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Improvement of the Bending Characteristics of Thin FRP Cylinders by Imitating Nodes of Bamboo

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Abstract

Thin cylinders of fiber-reinforced plastic (FRP) material are used in large quantities as a kind of structural material for robot arms, airplanes and aerospace applications because of their light weight and high strength. In order to improve the mechanical properties of these cylinders, this study applied the VaRTM method to develop a biomimetic design of a thin cylinder with nodes that imitate a bamboo structure. The effects of inserted nodes on the bending properties of a thin FRP cylinder were examined by the four-point bending test. It is evident that the flexural rigidity and bending buckling load were increased; the validity of the node has also been confirmed.

Keywords

Bending, FRP cylinders, nodes, bamboo, biomimetic design

1. Introduction

Fiber-reinforced polymer (FRP) composite materials have been widely used in various engineering fields because of their superior specific strength, lower density, and high corrosion resistance compared to monolithic metal alloys. FRP is widely used in thin cylindrical structures. Golf club shafts, robot arms, car drive shafts, and beams of space structures are some examples [1].

However, the thin FRP cylinder shells are very poor for bending generally. Metal materials are the same, too. When a thin cylinder bends, its cylinder shape begins to buckle, eventually breaking as depicted in Fig. 1. This is reportedly caused by

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the cylindrical section becoming flat and losing flexural rigidity when a bending moment occurs in the thin cylinder [2]. In a thin FRP cylinder structure, fiber in the cylinder axial direction (reinforcement) contributes to the bending properties. In order to reduce the flatness of the cylinder, various methods are applied to thicken the cylinder wall, such as winding fibers up the cylinder vertical to the cylinder axis [1].

Various animals and plants have adapted to the natural environment over a long period of time. Bamboo, a plant that grows widely in Japan and the Asian Far East, has strength and toughness for bearing external forces of wind and snow. The bamboo structure incorporates different materials on the cylinder wall, and the vegetable fiber of bamboo is oriented in the axial direction. From engineering strength theory, bamboo has a superior structure because of its high strength and lower density [3, 4]. Amata and coworkers [5, 6] assumed that bamboo is a composite material reinforced axially by fibers collectively called the bundle sheath, and they examined the microscopic gradient structure that provides radial strength distribution in order to adapt to bending stress due to wind loads.

Bamboo has a node structure with nodes at a suitable interval in a hollow cylinder (Fig. 2). The bamboo nodes contribute to bamboo's high strength and lower density

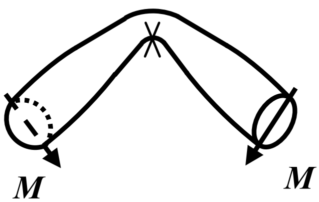

Figure 1. Buckling phenomenon of a thin cylinder.

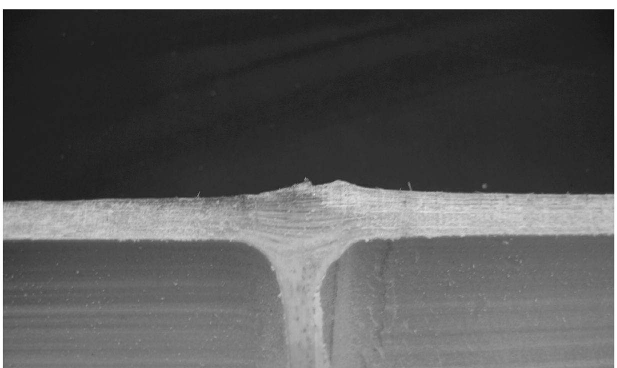

Figure 2. Vertical section of bamboo.

structure. Yamasaki [7] focused on the effect of bamboo nodes when discussing the bending characteristics of bamboo. The bending is calculated by a finite-element model (FEM) of shell structures for various portions of the bamboo cylinder with the nodes. In addition, the bamboo was also subjected to bending tests along several parts of the cylinder. However, analytical results differed considerably from the experiment results. How bamboo nodes affect the bending characteristics of bamboo is still largely unknown.

Many studies have been conducted on the bending characteristics of thin FRP cylinders [1, 2, 8]. Recently, Kasuya and Aoyama [9] reported the effect of laminated components on the buckling stress of carbon fiber/epoxy angle-ply laminated cylindrical shells under bending. However, nodes trial manufacture and nodes analyses to improve the bending characteristic of thin cylinders have not yet been conducted.

In order to improve the mechanical properties of the cylinder, this study developed a biomimetic design of a thin cylinder with nodes that imitate a bamboo structure using the Vacuum Assisted Resin Transfer Molding (VaRTM) method. The effects and the effectiveness of inserted nodes on the bending properties of a thin FRP cylinder are examined by the four-point bending test.

2. Making Thin FRP Cylinders with Nodes

Using VaRTM, composite materials have recently been applied to structures at low cost. We therefore tried to make a thin FRP cylinder with nodes that imitated bamboo. Figure 3 presents an outline of the molding method. Air inside the cylinder is extracted by a vacuum pump.

2.1. Materials

Unidirectional carbon fiber (UD, Toray Industries, Inc., TORACA, T300B-6k, Weight 1.76 g/cm^2) was used as the material for the wall of a thin FRP cylinder, unsaturated polyester resin (Showa Highpolymer Co. Ltd., REGOLAC, 158 BQTN)

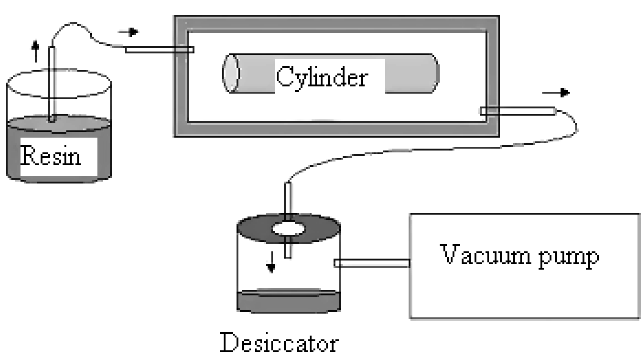

Figure 3. Schematic illustration of VaRTM method.

Table 1.
Foam characteristics

Sample	Density (kg/m^3)	E_{com} (MPa)
KM-30FA	25	4.9
KM-50FA	45	15.3
KM-60FA	53	19.6

was used as matrix, and PERMEK N (NOF Co. Ltd.) was used as the polymerization initiator.

To make the nodes for a thin FRP cylinder similar to those of bamboo, cores that do not contribute to reinforcement were inserted into the cylindrical hollow sections. Lightweight materials that did not absorb matrix resin were chosen for the core. The thin cylinder was produced experimentally with foaming polyethylene and foaming polyether of various kinds. Comparison of the results revealed that hard urethane foam was the most appropriate. Table 1 lists the characteristics of hard urethane foam (Central Innovation Product Company) used in this research.

The core is shrunk by evacuating air with a vacuum pump using the VaRTM molding method. The surface of the FRP thin cylinder wrinkled. In addition, there were some cavities between the fiber sheet and the core, suggesting that injection of resinous material and hardening had not gone well. When making thin FRP cylinders by the VaRTM method, it is necessary to find the minimum compression coefficient of elasticity (E_{com}) of the core.

Figure 4 is a photograph of a core compression test. The compression test machine was an AUTOGRAPH AG-20KND (Simatu Co. Ltd.) operated at a compression speed of 2 mm/min. The sample dimensions were $\phi 40 \times 50$ mm.

Figure 5 plots typical S–S curves of a compression test of a foam core. The compression coefficient of elasticity was determined from the initial gradient of the curves of Fig. 6. Table 1 presents the results. The trial manufacture results of a thin CFRP cylinder with KM-50FA and KM-60FA cores demonstrated that a cylinder that does not wrinkle can be produced. Therefore, producing a thin CFRP cylinder (outer diameter 40 mm, UD 2 ply) by the VaRTM method required that the core have compression coefficients of elasticity exceeding 15.3 MPa.

An acrylic plate, (Mitsubishi Rayon Co. Ltd., ACRYLITE; Young's modulus 3 GPa) that is easily cut by an NC milling machine into a circle, was used as the material for the nodes. The nodes are 5 mm thick with a diameter of 40 mm.

To lighten the FRP thin cylinder, the nodes were made of the same materials (CFRP plate) as the cylinder wall. Carbon cloth (Cloth, Toray Industries Inc., TORACA, T300B-6k, 317 g/m^2) was applied in six plies, A CFRP plate made by the VaRTM method was cut into a circle by an NC milling machine. The CFRP plate was about 2 mm thick. Figure 6 presents a photograph of the nodes with CFRP.

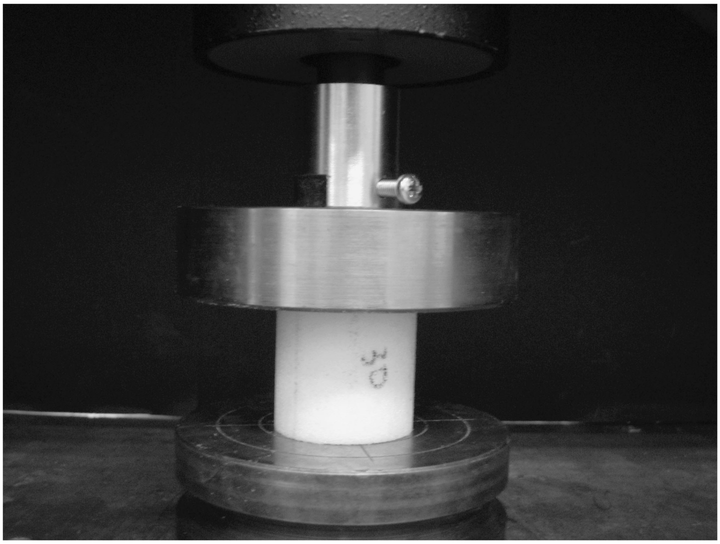

Figure 4. Compression test of foam material.

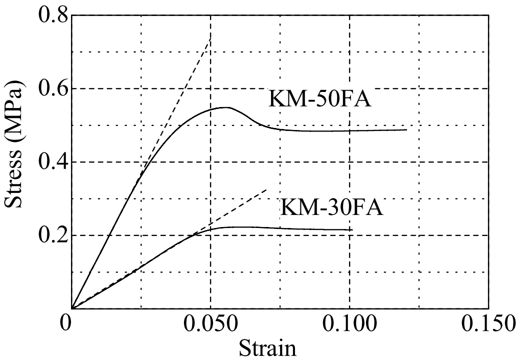

Figure 5. Compression stress–strain curves of the hard urethane foam.

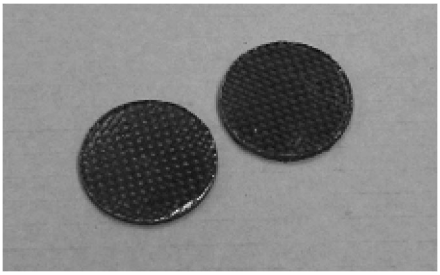

Figure 6. Node with CFRP.

2.2. Molding of the Thin Cylinder with Nodes

A powerful glue (Scotch Glue, Sumitomo 3M Co. Ltd., 7005) was used to glue the nodes (acrylic and CFRP) and the cores (foaming polyether foam) together (Fig. 7).

The carbon fiber sheet was wound around the core that was glued together in two plies. The fiber direction and a cylindrical axial direction are the same. The assembly was sealed in a film. When the pressure in the film decreased below 0.09 MPa, resin flowed into the mold. Afterwards, the vacuum pump was stopped, and the assembly was left to stand for 24 h. The cylinder pipe was post-cured for 12 h at a temperature of 60 degrees in a constant temperature, constant humidity chamber (ETAC Co. Ltd.: HIFLEX). Figure 11 presents a typical cross-section of a finished thin CFRP cylinder with the nodes.

2.3. Sample Specifications

To discuss the effects of two kinds of nodes in an FRP thin cylinder, a cylinder specimen of three standards was made (inside diameter 40 mm). Figures 8 and 9 present those samples. Figure 8 depicts a sample with a core but no nodes. An acrylic rod was inserted in both sides of a sample to prevent local breaks at load and support points during bending tests.

Figure 9 presents the specifications of samples with one or two nodes and spans of 250 mm. Figure 10 shows an example with two acrylic nodes in spans of 250 mm; Fig. 11 shows an example with one CFRP node and spans of 250 mm.

A thin CFRP cylinder with nodes of two kinds was produced experimentally without wrinkles on the surface, and impregnation of resin was adequate. The VaRTM molding method can therefore produce an FRP thin cylinder with nodes.

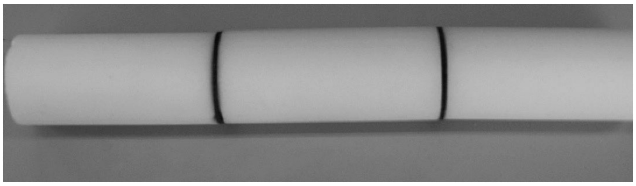

Figure 7. Core material.

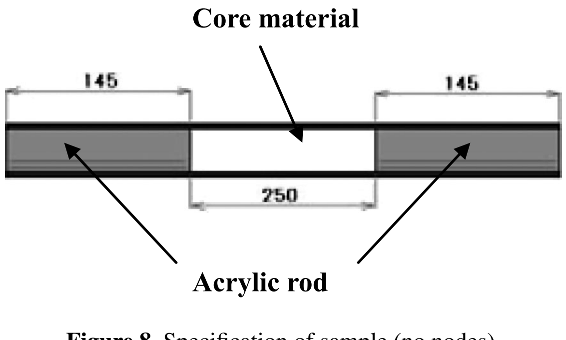

Figure 8. Specification of sample (no nodes).

2.4. Experimental Device for Evaluating the Bending Characteristics of Thin Cylinders

To evaluate the bending characteristics of a thin FRP cylinder with compartments similar to bamboo, the bending characteristics were measured by a four-point bending test, as depicted in Fig. 12. The contact of support and load points was added to a 30 mm radius arc, and a 0.5 mm thick rubber seat was inserted. Considering the space of an existing bending-test machine and the cylindrical diameter, a and b in

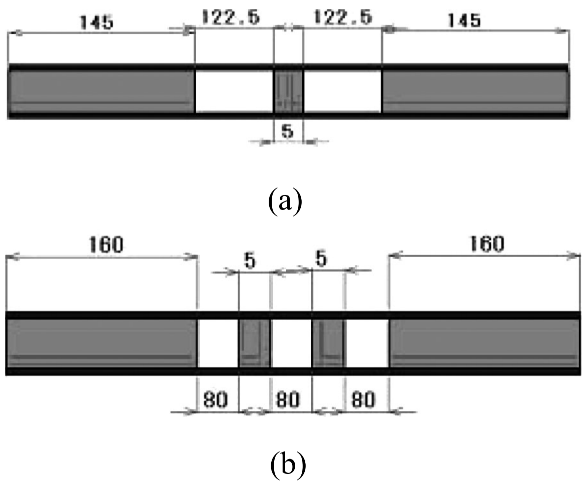

Figure 9. Specifications of sample with acrylic nodes: (a) one node, (b) two nodes.

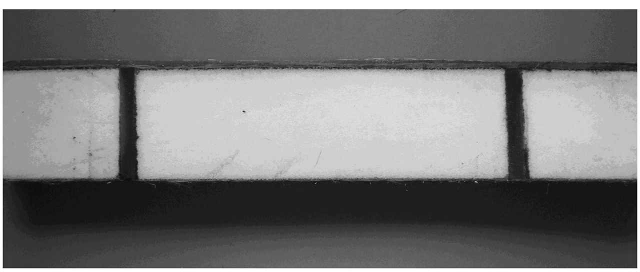

Figure 10. CFRP cylinder that with acrylic node (span 250 mm, two nodes).

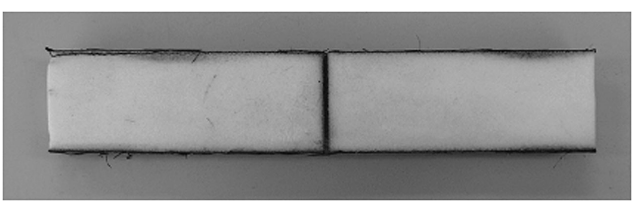

Figure 11. CFRP cylinder that with CFRP node (span 250 mm, one node).

Fig. 13 were set to 85 mm and 250 mm, respectively. The load point and support point have a combined width of 20 mm.

The cylindrical flexural rigidity (EI, Nm^2) is defined as follows:

$$EI = \frac{ab^2}{8} \cdot P/\delta. \tag{1}$$

Here, P/δ is the initial gradient of the load–deflection curves, δ is the deflection at central point CD for load point C, D.

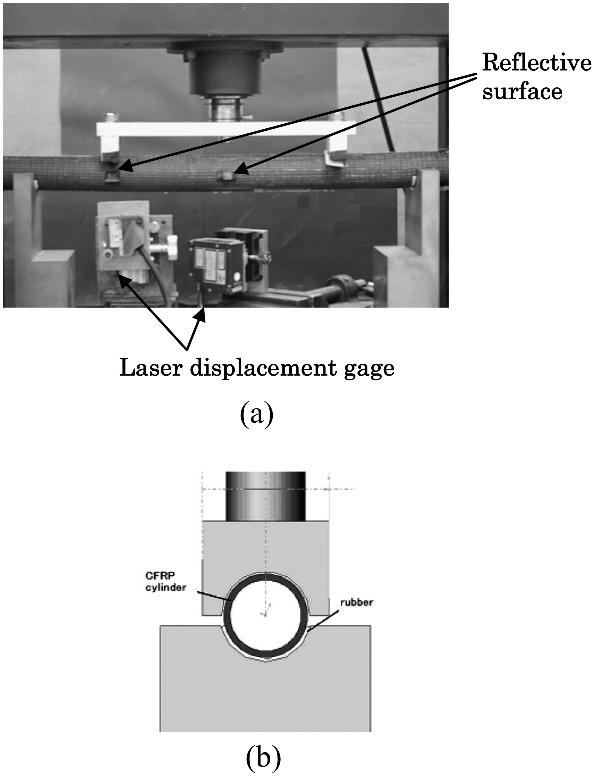

Figure 12. Device for four-point bending test: (a) photograph of the device, (b) schematic of the fixed part.

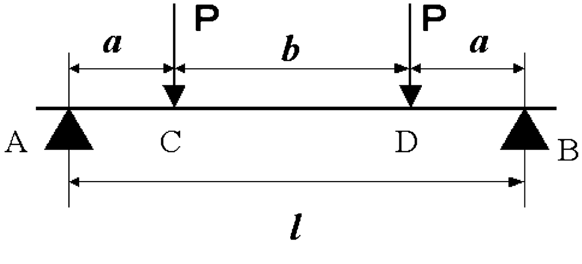

Figure 13. Four-point bending test.

Laser reflective surfaces were installed on cylindrical neutral axial point C and the central point. The displacement of two points was measured with a laser displacement gage (Keyence Co. Ltd., LB-080). The difference is the neutral axial deflection (δ).

The bending test machine is an Autograph AG-20KND (Simatu Co. Ltd.), with a head speed of 2 mm/min.

3. Results and Discussion

3.1. Thin FRP Cylinder with Acrylic Nodes

Three samples of a thin FRP cylinder with acrylic nodes (no node, one node, and two nodes) were produced and subjected to bending tests. There were no wrinkles on the surface of the experimentally produced thin FRP cylinders. A section of thin cylinder was observed after the bending test. Nodes remained well glued to the thin cylinder wall, and there was no exfoliation after the bending test.

Figure 14 presents the experiment results of the four-point bending tests described in this research. Figure 15 is a photograph of a damaged thin FRP cylinder. It is generally believed that the break location of the pipe occurred possibly at anywhere except nodal points. All samples cracked and the cracks propagated in areas without nodes and on the cylindrical compression side; all samples exhibited the buckling break mode.

Figure 16 plots the flexural rigidity derived from the load–deflection curve of Fig. 14. Increasing the number of nodes in span b improves the flexural rigidity.

The load drops suddenly at the maximum point in the load–deflection curve (Fig. 14). The product of distance and maximum load is defined as the bending–buckling moment (M_{cr}) [8]. Figure 17 demonstrates that the bending–buckling moment also improved as the number of nodes was increased. We think that the

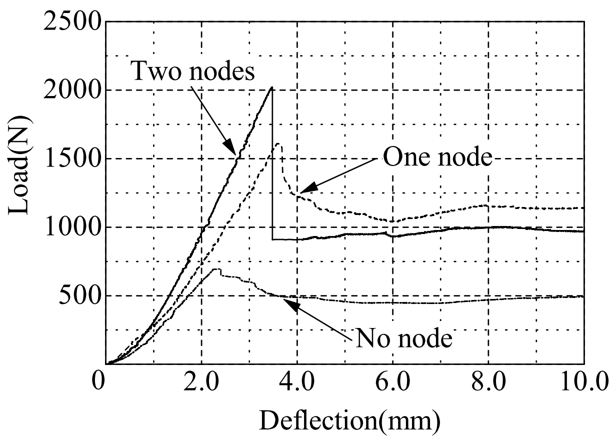

Figure 14. Example for bending load–deflection curve of each specimen for acrylic node (span $b = 250$ mm).

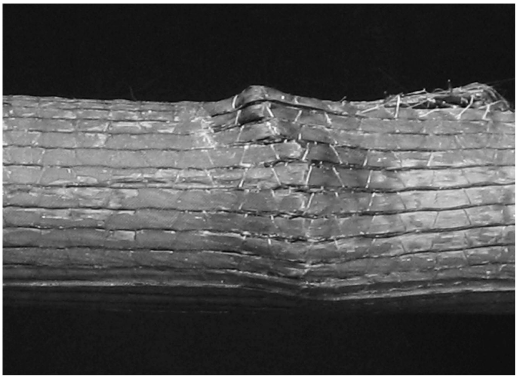

Figure 15. Specimen cracking (acrylic node 1).

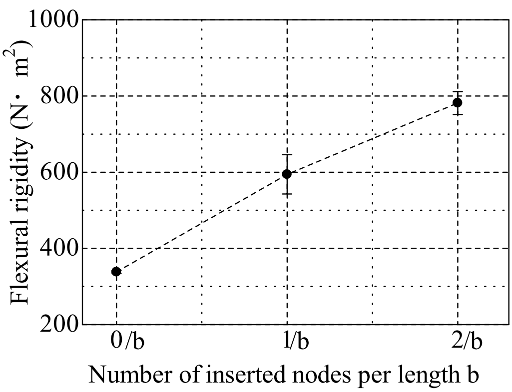

Figure 16. Relationship between flexural rigidity and number of inserted nodes for a thin cylinder (span $b = 250$ mm, acrylic nodes).

flexural rigidity and bending–buckling moment improved as the nodes restrained the tendency of the thin FRP cylinder section to flatten out.

3.2. Thin FRP Cylinder with FRP Nodes

Three samples of a thin FRP cylinder with CFRP nodes (no nodes, one node, and two nodes) were produced and subjected to the bending test. The surfaces of the experimentally produced thin FRP cylinders did not exhibit wrinkles. Nodes remained well glued together with the thin cylinder wall, and there was no exfoliation after the bending test.

Figure 18 plots the experiment results of an FRP thin cylinder with CFRP nodes by the four-point bending test suggested in this research. As compared with Fig. 14, the result values are close to each other. Cracks occurred in all samples and propagated in areas without nodes and the cylindrical compression side; all samples also exhibited the buckling break mode.

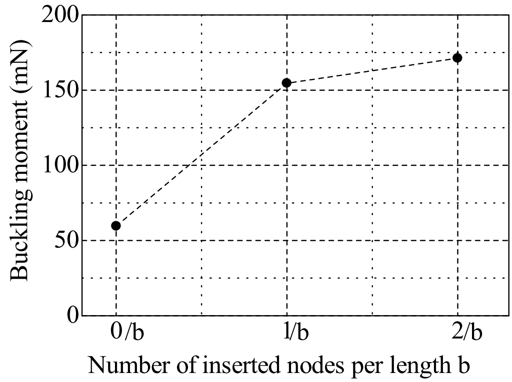

Figure 17. Relationship between bucking moment and number of inserted nodes for a thin cylinder (span $b = 250$ mm, acrylic nodes).

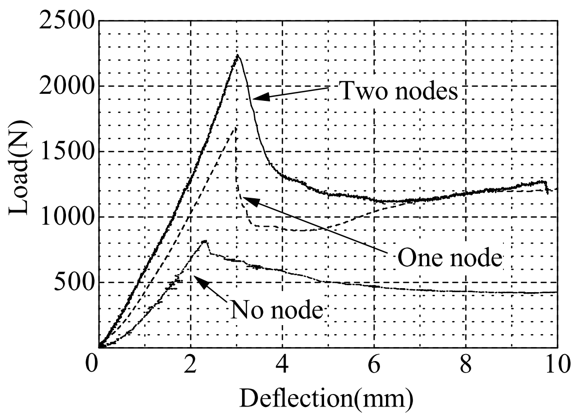

Figure 18. Example for bending load–deflection curve of each specimen for CFRP node (span $b = 250$ mm).

Figure 19 plots the results of flexural rigidity derived from the load–deflection curve in Fig. 18. As the number of nodes in span b increases, the flexural rigidity improves.

The load drops suddenly at the maximum point in the load–deflection curve (Fig. 18). As demonstrated in Fig. 20, the bending–buckling moment also improved as the numbers of nodes increased. In addition, it was confirmed that bending characteristics (flexural rigidity and buckling moment) of the FRP thin cylinder with nodes has been improved even with the CFRP nodes.

Figure 21 illustrates the relationship between the increment of bending characteristic and increment of volume of FRP thin cylinders due to the insertion of the CFRP nodes. Inserting one node increased the volume of FRP 6.4 percent, but flexural rigidity (bending–buckling moment) was increased 97.8 percent (150.3 per-

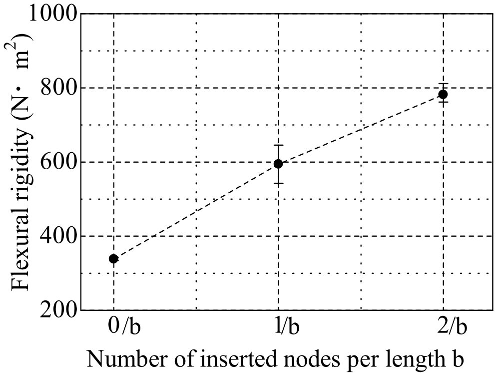

Figure 19. Relationship between flexural rigidity and number of inserted nodes for a thin cylinder (span $b = 250$ mm, CFRP nodes).

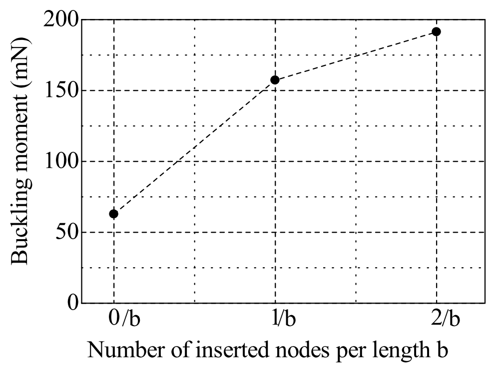

Figure 20. Relationship between bucking moment and number of inserted nodes for thin cylinder ($b = 250$ mm, CFRP nodes).

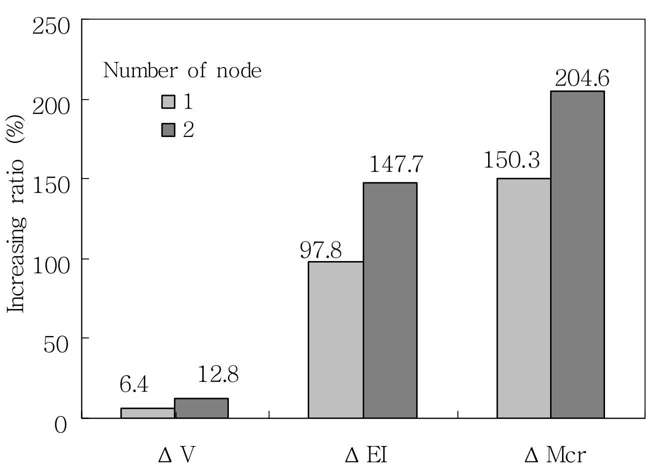

Figure 21. Improvement of bending characteristic by adding nodes.

cent). Inserting two nodes increased the volume of FRP 12.8 percent, and flexural rigidity (bending–buckling moment) by 147.7 percent (204.6 percent).

Inserting nodes to increase flexural rigidity and the bending–buckling moment is known to be markedly more effective than conventional methods such as thickening the cylindrical wall.

Increasing the number of nodes improves the bending characteristics. However, when many nodes are inserted, a thin cylinder begins to approach becoming a circular rod, and it becomes difficult to achieve both high strength and lower density.

We believe that there is an optimum flexural rigidity and bending–buckling moment for a specific weight depending on the materials, cylinder diameter, wall thickness, and node interval and thickness in a thin FRP cylinder and we will examine this in the future.

4. Conclusions

We investigated the structure of natural bamboo cylinders with nodes. We subsequently developed a thin FRP cylinder with nodes that imitated bamboo and examined the improvement in bending characteristics.

Molding a CFRP thin cylinder with nodes using the VaRTM method was also suggested. If the core has a high compression coefficient of elasticity of hard urethane foam, both acrylic nodes and CFRP thin cylinders with CFRP nodes can be molded well.

The flexural rigidity and bending–buckling moment of a thin FRP cylinder can be improved more than just by inserting nodes. Nodes can be effectively utilized to develop lightweight thin FRP cylinders with high strength.

Acknowledgements

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