Development of a Simple Molding Method for Continuous Fiber Reinforcement FRP in Shapes with Highly Curved Corners

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Abstract
Portable devices are among the products made from fiber-reinforced plastic (FRP), which is characterized by high strength and low weight. The molding method for small devices involves use of flat sheets, but use of such methods for structures with highly curved corners, for example portable devices with right angles, either results in wrinkles or requires that the FRP be cut into pieces, introducing discontinuities where failure is more likely to occur. This issue results when structures with highly curved corners are made using flat fabric, and it can be solved by creating a three-dimensional fabric. This study proposes a new method for manufacturing three-dimensional fabric to cover highly curved corners and edges. The authors also carried out a four-point bending test of the edge portion of such fabric based on the method described in ASTM D 6435. The result is a new molding method for three-dimensional fabric FRP that promises to play a more useful role than conventional molding processes in manufacturing future portable devices.

Key Words: FRP, 3D fabric, High curvature, Portable device, L-shaped specimen, 4-point bending test

1. Introduction

Continuous fiber-reinforced plastic (FRP), a material that combines continuous reinforcing fibers with a matrix, is used in a broad array of fields due to its excellent specific strength and specific modulus. A particularly common use of FRP is to reduce the weight of structures and portable devices. At the same time, the poor formativeness of FRP when used to fabricate three-dimensional shape structures has been widely acknowledged. To date, FRP molding methods involve layering flat fabric or unidirectionally reinforced material woven at a textile plant, impregnating the material with resin, and then curing it. Consequently, although FRP’s high specific strength can be achieved on the planes of flat structures, wrinkles such as those shown in Fig. 1 occur when the material is used to fabricate structures with sharply curved surfaces, which it is not possible to cover with high-strength continuous fiber. Due to the inability to arrange the reinforcing fibers based on the stress distribution, it is not possible to take full advantage of the material’s excellent mechanical characteristics.

In an investigation of formativeness and three-dimensional shape structures, Shinohara utilized the special shear characteristics of fabric to propose a method for wrapping complex surfaces and verified its effectiveness in tests using clothing. Robertson applied a wrapping method that applied the shear characteristics of fabric to FRP and conducted a detailed study of topics such as shear angle distribution and boundaries with regard to curved surfaces. However, the method did not allow for arranging reinforcing fibers based on the stress distribution, making it difficult to apply it to structural materials. Recently, experimenters have attempted to apply an approach known as the deep drawing method, which is used in fabricating metal materials, to fabrics and knit composite materials. Yoneyama and Hineno used deep drafting of fabric to propose a method for wrapping complex surfaces and verified its effectiveness in tests using clothing. Robertson applied a wrapping method that applied the shear characteristics of fabric to FRP and conducted a detailed study of topics such as shear angle distribution and boundaries with regard to curved surfaces. However, the method did not allow for arranging reinforcing fibers based on the stress distribution, making it difficult to apply it to structural materials.
to prototype a highly practical complex structure, while Zako[8] and Takano[9] carried out a deep drawing molding simulation for FRP. Although FRP deep drawing is a highly practical molding method, it cannot be applied to highly curved structures, and it was not possible to take the mechanical characteristics of the structures into account. Consequently, methods such as applying flat sheets of FRP with adhesive to form box-shaped bodies are used in practice. However, because the fibers are non-continuous at corners and edges, with the result that only the strength of the resin remains in those areas, the method is unable to deliver the strength that composite materials promise. In some cases, structures incorporate more rounded features to avoid wrinkling, but waste occurs due to the inability to arrange the material in a gapless manner. These issues arise due to attempts to align conventional flat fabric with the underlying structure.

Based on their belief that FRP with continuous fibers can be fabricated without wrinkles at corners by creating a fabric that fits the shape of the target structure, rather than by forcing it to accommodate the structure, the authors propose a method for creating three-dimensional fabric that can be used to cover corners and edges with continuous fibers while fitting around a structure with highly curved corners such as a portable device. They built a prototype machine to manufacture this fabric, molded a structure with highly curved corners, evaluated its mechanical characteristics, and verified the superior strength of the proposed structure.

2. Method for fabricating three-dimensional fabric

The authors propose the layered winding method as a technique for producing a new type of fabric that fits around structures with highly curved corners by covering its corners and edges with continuous fibers in a wrinkle-free manner. Fig. 2 (unidirectional fiber sheet) and Fig. 3 (fabric) illustrate the production process.

The following steps are performed using high-strength, crimp-free unidirectional fiber sheets provided by a fiber manufacturer:

1. Align the unidirectional fiber sheet shown in Fig. 2(a) with the mold. Sandwich and restrain both ends of the fiber sheet with restraining plates.
2. Move the plates to bend the unidirectional fibers around the mold to cover it (Fig. 2(b)). Similarly, place unidirectional fiber sheets in other orientations and bend them to cover the mold (Fig. 2(c)(d)).
3. Wrap the mold in filament fiber while moving it up and down (Fig. 2(e)).
4. Repeat Steps (1) through (3) to create several layers. Fig. 2(f) provides a cross-sectional view of the completed three-dimensional fabric.

Somewhat complex shapes can be produced using fabric sheets provided by fiber manufacturers, as described below:

1. Draw the warp and weft of the fabric being folded (the gray portion) as shown in Fig. 3(a) so as to create the configuration shown in Fig. 3(b). Use the result as a reinforcing material sheet (prepare multiple sheets).
2. Align the fabric portion with the surface of the mold. Sandwich
and restrain both ends of the fiber sheet with restraining plates.
(3) Move the plates to bend the fabric around the mold to cover it
(Fig. 3[c]).
(4) Wrap the mold in filament fiber while moving it up and down
(Fig. 3[d]).
(5) Repeat Steps (1) through (3) to create several layers. Fig. 3(e)
provides a cross-sectional view of the completed 3D fabric.

The authors built a prototype layering and winding machine to
produce three-dimensional fabric. The device borrows its tensioner
structure and feed mechanism from the filament winding method
and adds a mechanism for bending fibers and grabbing the fibers
that will be affixed to the side (Fig. 4 provides an overview). Simple
in construction, the machine is capable of producing a sample
measuring 100 × 100 mm in about 4 minutes.

3. Material composition of test samples and FRP molding

The authors created a three-dimensional FRP structure with
highly curved corners requiring a fairly complex fabrication
procedure out of fabric using the proposed molding method
and machine. The glass fiber fabric (WFA230-100BS6, from
Nitto Boseki Co., Ltd.) had a weight per unit area of 328 g/m², a
thickness of 0.33 mm, and a warp and weft density of 19/25 mm.
The glass fiber filament (RS440 RR-520, from Nitto Boseki Co.,
Ltd.) used for the winding step had a count of 4400 g/1000 m. To
improve the adhesion of resin to these two types of glass fibers, the
fibers were cleaned in an acetone solution (from Junsei Chemical
Co., Ltd.) to remove oil and dirt from their surface. The surface of
the fiber was then treated with silica coupling (KBM402, Shin-Etsu
Chemical Co., Ltd.). Epoxy resin (DENATITE XNR 6815, from
Nagase ChemteX Corporation) and curing agent (DENATITE XNH
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4. Four-point bending test and evaluation of the structure’s mechanical characteristics

The mechanical characteristics of a three-dimensional structure with highly curved corners should be evaluated at the point of peak curvature, but no test method exists to do so. Based on a belief that highly curved corners such as those shown in Fig. 7 combine three edges and that the mechanical characteristics of the edges are reflected in the characteristics of the corners, the authors carried out bending tests of L-shaped samples in accordance with the 4-point bending test evaluation method set forth in ASTM D 6435. Fig. 8 provides an overview of those tests. Anticipating application of the method to the enclosure of a conventional mobile phone, the test uses a sample thickness \((h)\) of about 2 mm, a width \((b)\) of 15 mm, a fulcrum-to-fulcrum distance \((L)\) of 45 mm, and an indenter-to-indenter distance \((l)\) of 15 mm. An autograph from Shimadzu Corp. (AG20kN, load cell: 200 KN) was used with the load point moving at a speed of 2 mm/min. The load \((F)\) obtained from the 4-point bending test was used to calculate the bending moment \(M\) and the maximum bending stress \(\sigma\) via Equations 1 and 2:

\[
M = \frac{L - l}{2} \cdot \frac{F}{2}
\]

\[
\sigma = \frac{6M}{bh^2}
\]

5. Mechanical characteristics of highly curved corners

Bending testing of L-shaped samples was utilized as a means of measuring the mechanical characteristics of highly curved corners. The three-dimensional FRP with highly curved corners fabricated in Section 3 was cut into five L-shaped samples for each of the types shown in Fig. 9(a) (“3D FRP”). Another set of L-shaped samples was created by molding three-dimensional FRP with highly curved corners after the surface of the fibers was treated with silica coupling (KBM402) (“3D FRP M”). For comparison purposes, a
GFRP plate with a thickness of 2 mm was molded using glass fiber fabric (WFA230-100BS6, from Nitto Boseki Co., Ltd.) and Epoxy resin (DENATITE XNR 6815, from Nagase ChemteX Corporation) and the VaRTM method. The fiber content percentage was about the same as for the three-dimensional structure FRP with highly curved corners. The plate was then cut to prepare samples for a flat 3-point bending test. The result (“Plate FRP”) is shown in Fig. 9(b). The cut GFRP was also applied using epoxy resin (DENATITE XNR 6815, from Nagase ChemteX Corporation) to prepare L-shaped samples (“Bonded FRP”) as shown in Fig. 9(d). The 2 mm thick resin case fabricated using epoxy resin (DENATITE XNR 6815, from Nagase ChemteX Corporation) was sliced into L-shaped samples (“Ep”), shown in Fig. 9(c). Five samples of each type were prepared.

Fig. 10 provides an example relationship diagram depicting the maximum bending stress as calculated from the load measured during the bending tests using Equation 2 and the indenter stroke. The sample is 3D FRP. The curve resembles the bending test curve for standard GFRP sheet, and the maximum bending stress at the fracture point was used as each sample’s bending strength.

Fig. 11 summarizes each sample’s bending strength. The samples to which GFRP sheet was applied using epoxy resin exhibited about the same bending strength as the L-shaped samples cut from the epoxy resin case. The corners were formed out of resin and in all cases fractured under complex stress conditions. The material exhibited about the same bending strength and failed to yield the performance of high-strength GFRP.

The three-dimensional FRP samples with corners covered by continuous fibers exhibited significantly greater bending strength than the Ep and bonded FRP samples (2.14 times greater). The material fractured at the corners between layers rather than at the surface of the FRP (Fig. 12). These results indicate that, as pointed out by Guillaume[10], Makiuchi[11], and Suemasu[12], bending an L-shaped sample with a given amount of curvature imposes not only high bending stress on both faces of the sheet, but also high tensile stress (out-of-plane stress) between layers. Inter-layer tensile stress peaks about two-thirds of the way in from the outer
edge of the L-shaped sample and varies inversely with the radius of curvature. It is estimated that the three-dimensional FRP samples with high curvature fractured due to the high level of this inter-layer tensile stress.

Consequently, the authors attempted to improve inter-layer adhesive force by surface-treating the material with glass fiber using silica coupling as described in Section 3. Following this treatment, the samples (“3D FRP M”) exhibited higher bending strength than both the bonded FRP (4.03 times greater) and the 3D FRP (1.9 times greater). However, the samples continued to exhibit inter-layer fractures at the corners and yielded bending strength that was 70% that of the GFRP sheet. The authors believe it is necessary to incorporate a material such as reinforcing fibers between the layers.

6. Summary

The authors propose a method for fabricating three-dimensional fabric that can follow the shape of structures with highly curved corners and cover the corners and edges of such structures with continuous fibers.

1. The authors built a simple machine for fabricating this new fabric using the proposed method and used it to fabricate three-dimensional fabric.
2. The authors formed a three-dimensional FRP structure with highly curved corners and used bending tests of L-shaped samples to evaluate its mechanical characteristics.
3. The proposed structure exhibited high bending strength than the currently practical structure (Bond FRP), confirming the effectiveness of the method.