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The Fracture Behaviour of Fresh Bamboo Under Uniaxial Compressive Loading Condition

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Abstract: This study investigates the development of the crushing strength of fresh Bamboo samples (*Bambusa vulgaris*). Crushing strength experiment was performed using Uniaxial Compression Machine. The data is plotted as crushing stress versus height, load versus time of failure and crushing stress versus thickness. Microstructures were also analyzed. Moisture content of bamboo was carried out to know the effect of moisture on the crushing strength. Results show that, increase in height reduces the strength of the bamboo and vice versa. Increase in moisture content increases the strength of the Bamboo. The height of the fresh bamboo decreases as the crushing load increases and the time of failure also increase. The effect of thickness does not depend on only the crushing stress but also the amount of moisture in the bamboo. The crushing stresses for a height of 250, 210, 170, 130, and 90 mm were 51.3093, 71.1447, 74.5867, 79.5905 and 85.2036 MPa, respectively. The cup zone, the cone zone and the cylindrical zone experienced several crack initiations. The microstructure shows a contour-like pattern due to the extent of deformation caused by the subjected load on the bamboo. The deformations in these cases were severe with few brownish-dark areas representing the stress concentration areas.

Key words: Bambusa vulgaris, crushing experiment, crushing strength, cup zone, cone zone, cylindrical zone, loading failure, moisture content

INTRODUCTION

Ghana as a country is endowed with considerable forest reserve but faces the threat of losing its forest cover in about 23 years and becoming a desert if the current alarming rate of deforestation of 65000 ha annually continues without support from all stakeholders. In efforts to solve this menace, agriculturalist and botanists have resulted to the use of regenerative and early maturing plant species such as bamboo. Bamboo is a grass and not a product derived from forestry (Yusoff *et al.*, 1992). As a result, bamboo is considered a highly renewable and sustainable product that can save our ever-dwindling forests. In view of this, most construction firms in Ghana have switched to the use of bamboo. They use bamboo for the construction of formwork and most times as a prop or supporting systems in building construction. In addition, bamboo is used for the manufacture of wooden flooring panels, support in traditional housing and structural reinforcement (Oteng-Amoako and Obiri-Darko, 2002). Despite the aforementioned applications of bamboo, accidents do happen with the use of this material as well as its general constructional usage. It is therefore, very imperative to understand the failure or breaking stress of bamboo (i.e., the stress at which bamboo under loading will fail disastrously). Hence, the major aims for this paper are to investigate and educate the public on the crushing strength of bamboo, to identify the effect of height on the crushing strength of the bamboo (failure or breaking stress), to study crack nucleation sites and established a baseline microstructure analysis for the bamboo.

Background history: Bamboo is a naturally occurring composite material which grows abundantly in most of the tropical countries. It is considered a composite material because it consists of cellulose fibers imbedded in a lignin matrix (Xiaobo, 2004). Cellulose fibers are aligned along the length of the bamboo providing maximum tensile flexural strength and rigidity in that direction (Lakkad and Patel, 1981). Over one thousand two hundred (1200) species of bamboo have been identified globally.

Bamboo has a very long history with human kind. Its chips were used to record history in ancient China and it is also one of the oldest building materials used by human

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Table 1: Composition of Bambusa Vulgaris

Weight(%)	Starch	Deoxidized saccharide	Fat	Protein	Water
	5	2	3	5.5 %	84.5 %

kind, for household products and extended to industrial applications due to advances in processing technology and increased market demand (Wang and Shen, 1987). In Asian countries, bamboo has been used for household utilities such as containers, chopsticks, woven mats, fishing poles, cricket boxes, handicrafts, chairs, etc. It has also been widely used in building applications, such as flooring, ceiling, walls, windows, doors, fences, housing roofs, trusses, rafters and purling (Hardin *et al*., 2009). It is also used in construction as structural materials for bridges, water transportation facilities and skyscraper scaffoldings. There are about thirty five (35) species now used as raw materials for the pulp and paper industry. Massive plantation of bamboo provides an increasingly important source of raw material for pulp and paper industry in China (Hammett and Youngs, 2002).

There are several differences between bamboo and wood. In bamboo, there are no rays or knots, which give bamboo a far more evenly distributed stresses throughout its length. Bamboo is a hollow tube, sometimes with thin walls, and consequently it is more difficult to join bamboo than pieces of wood. Bamboo does not contain the same chemical extractives as wood, and can therefore be glued very well (Janssen, 2000). Bamboo's diameter, thickness, and inter-nodal length have a macroscopically graded structure while the fiber distribution exhibits a microscopically graded architecture, which lead to favourable properties of bamboo (Amada *et al*., 1998). Bamboo has a long history as a building material in many parts of the world. It is light, strong and easy to grow. In spite of these advantages, it is widely perceived as a temporary, poor man's material. However, with careful specification and design, safe, secure and durable bamboo shelter is achievable at a price that is within reach of even the poorest communities in developing countries.

Even when issues of durability and strength are resolved, the question of acceptability remains. Bamboo building need not look 'low-cost'. Imaginative design and the use of other locally available materials within the cultural context can make the building desirable rather than just acceptable. For example, in Central America, a region with a long tradition of bamboo construction, bamboo buildings of every description can be found. The prices of such bamboo building range from a few hundred dollars to a few million (Varmah and Pant, 1981). In Ghana, the shortage of affordable housing is one of the acute social problems associated with the country's economic condition. The housing accumulation is already four hundred and twenty (420,000) units, and increasing annually by one hundred and twenty (120,000) units (Oteng-Amoako and Obiri-Darko, 2002). Here, bamboo assumes special significance by offering an environment-friendly alternative to declining timber supplies, high embodied energy materials, oil-based plastics and expensive imports. In rural areas, shortages extend to basic public infrastructure. Only 76% of children obtain primary school education, decreasing to 37% at secondary school (Oteng-Amoako, and Obiri-Darko, 2002). Many children in rural villages are deprived of primary education simply due to lack of school facilities in the village or immediate neighbourhood. Such circumstances demand cost-effective, quick and sustainable solutions. Bamboo construction offers significant potential, with simple technology able to provide permanent solutions to building shortages nationwide. With regards to the aforementioned histories and applications governing bamboo, failure still occur with its usage. It is therefore pertinent for one to understand the crushing strength, the microstructure and the effect of moisture content on the crushing strength of bamboo.

MATERIALS AND METHODS

Materials: The type of Bamboo specie used for this research is Bambusa Vulgaris (fresh bamboo). Bambusa Vulgaris comprises the following; 5% starch, 2% deoxidized saccharide, 3% fat and 5.5% protein. The weight percentages are shown in Table 1. Bambusa Vulgaris was obtained from University of Mines and Technology, Ghana. The experiments were carried out in the Geological Engineering Laboratory of the University of Mines and Technology, Ghana in June, 2010.

Sample preparation: The fresh Bambusa Vulgaris (the green type) as received from the forest fields were free from insect infestation. The specimens were polished to be free of nicks, dents and scratches. The specimens were polished with P 1200, P 120 and P 60 abrasive paper. This was done to reduce the degree of crack initiations. Compressed air was blown on the surface of the specimen to remove dirt particles. The specimens were carefully cut such that, the node lies at the centre of the height. The maximum specimen height for the experiment was 250 mm. It was then reduced with an interval of 40 mm to the lowest height of 90 mm.

Specimen design: Figure 1 and 2 shows Bambusa Vulgaris specimen and it cross-section.

Specimen was cut into the requisite shape by the use of the cross-cut saw machine. Specimen height is from 90 to 250 mm with 40 mm interval. External diameters "D_o" of the specimen are between 50 to 62 mm and thickness "T" between 5 to 10 mm.

Experimental: Crushing experiment, moisture content experiment and microstructural analysis was conducted on the specimen.

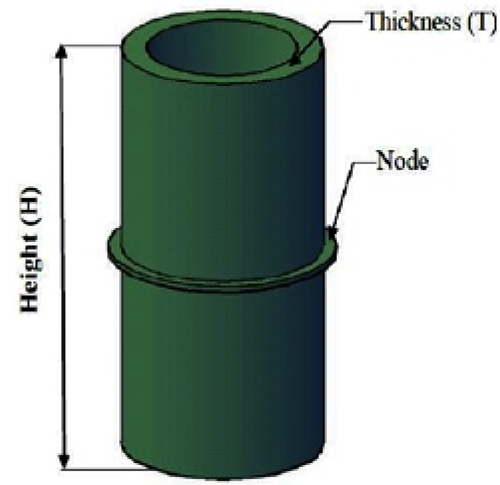

Fig. 1: Bambusa vulgaris specimen

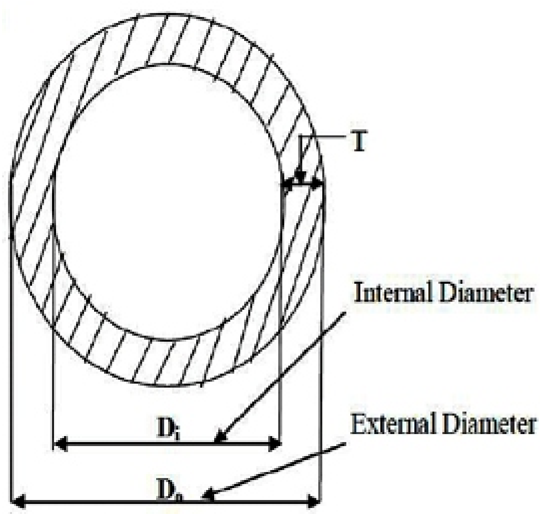

Fig. 2: Cross-section of the specimen

Crushing strength experiment: The crushing strength experiment was performed with the used of the uni-axial compressive machine at a room temperature of 25ºC. Four hundred specimens were used to carry out the experiment. The various specimens were cleaned and polished with abrasive paper of grades P 1200, P 120, P 80 and P 60, so as to avoid stress concentration points caused by any scratch or dent on the specimens' surface. After which the diameter and the thickness of the specimens were measured with a vernier calliper. The maximum height of the specimens was 250 mm but was stepped down by 40 mm interval hence obtaining heights of 210, 170, 130 and 90 mm. Each specimen with the specific height was placed inside the uniaxial compressive machine. The machine's frame was properly closed and the controlling unit was triggered to start compression and the specimen

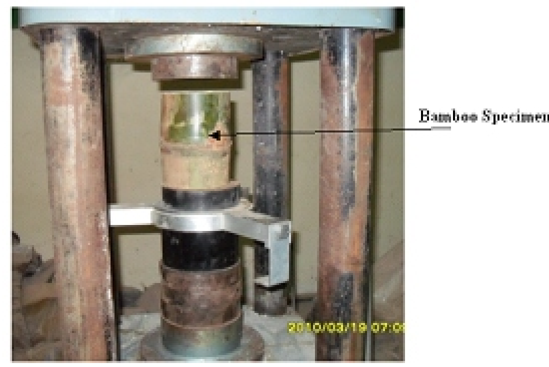

Fig. 3: Bamboo specimen under crushing test

is tested to failure. The machine automatically cut off when the specimen was crushed and the load of failure is displayed on the monitor. The monitor displays a graph of load of failure (crushing strength) against time of failure. Figure 3 shows Bamboo specimen under crushing test.

Microstructure experiment: Microstructure of the specimens was performed before the specimen was tested and after the specimen was tested. Before the crushing test, two pieces fresh bamboo of dimension 30 mm × 30 mm were cut out. Highly compressed air was blown over the specimens to get rid of all dirt on the surface. The specimen were grinded with abrasive paper of grades of 1200 P, 120 P and 60 P especially on the face where the investigation was to be carried out. The specimen was firmly secured on a plasticizer by a press machine. Electronic microscope was used to the take the microstructure. Magnification of 10x was used in this experiment.

After the specimens were tested in a uniaxial compression machine, two pieces of fresh bamboo specimens of dimension 30 mm × 30 mm were also cut out. The specimen's surface was blown with compressed air to get rid of all dirt. The surface to be investigated was grinded with abrasive paper. The specimen was firmly secured on a plasticizer and electronic microscope was used to expose the microstructure of the specimen.

Moisture content experiment: This moisture content experiment was performed to know the amount of water present in the fresh Bamboo specimens and it effect on the crushing strength of the bamboo. Since the bamboo samples were all from one culm four specimens of the fresh bamboo after crushing were weighed and recorded. After that the specimens were oven dried for a day, weigh and recorded.

According to (Head, 1992), the moisture content formula is given by:

Table 2: Detailed results of crushing strength and moisture content of the fresh Bamboo

Specimen Type	Height (mm)	External Diameter D_o (mm)	Internal Diameter Di (mm)	Area (mm^2)	Load of Failure (KN)	Crushing Stress (Mpa)	Thickness T(mm)	Mass (g)	Mass at 110ºC	MC %
FRESH	250.0	60.0	40.0	1570.7963	58.3	37.1149	10.0	504.0	404	24.75
FRESH	250.0	55.0	43.0	923.6282	62.2	67.3431	6.0	430.0	330	30.30
FRESH	250.0	46.0	30.0	955.0442	70.0	73.2950	8.0	281.3	181.3	55.16
FRESH	250.0	58.0	44.0	1121.5486	59.5	53.0516	7.0	429.1	329.1	30.39
FRESH	250.0	56.0	36.0	1445.1326	37.2	25.7416	10.0	350.0	250.0	40.00
Average	250.0	55.0	39.0	1203.2299	57.4	51.3093	8.2	398.9	298.9	36.12
FRESH	210.0	45.0	31.0	835.6636	74.6	89.2704	7.0	286.9	186.9	53.50
FRESH	210.0	49.0	29.0	1225.2211	51.8	42.2781	10.0	359.0	259.0	38.61
FRESH	210.0	56.0	44.0	942.4778	64.5	68.4791	6.0	280.0	180	55.56
FRESH	210.0	58.0	42.0	1256.6371	83.0	66.0493	8.0	372.0	272	36.76
FRESH	210.0	54.0	44.0	769.6902	69.0	89.6465	5.0	411.0	311	32.15
Average	210.0	52.4	38.4	1005.938	68.6	71.1447	7.2	341.78	241.78	43.32
FRESH	170.0	60.0	40.0	1570.7963	74.2	28.9662	10.0	291.0	191	52.35
FRESH	170.0	42.0	30.0	678.5840	66.5	97.9982	6.0	365.0	265	37.74
FRESH	170.0	46.0	32.0	857.6548	69.8	75.5549	7.0	260.0	160	62.50
FRESH	170.0	53.6	35.6	1261.0353	73.8	58.5233	9.0	269.0	169	59.17
FRESH	170.0	40.0	26.0	725.7079	81.2	111.8907	7.0	302.0	202	49.50
Average	170.0	48.3	32.7	1018.8	73.1	74.5867	7.8	297.4	197.4	52.25
FRESH	130.0	45.0	29.0	929.9114	76.0	81.7282	8.0	349.0	249	40.16
FRESH	130.0	49.0	37.0	810.5309	73.7	90.9281	6.0	327.0	227	44.05
FRESH	130.0	50.0	30.0	1256.6371	80.5	64.0599	10.0	408.0	308	32.47
FRESH	130.0	40.0	26.0	725.7079	69.5	95.7686	7.0	360.0	260	38.46
FRESH	130.0	56.0	38.0	1328.8937	87.0	65.4680	9.0	278.0	178	56.18
Average	130.0	48.0	32.0	1010.3362	77.3	79.5905	8.0	344.4	244.4	42.26
FRESH	90.0	60.0	42.0	1441.9910	64.7	44.8685	9.0	223.0	123	81.30
FRESH	90.0	43.0	27.0	879.6459	77.5	88.1036	6.0	259.0	159	62.89
FRESH	90.0	46.0	30.0	955.0442	83.6	87.5352	7.0	115.1	115.1	86.805
FRESH	90.0	40.0	24.0	804.2477	79.6	98.9745	8.0	333.0	233	42.91
FRESH	90.0	42.0	28.0	769.6902	82.0	106.5364	7.0	358.0	258	38.76
Average	90.0	46.2	30.2	970.1238	77.48	85.2036	7.4	257.6	157.6	62.53

$$\text{Moisture Content (MC \%)} = \frac{(w_1 - w_2)}{w_2} \times 100\%$$

where,
(MC) is the moisture content of bamboo specimen
(w_1) is the mass of crushed specimen
(w_2) is the mass of crushed sample after 24 h of oven drying at 110ºC

RESULTS AND DISCUSSION

Experimental results on the crushing strength and moisture content are shown in Table 2. Five specimens of the same height were crushed and for the sake of accuracy of results, an average load of failure of specimen was calculated. For instance, for a height of 250 mm, five specimens of height 250 mm were crushed and average load of failure was calculated. A similar trend was followed for the heights of specimen of 210, 170, 130 and 90 mm. From Table 1, the crushing stress for a height of 250, 210, 170, 130 and 90 mm was 51.3093, 71.1447, 74.5867, 79.5905 and 85.2036 MPa, respectively. It could be seen that as the height increases the crushing strength decreases. Therefore, the height has significant influence on the crushing strength of the fresh bamboo. The load of failure also has tentative influence on the height of the bamboo. Results from the moisture content experiment of the fresh bamboo did not show any significant trend this may be due to the varying lignin water absorption capacity and the effect of ageing of the fresh bamboo.

Figure 4 shows the results of fresh bamboo specimen subjected to uniaxial compressive load. The appearance of the fractured sections of the fresh bamboo gives information about the magnitude of the stress that caused the cracks. It was observed that several cracks initiated from the cup zone (AB). At point A, the smashed surface was caused by the opening and closing of the crack during its development. The cracks in the cup zone started when the compressive load applied exceeded the strength of the weakest grain on a cross section. Continued operation caused the crack to grow persistently as the strength of say adjacent grains was exceeded by the high stress at the crack tip. If the compressive load is at high value, the strength at a number of grains around the edge of the smashed surface was probably exceeded. This will cause cracks to start and spread till they unite with one another. These cracks progressed toward the cone zone (BC). Within the cone zone, the cracks grow concurrently toward the longitudinal axis. The measured angle of orientation of the cracks with respect to the longitudinal axis was approximately 44.6º. The stress in the cone zone was considerably greater than the endurance limit of the material at that state. Therefore, very large cracks were seen and failure of the material would be caused by only a small compressive loadings applied on the material. The cylindrical zone (CD) did not experience many crack initiations. The cracks propagated parallel to the longitudinal axis of the material. These cracks grown until it got to the node. The node of the bamboo is designed naturally to resist cracks. Higher compressive loadings were needed to break the resistive forces at the node. It was therefore observed that the cracks at the cylindrical zone did not propagate beyond the node before failure of the entire material.

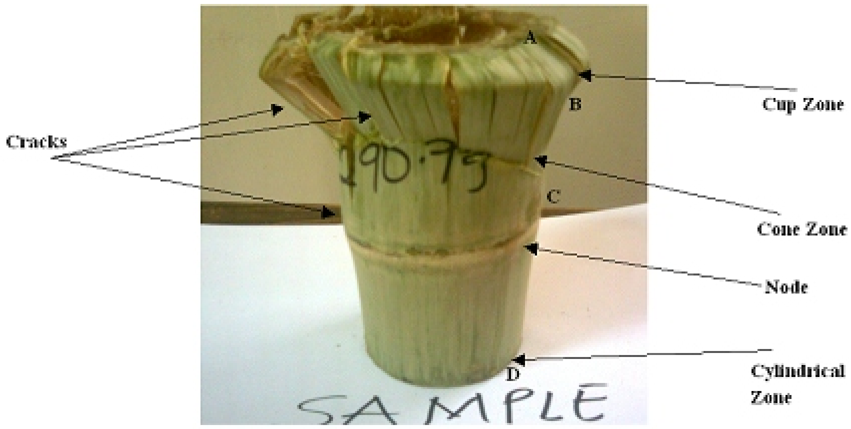

Fig. 4: Fresh Bamboo subjected to uniaxial compressive loading

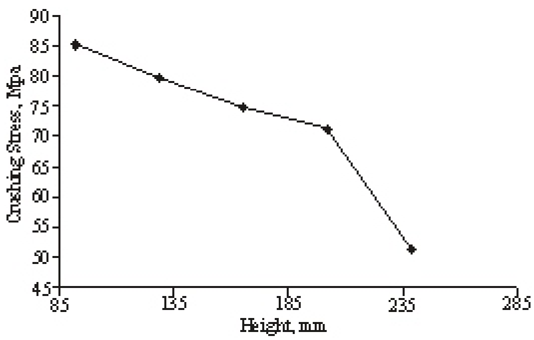

Fig. 5: A graph of crushing stress versus height

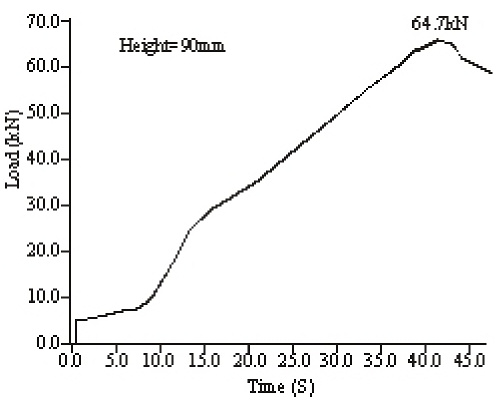

Fig. 6: Crushing load versus time of failure

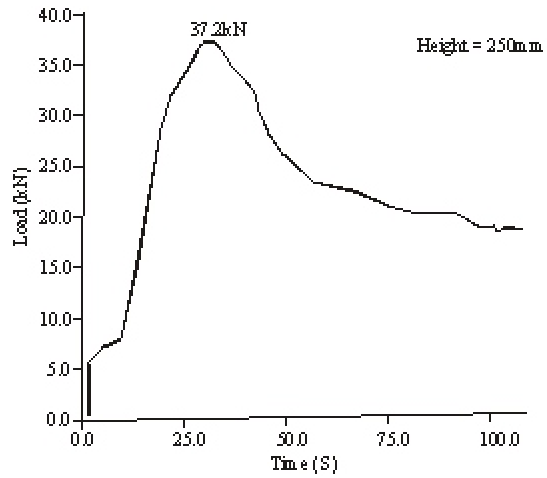

Fig. 7: Crushing load versus time of failure

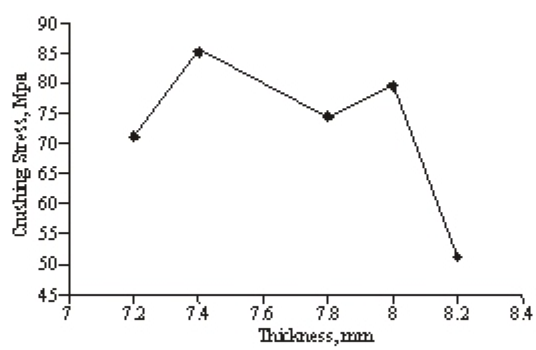

Fig. 8: A graph of crushing stress versus thickness

From Fig. 5, it is clear that the crushing stress of fresh bamboo decreases as the height of the bamboo increases. At a height of 250 mm the crushing stress is 51.3 kN/m^2 whiles at a height of 90 mm the crushing stress is 85.2 kN/m^2.

From Fig. 6, it could be seen that a 90 mm height of fresh bamboo failure disastrously at a crushing load of 64.7 kN. This crushing load happens at approximately forty three seconds. This time signifies the time of failure when a load of 64.7 kN is placed on a 90 mm height of a fresh bamboo. Concurrently, Fig. 7 also gave similar meaning of what is happened in Fig. 6. In Fig. 3, 250 mm height of fresh bamboo failed disastrously at a crushing

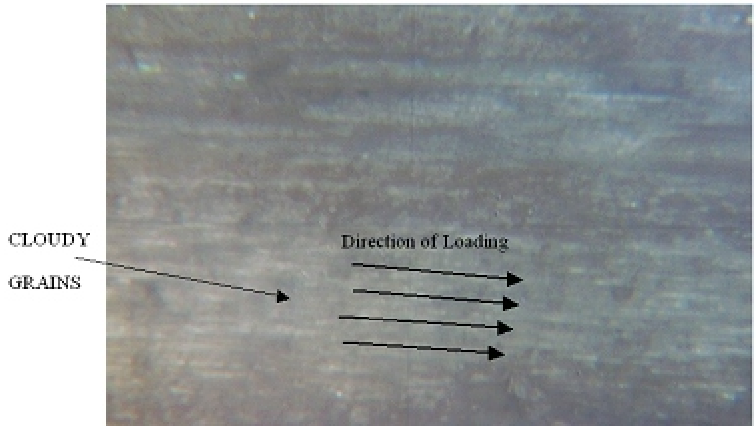

Fig. 9: Microstructure of fresh bamboo before compressive loading

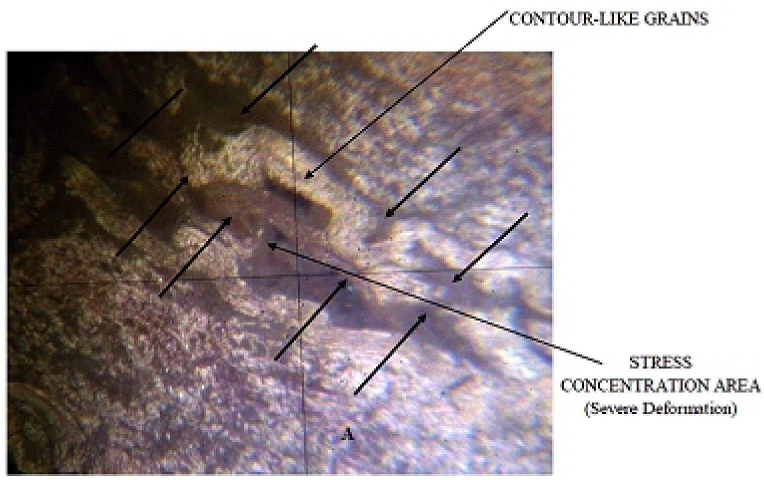

Fig. 10: Microstructure of fresh bamboo after compressive loading

load of 37.2 kN which related to a failure time of thirty five seconds. It is vital then to conclude that as the height of the fresh bamboo decreases the crushing load increases and the time of failure increases.

Figure 8 shows a scatter diagram where crushing stress is plotted against the thickness. Figure 5 did not show a significant trend for a meaningful deduction to be made. A decrease in the thickness did not give say an increase in the crushing stress or vice versa. At a thickness of 8.2 mm a crushing 51.3 kN/m^2 is achieved. At a thickness of 7.4 mm a crushing stress of 85.2 kN/m^2 is achieved. From Figure 8, it is obvious that the effect of thickness does not depend on only the crushing stress but also the amount of moisture in the bamboo.

This experiment was performed to appreciate the deformation behaviour of the Bamboo before and after being crushed. This result is important because it will serve as the basis of comparison with other microstructure of other species of bamboo for further investigations. Figure 9 shows the microstructure of fresh Bamboo before test. The direction of loading of the grain is shown with the parallel arrow lines. From Fig. 9, it was observed that the grains are aligned parallel but look dark cloudy and not very bright due the relatively high Moisture Content (i.e., high water presence).

From Fig.10, the grains of the fresh Bamboo after crushing shows a contour-like pattern due to the extent of deformation caused by the subjected load on the bamboo specimen. The deformations in these cases were severe with few brownish-dark areas representing the stress concentration areas (i.e., severe deformation). Several cracks were seen and these are illustrated by the dark arrows. Cracks initiations of the various deformations in the microstructure are also shown by the dark arrows. Deformation mimics that of a twisted bundle of sticks. Explaining the fact that the grains of the deformed fresh bamboo are packed and cracks initiations could have started from any of the highly stressed areas shown in the microstructure. At arrow *A*, crack could have started from that point and propagated through the material till failure of the entire material. It is therefore obvious that cracks initiations in the microstructure could have stated anywhere within the material provided those areas are stress concentrated points.

CONCLUSION

- Increase in height reduces the strength of the bamboo and vice versa. Therefore, height has significant influence on the crushing strength of the fresh bamboo.
- The crushing stresses for a height of 250, 210, 170, 130 and 90 mm were found to be 51.3093, 71.1447, 74.5867, 79.5905 and 85.2036 MPa, respectively.
- The failure loads for a height of 250, 210, 170, 130 and 90 mm were found to be 57.4, 68.6, 73.1, 77.3 and 77.48 kN, respectively.
- Deformation of fresh bamboo mimics that of a twisted bundle of sticks.
- The microstructure shows a contour-like pattern due to the extent of deformation caused by the subjected load on the bamboo. The deformations in these cases were severe with few brownish-dark areas representing the stress concentration areas.
- The cup zone, the cone zone and the cylindrical zone experienced several crack initiations.
- Increase in moisture content increases the strength of the Bamboo
- Height of the fresh bamboo decreases as the crushing load increases and the time of failure increases.
- The effect of thickness does not depend on only the crushing stress but also the amount of moisture in the bamboo.

RECOMMENDATION

- Further research should be carried out on the effect of ageing on the crushing strength of fresh bamboo.
- Extensive research into the application areas of bamboo in Ghana should be encouraged.

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