks are laid side by side into the wind turbine blade mould, sandwiched between an inner and an outer layer of ±45˚ glass cloth, ready for infusion with epoxy resin to create the structural shell of the wind turbine blade. So this is a further averaging effect. The infusion also seals the bamboo in epoxy, thus preserving its dryness. One further detail preserves the full strength of the bamboo blade shell. In bamboo, because all the fibres are longitudinal, the shear strength is relatively low. So planks laid end to end are overlapped using a 25:1 chamfer

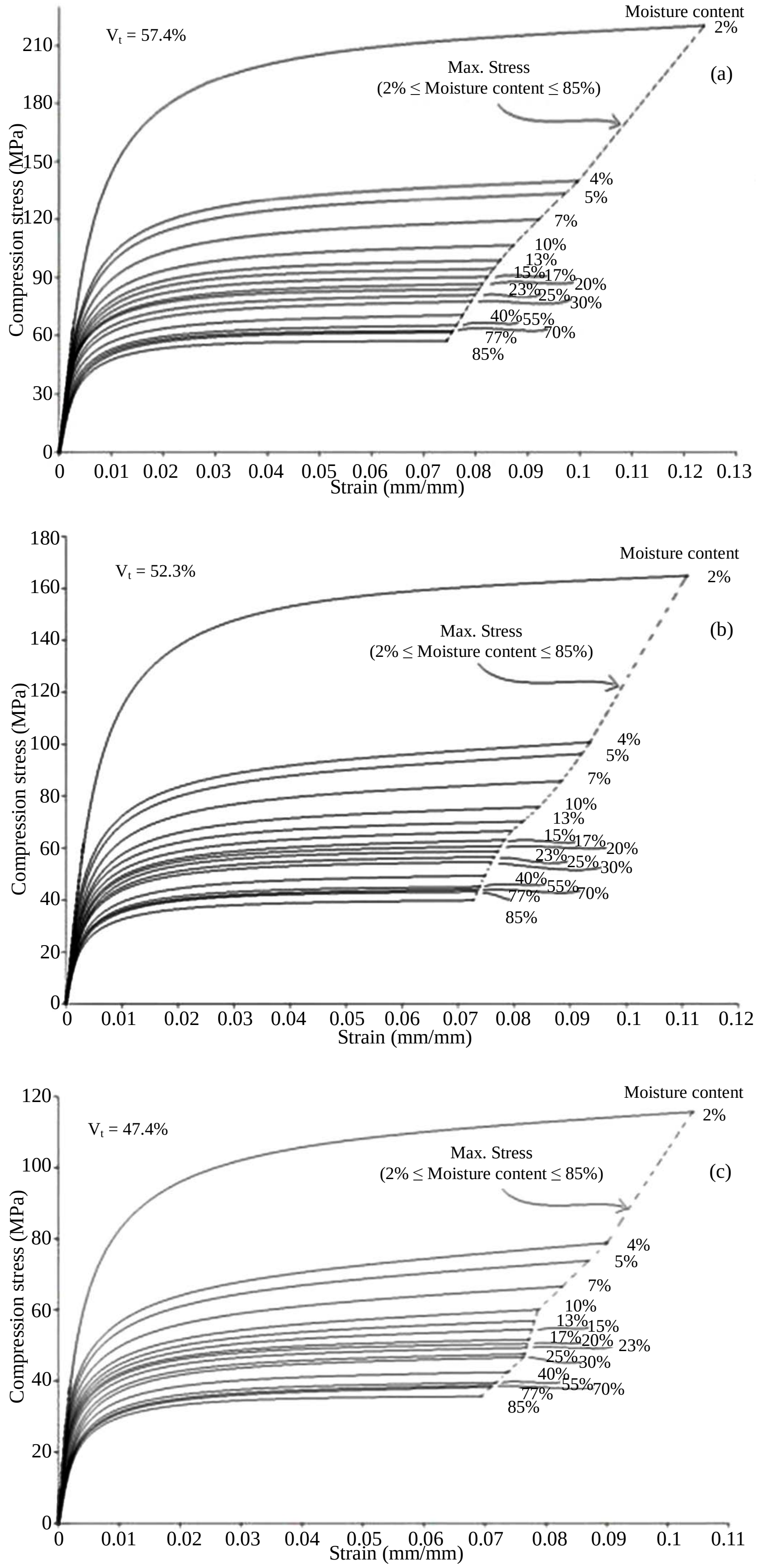

Figure 7. Moisture content effects on compressive stress-strain of DG bamboo.

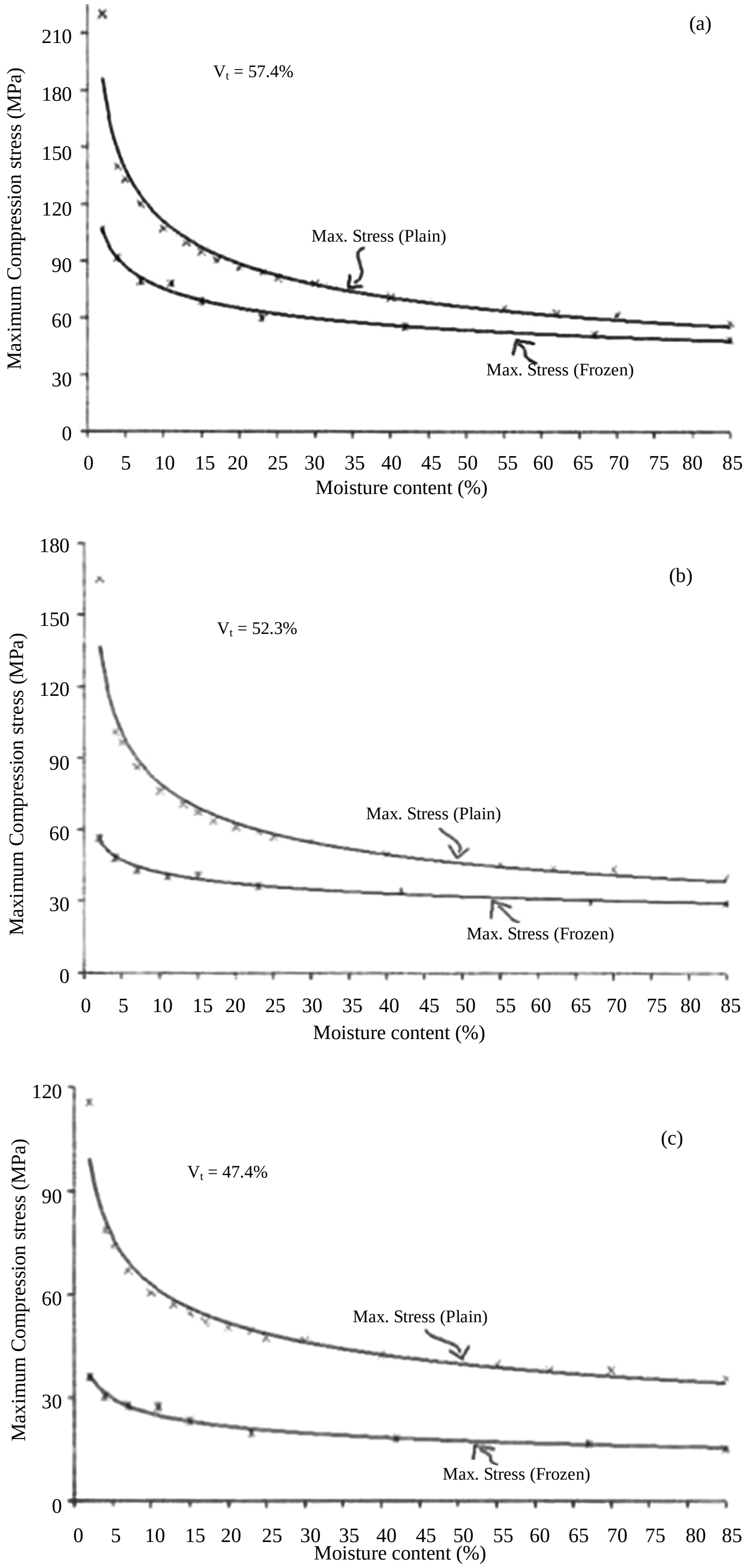

Figure 8. Loss of strength in frozen DG bamboo (−18˚C).

joint giving a long shear bond line at a sufficiently low angle that structural failure is tensile failure of the fibres, not a shear failure of the matrix in the joint. So, from a structural point of view, the joints are invisible and they are not a source of weakness. **Figure 9** shows an unpainted test blade 25 m long made using Moso bamboo in this manner. The arrangement of the bamboo planks can be seen on the blade.

Moso bamboo does not have as high a tensile strength as DG bamboo but is has proportionally far better compressive strength, with mean values of 250 MPa and 140 MPa respectively in tension and compression, with a tensile stiffness of 28 GPa, with an average moisture content of 4% in the test samples. Design processes use design strengths of (mean—3 S.D.), which are 180 MPa and 120 MPa respectively for tension and compression (there is much higher variation in the tensile strength) and this introduces one final statistical effect that has to be taken into account for quality control sample testing of delivered batches of planks. In a small sample set for testing from a batch of planks, there will of course be a spread of individual results and the mean will be close to the large sample mean for the material. But it is possible to get the occasional very high strength value and in a small sample set this distorts the S.D. value and would give an unacceptably low and unrepresentative (mean—3 S.D.) value, because the strength distribution is not a Normal distribution but is skewed, with a tail of high values not mirrored by an equivalent tail of low values. What is being sought from quality control testing is "is it safe?" and it is always safe to omit from test samples individual high strength results that unreasonably distort the S.D. value. So this is done.

2.3. Fatigue Strength

Fatigue testing was carried out for the Moso bamboo using small test pieces laminated from 1 mm strips of the outer bamboo "skin", with the test samples manufactured to ensure that each had a 25:1 chamfer joint running through the centre of the test zone. These were tested at an R ratio of −1, with 5 specimens tested at each loading level. The fatigue results are shown in **Figure 10**.

No laboratory tests have been done on frozen Moso bamboo, but the testing of the blade shown happened to take place outside in seriously sub zero temperatures (−15˚C). The blade was tested to failure and the failure load was predicted by repeating the strength calculations with all the safety factors and materials factors taken out. The blade failed at mid span at what, on inspection, proved to be a very poorly made final bonded joint between the GRP web and the bamboo composite shell, at 97% of the predicted load. The Moso bamboo, which grows in these sub-zero winter temperature regions, did not show any weakening at this low temperature.

Figure 9. 25 m wind turbine blade showing Moso bamboo plank construction.

2.4. Energy Efficient Manufacturing

In seeking to use natural materials for serious structural purposes, reducing the material down to fibre level is an inefficient process when nature itself has provided the fibres with a matrix already. It is far more efficient to use normal woodworking processes to produce strips, if it is bamboo, or to use rotary peeling, as was used to produce the laminations of Finnish birch in Europe for the more than 10,000 40 m blades for the highly successful Vestas V82 1.65 MW wind turbine [4] (**Figure 11**). Using normal woodworking to produce planks, which are then integrated with glass fibre and other components into a moulded wind turbine blade shell using resin infusion, minimizes the use of resin, and allows rapid cure cycles because the resin is only ever in thin layers and is thus protected from exotherm runaway of the curing process. The 40 m blades were originally developed for what was the NEG Micon 82 m diameter wind turbine. When NEG Micon and Vestas merged, there was the opportunity to compare it with the Vestas 40 m carbon prepreg blade for the equivalent application. The aerodynamics, weight, dynamic behaviour and fatigue life was exactly as the carbon blade, at half the price, half the manhours in manufacture and a sixth of the factory investment needed to do it. In terms of the embodied energy content of the manufactured blade is was less than a fifth of the carbon blade, and of course timber has a negative carbon footprint because it is a carbon sequestration process in its own right. And the best sustainability involves re-use at the end of its operational life. The furniture shown in **Figure 12** was made from bamboo taken from the blade shown in **Figure 9** after it had been tested to destruction.

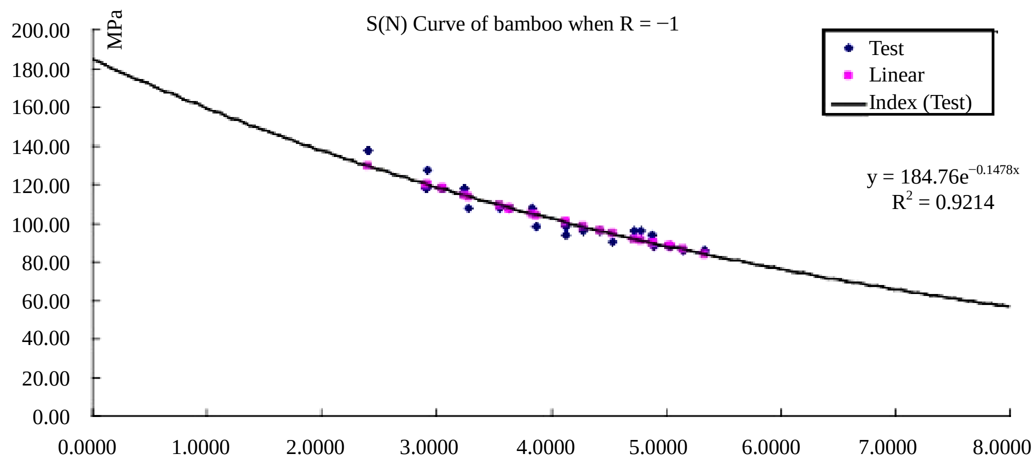

Figure 10. S(N) fatigue curve for Moso bamboo at R = −1.

Figure 11. NEG Micon 40 m birch-wood/composite blade on test.

Figure 12. Furniture made from the Moso bamboo planks of the 25 m blade shown in **Figure 9** following destructive testing.

3. Conclusion

Tensile and compressive strength test results are presented for Brazilian Dendrocalamus Giganteus bamboo with moisture content ranging from 2% - 85% demonstrating the significance of the moisture content on both strength and stiffness values. This suggests that developing and maintaining the dryness of wood are important for high-tech use and fatigue results are presented for Chinese Moso bamboo tested at 4% moisture content. Coating the bamboo with epoxy resin provides a complete vapour barrier and preserves this dryness throughout its technical life and this has been used globally in the design and manufacture of many thousands of highly successful wind turbine blades over three decades. Within these manufacturing processes, details have been developed to handle the innate variability of a natural material by making planks out of many parallel strips and then structures out of many parallel planks, creating a strong averaging effect, and then allowing for this in the quality control sampling process and in the design values used for strength. A very structurally efficient product results and a very cost effective and energy efficient manufacturing process with a low carbon footprint.

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