https://doi.org/10.20965/ijat.2019.p0301

Paper:

Development of Press Molding Preform Design and Fabrication Method with Unfolded Diagram for CFRP

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[Received April 10, 2018; accepted October 15, 2018]

In this study, a novel design and fabrication method that corresponds to simple and optimized press molding for carbon fiber reinforced plastics (CFRP) is proposed based on CAD data. Specifically, in recent years, CFRP has been widely used for weight reduction of transportation equipment. However, optimization of the production process is required to expand the range of applications of CFRP. To satisfy the aforementioned requirements, this study focused on the press molding technique. It was assumed that partial excessive or partial breakage of the fiber occurs due to the drawing of the fiber by the deformation force. A design and fabrication method was proposed for CFRP preform that exhibits the unfolded diagram shape of an objective three-dimensional (3D) model by using a tow prepreg as a solution for the aforementioned problems. A calculation method to generate the unfolded diagram was also proposed. Furthermore, the validity of the unfolded diagram was confirmed by reproducing the diagram for a 3D shape.

Keywords: CFRP, press molding, preform, CAD/CAM, papercraft

1. Introduction

In the study, a novel design and fabrication method of preform material that enables easy design fiber orientation and simplification of the manufacturing process of carbon fiber reinforced plastics (CFRP) is proposed.

Specifically, CFRP is recently used in a widespread manner as a high specific strength material for weight reduction of transportation equipment. Conversely, there is a paucity of adoption examples with the exception of the aeronautics industry and high-performance vehicles. In order to expand their range of applications, several short-cycle time processes, such as RTM and press molding, are developed [1]. The RTM corresponds to a three-dimensional (3D) preform composed of dry fabric or semi-impregnated material that is placed in the mold, and the 3D preform is impregnated with fast curable resin and cured.

In the case of press molding method, woven materials or prepreg are used because the movement of fibers is restricted by the fabric structure and the resin, and local buckling or breakage of the fibers occurs due to the deformation force via the molding process [2–4].

In order to prevent the phenomenon, pre-formed materials termed as 3D preform (that exhibit an objective 3D shape) are used in the RTM. In several cases, the preforming includes a handwork process, and the shape of the cut fabric utilized for preforming is finally dependent on the present experience and skills of workers. A designed fiber orientation is necessary to achieve high specific strength and the physical properties of fiber-reinforced materials. Specifically, CFRP exhibits fiber reinforced resin structure and anisotropic physical properties because most of the tensile strength relies on the fibers. Most CFRP products, such as the 3D preforms described earlier, exhibit shell shapes, and the laminated fabrics are prepared via cutting and deforming to conform to the objective shape. The shell shapes are composed of sheet-like materials, and thus each formed fabric layer exhibits a shape like an unfolded diagram (developed view) of objective shape (although not precisely a developable surface). In order to unfold the shell shape to a flat surface, it is necessary to cut a part of the shape to the approximated developable surface.

The developable surface is a smooth surface with zero Gaussian curvature. Therefore, with respect to the free-form surface, it is difficult to maintain the continuity of the fibers in the same laminated layer of CFRP, and specifically to prepare an unfolded diagram based on the experience and skills of workers.

Methods of fiber placement by using robots are developed and include auto tape laying (ATL) and auto fiber placement (AFP) as methods for arranging continuous fibers in the designed orientation on a curved surface. The ATL is a fiber placement method that uses multi-axis robots and placement of the tape on the curved surface mold with fiber placement head that maintains the perpendicular angle to the free curved surface. The AFP is similar to ATL. However, when compared with ATL the AFP uses a narrower tape, and the target shape is more complicated. The aforementioned methods are mainly used in the aeronautics industry.

Studies on optimization of the rigidity of CFRP plates based on the curvilinear trajectory of fibers, such as variable angle tow (VAT) [5–8] and fiber placement, by using an embroidery machine [9] have been conducted as an application thereof. Specifically, VAT is an advanced application of ATL and AFP, and it is a method of placing fibers in a curved trajectory.

The methods and filament winding (FW) are used to manufacture fuselages and aircraft wings. The FW is a method of winding a fiber bundle around a mold and laminating fibers. However, the aforementioned methods require a very large molding apparatus including an ATL/AFP facility, autoclave, and a long molding time, and thus they are inevitably expensive. Furthermore, they can only deal with rotationally symmetrical shapes such as pressure vessels.

The methods are used for CFRP with thermosetting resins. Currently, studies on CFRP examine the use of a thermoplastic resin that can be molded by a straightforward technique and short cycle. When compared with thermosetting CFRP, the thermoplastic resin CFRP is inferior in terms of heat resistance. Additionally, the thermoplastic resin exhibits high viscosity at the time of impregnation into fabrics and low affinity with the fiber. Hence, thermoplastic CFRP is inferior to thermosetting CFRP in terms of strength. The thermoplastic CFRP can be molded by vacuum molding or hot pressing via a method similar to that for an unreinforced resin plate. Given the utilizing discontinuous fiber, injection molding and 3D printing of CFRP are realized. Given the invention of thermoplastic epoxy resin, the strength of thermoplastic CFRP is improved on an annual basis. Given these circumstances, attention to thermoplastic CFRP is increasing in recent years. A long curing time is not required, and the post-formation process is possible. Thus, molding cycle time is short, and studies on molding are performed [10].

As mentioned above, the current molding method of composite materials exhibits a trade-off relationship between the degree of freedom and cost of designing fiber orientation. The objective of the study involves developing a new molding method by using 2D preform for press molding / the RTM with the use of CAD/CAM and papercraft technique, and this can realize the design and fabrication of CFRP parts with a high degree of freedom in fiber orientation. An arbitrary fiber orientation, such as the ATL, can be obtained even in press molding or the RTM by separating the fiber placement process and molding process.

The two-dimensional (2D) preform proposed in this study is a 2D sheet with fiber oriented based on the unfolded diagram of the objective shape. With respect to the application of the unfolded diagram, it is possible to arbitrarily arrange the discontinuous portions of the fibers in each of the laminated layers, and easy design with the sufficient rigidity of the molded parts is realized. The 2D preform is designed by using CAD/CAM and the technique that is used for papercraft. In the method, the shape defined by CAD is converted to a polygon mesh with polygon vertices of the arbitrary array using CAM, and the unfolded diagram is then generated via real-length unfolding to the flat surface.

In the study, a method to generate an unfolded diagram that is used to fabricate a preform is reported.

2. Outline of the Molding Method

In the study, a method to generate an unfolded diagram by considering the continuity of fibers is developed. The molding procedure proposed in the method is as follows.

1. Generate the unfolded diagrams of the objective shape with multiple cutting line orientations based on CAD data.

2. Place fibers or cut prepregs that conform to the unfolded diagram.

3. Laminate and mold all 2D preforms.

The molding method that utilizes the 2D preform via the unfolded diagram is applicable to multiple materials such as thermoplastic woven fabric prepregs, thermosetting unidirectional prepregs, tow prepregs, and dry woven fabrics for the RTM. A thermoplastic prepreg is a single layer of woven fabric with impregnated thermoplastic resin that exhibits elastic bending deformation capability. The 2D preform is easily produced by cutting the material conforming to the unfolded diagram via cutting plotters or the fiber placement devices. It is possible to achieve sufficient rigidity of the molded article even on a free-form surface by laminating the preforms with multiple different cutting line orientations. Fabrication of 3D preforms used for the RTM enables the efficient manufacture of the preform by an automated method that does not rely on the experience and skills of workers realized via the application of the unfolded diagram for cutting the dry fabric.

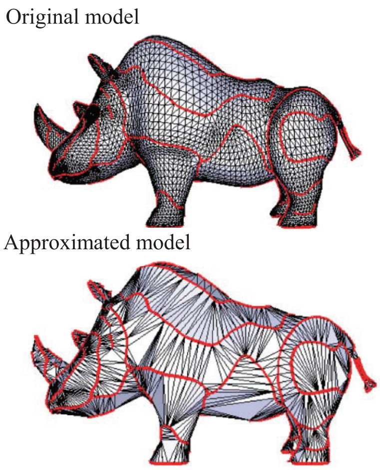
A forming experiment by using thermosetting tow prepreg is planned as the first application of the unfolded diagram. The thermosetting tow prepreg is a fiber bundle-like material impregnated with a thermosetting resin that is mainly used for filament winding (FW). Tailored 2D preforms are manufactured by placing the tow prepreg by using the VAT to conform to the unfolded diagram. The fiber trajectory on the 2D preform is curvilinear, and thus the fibers are placed by using the VAT.

Furthermore, the utilization of the unfolded diagram enables the application of optimization methods of fiber trajectory that deal with fiber placement on the flat surface (e.g., continuous tow shearing (CTS)).

3. Unfolding Method

3.1. Conventional Unfolding Method

There are several methods for unfolding the surface of the free-form surface to the flat surface. These methods are divided into two types, namely those using polygons and others. Specifically, the method without using polygons is based on curvature line, and this is used for



Source: ACM Trans. Graph., Vol.23, No.3, pp. 259-263, 2004 [13].

Fig. 1. Approximation to the strip-shape developable surface.

the free-form surface of the outer shell of the ships and is studied as a means of molding the free-form surface of CFRP. The method can reproduce a free-form surface with high precision by utilizing a mathematically orthogonal pair of curves termed as the maximum curvature line and the minimum curvature line [11]. However, the width of parted shapes and the direction of the parting line depend on the curvature distribution of the curved surface, and thus it is not suitable for the applications in the present study.

The typical applications of unfolding by using polygons involve generation of the texture atlas and drawings for papercraft. In the method, the original shape is converted to a low-polygon model and the shape around the edge line of the polygon is unfolded as an axis. However, the shape defined by CAD consists of a parametric surface, and conversion is necessary to approximate the surface to the developable surface. Additionally, the conversion to low polygon model is irreversible from the original shape [12]. Fiber placing in an arbitrary trajectory while maintaining fiber continuity is challenging because the trajectory of parting lines depends on the array of the edges of polygons.

With respect to the reproduction of free-form surfaces in papercrafts, studies on unfolding by using an approximation to strip-like developable surfaces were conducted by Mitani et al. [13, 14] and Massarwi et al. [15]. As shown in **Fig. 1** [13], in the method, a curved surface is divided into a strip-shaped surface, and the divided surface is approximated to the developable surface. The feature of the method is that it exhibits an unfolded diagram approximated to a strip shape, and this acts as an advantage that guarantees fiber continuity on the unfolded diagram.

3.2. Proposed Unfolding Method

A methodology of unfolding is that a polygon mesh with continuity of fibers is generated by using the CAM system, and approximate unfolding of the objective shape is developed.

The required features of the CAM system are given below.

- Generation of the unfolded diagram based on CAD data.
- Approximated unfolding of the free surface into the strip-based developable surface.
- Arbitrary placement of the parting line on the free surface.

As per the method proposed by Mitani et al., the original curved surface is approximated by a strip having the largest possible width given the ease of assembly of the unfolded diagram as papercraft. A significant feature of the method corresponds to the non-necessity of changing the vertex position of the polygon from the original model while approximating the original model into the strip-based triangular polygons. The feature enables the conversion of the free surface into the set of the developable surface without significantly impairing the original curved surface shape.

In the proposed method, the position of the polygon vertices of the strip-based developable surfaces is acquired from CAD data by utilizing the developed CAM system. It realizes unfolded diagram generation that exhibits a relatively small shape difference between the original curved surface and surface of the assembled unfolded diagram.

As per the method proposed by Mitani et al., the trajectory of parting lines on the surface is determined by using a method of surface segmentation proposed by Lévy et al. [16] and Guskov et al. [17].

With respect to the design of fiber-reinforced materials, it is necessary to ensure that any fiber orientation can be expressed. Additionally, the width of the strip-based developable surface should be configured as identical to the width of the fiber bundle. Therefore, the strip width should be set arbitrarily.

In the proposed method, arbitrarily designed parting lines are placed on the surface of the CAD model, and the surface between adjacent parting lines is subsequently approximated to the developable surface. Therefore, reproducibility of the curved surface is limited when compared to that of the method shown above. Conversely, in the proposed method, it is possible to array the parting lines with a high degree of freedom. By using the method, the unfolding method with continuity of strip-based developable surface and arbitrarily designed parting line is realized.

As per the method proposed by Mitani et al., the requirement to divide the surface is determined via the use of surface segmentation. In the case wherein the unfolded diagram is generated to preform the fiber-reinforced material, the layout of parting lines represents the layout of the fiber bundle boundary. However, an unnecessarily complicated unfolded diagram is generated when all the boundary lines of the fiber bundle are used as parting lines. In order to compensate for the negative effect, in

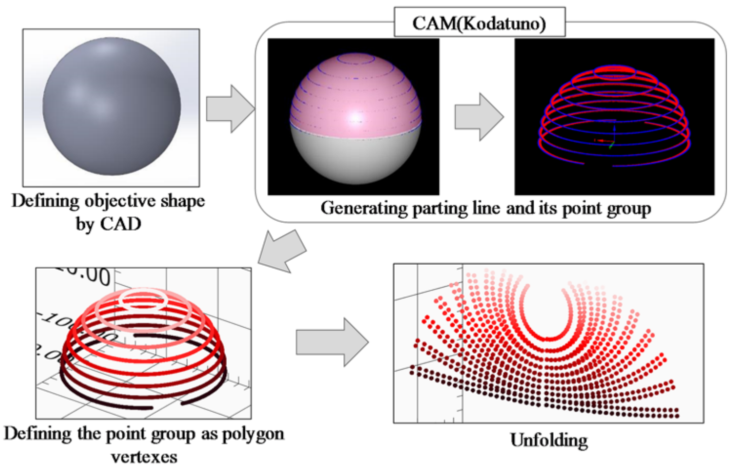


Fig. 2. Procedure of the proposed unfolding method.

the proposed method, the method used for surface segmentation in the conventional unfolding method is utilized to detect the developable surface, and the surfaces are merged onto a single surface if the developable surfaces are adjacent.

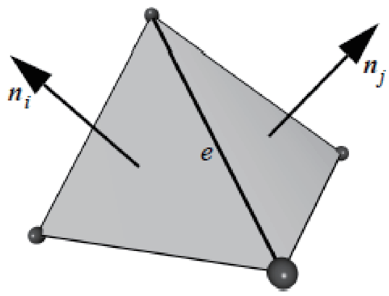
Essentially, while generating an unfolded diagram of a papercraft, the reason for converting the original model to the low polygon involves the formation of the surface of the developable surface. The developable surface is a "surface that can be flattened onto a plane without distortion" and is "a smooth surface with zero Gaussian curvature." In strict terms, developable surfaces only correspond to conical surfaces and cylindrical surfaces. Therefore, most curved surfaces are not developable surfaces. Thus, surpluses and deficiencies of fibers occur given the approximation to the developable surfaces even with respect to the proposed method.

3.3. Procedure of the Unfolding Method

The procedure of the unfolded diagram generation method proposed in the study is shown in **Fig. 2** and is as follows:

1. Define an objective shape via CAD.
2. Generate polygon mesh / parting line on the target surface by CAM.
3. Select the parting lines by surface segmentation.
4. Unfold the polygon mesh.

First, a target shape is defined by a commercial CAD. Geometric data is stored in IGES format to transfer to CAM. Subsequently, a point group is generated from the CAD model by using the proposed developed CAM. The point group corresponds to a parting line of the unfolded diagram. The point number of each parting line is equal. The point group is arranged by considering fiber orientation and fiber continuity. The most distinguishing feature of the unfolding method corresponds to a polygon vertex that is generated based on the arbitrary datum line obtained from CAD data via the CAM system. Additionally, the conventional unfolding technique of polygons is used in the method. In the study, the point group is arrayed based on contour lines as an example for ease of comprehension. A polygon mesh is then generated with the point cloud as vertexes of a polygon. The edge used as the parting lines is selected while generating the mesh. The CAM is an indigenously developed system powered by "Kodatuno" (Kodatuno is Open Developed Alternative Trajectory Utility Nucleus Object) that is an open source CAM kernel developed in Kanazawa University [18, 19].



Source: SIGGRAPH '99 Proc. of the 26th Annu. Conf. on Comput. Graph. and Interact. Tech., pp. 325-334, 1999. [17]

Fig. 3. SOD operator.

Based on the shape of the curved surface and the trajectory of the parting lines, there are cases wherein adjacent bands are approximated to a single developable surface. In the aforementioned case, the surfaces are treated as a single surface, and handling is simplified. In order to determine the necessity of the parting lines, surface segmentation utilizing the second order difference (SOD) operator as proposed by Hubeli et al. [20] and Guskov et al. [17] is used as shown in **Fig. 3**. The SOD is derived as follows [20]:

$$w(e) = \cos\left(\frac{n_i}{\|n_i\|} \cdot \frac{n_j}{\|n_j\|}\right)^{-1} \quad \dots\dots\dots \quad (1)$$

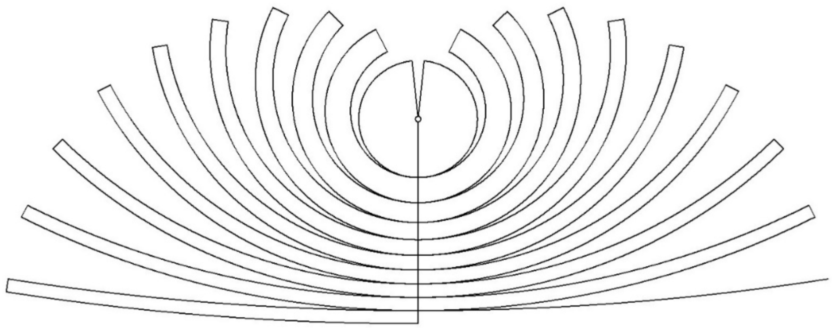


Fig. 4. Unfolded diagram of the half sphere.

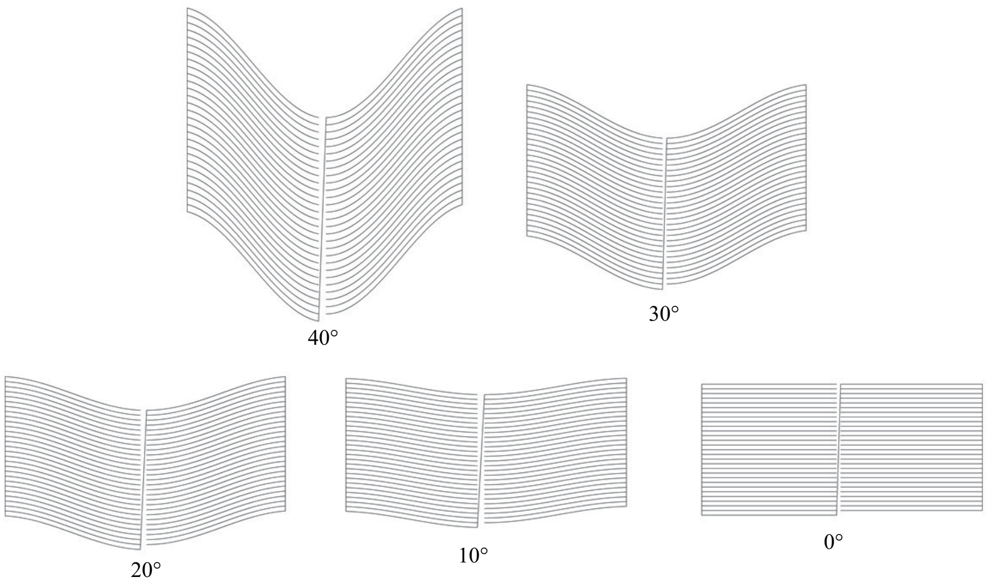


Fig. 5. Unfolded diagram of the inclined cylinder.

where n_i and n_j denote normal vectors.

In the surface segmentation used to generate the texture atlas, the shape boundary is recognized by detecting the change in the angle of the normal vectors by using the SOD.

The SOD can detect a change in the angle of the surface with respect to the width direction of the fiber bundle. For example, if the SOD is 0, the surface is a cylindrical surface or conical surface, and Gaussian curvature is 0.

In the proposed method, the SOD is utilized for the detection of the developable surface. If the SOD between the adjacent developable surfaces is 0, the surface that merges both the developable surfaces also corresponds to a developable surface. Unnecessary parting lines are omitted by using the technique.

Finally, the polygon mesh is unfolded. Polygons configured in a strip-like shape are developed by merely developing it with the edge line between adjacent polygons as its rotation axis. Therefore, it is possible to develop the same with the actual length without deforming the mesh. The development method is identical to the conventional unfolding method.

4. Confirmation of Validity

The geometric validity of the unfolded diagram is confirmed by reconstructing the unfolded diagram into a 3D shape utilizing papercraft. Examples of the unfolded diagrams of primitive shapes and reconstructed shapes are given below. **Fig. 4** shows the unfolded diagrams of the hemisphere, and **Fig. 5** shows inclined cylinders with different inclined angles corresponding to 0°, 10°, 20°, 30°, and 40°. **Fig. 6** shows the reconstruction of the shapes, and the reconstruction is verified as geometrically correct. If the ruled lines are drawn on the surface, the spherical shape can be correctly unfolded by reproducing the length of each ruled line on the plane. However, in the case of an inclined cylinder, it includes the twist of the surface within the rectangle formed by the ruled line, and thus it can be only unfolded with a triangular polygon mesh. It was confirmed that the accurate reconstruction of the shapes allows the target shape after approximation to polygon mesh to be accurately unfolded in the original edge length.

Subsequently, the validity of the unfolded diagrams

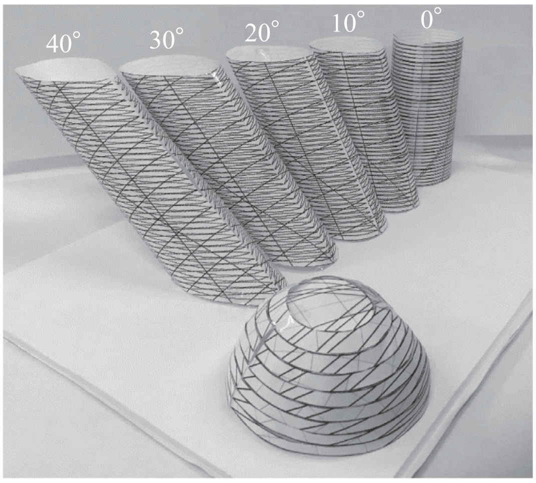


Fig. 6. Reconstructed papercraft model.

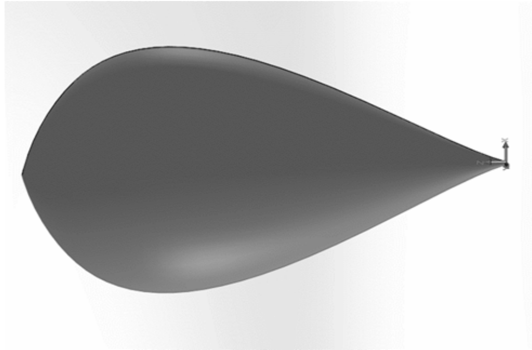


Fig. 7. Water-drop shape.

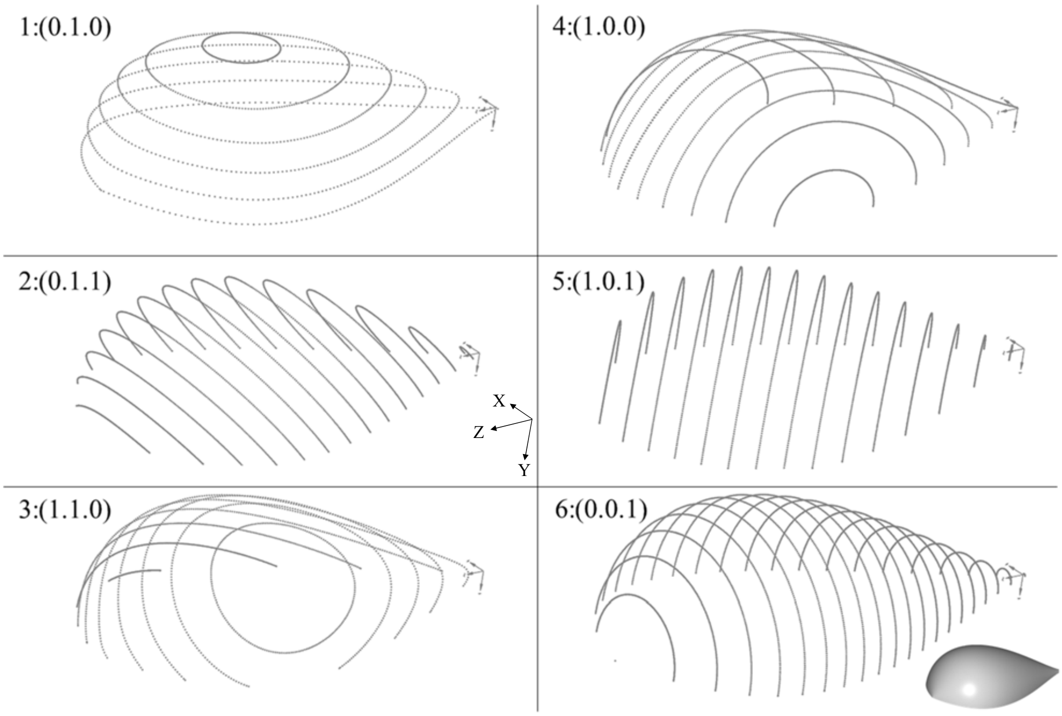


Fig. 8. Parting line array on the water-drop shape.

was verified by the same method when the same free-form surface shape is unfolded in different directions of parting lines. As shown in **Fig. 7**, the water drop shape that exhibits continuous curvature changes is used in the confirmation. The array of point group on the parting lines used for polygon mesh generation is arbitrarily determined based on fiber orientation.

However, contour lines are used for ease of understanding in the study. The orientation of the parting lines used for unfolding corresponds to contour lines with reference to a plane rotated by 45°/90° to each of the lines in **Fig. 8** showing the parting lines generated on CAD data by using CAM system.

Figure 9 shows the unfolded diagrams. **Fig. 10** shows the reconstructed shape of the diagrams.

The coordinates of **Fig. 8** show the directions of the normal vector of contour lines. The position and clearance of the unfolded diagrams are adjusted from the standpoint of viewability. The results indicate that all shapes are correctly reconstructed.

In the fabrication of the 2D preform, the unfolded diagrams should be simplified for the ease of molding. In the SOD, a threshold is set to the angle difference between the surfaces of adjacent bands. An example of omission by the SOD corresponds to an unfolded diagram of a shape with a cylindrical surface, conical surface, and spherical

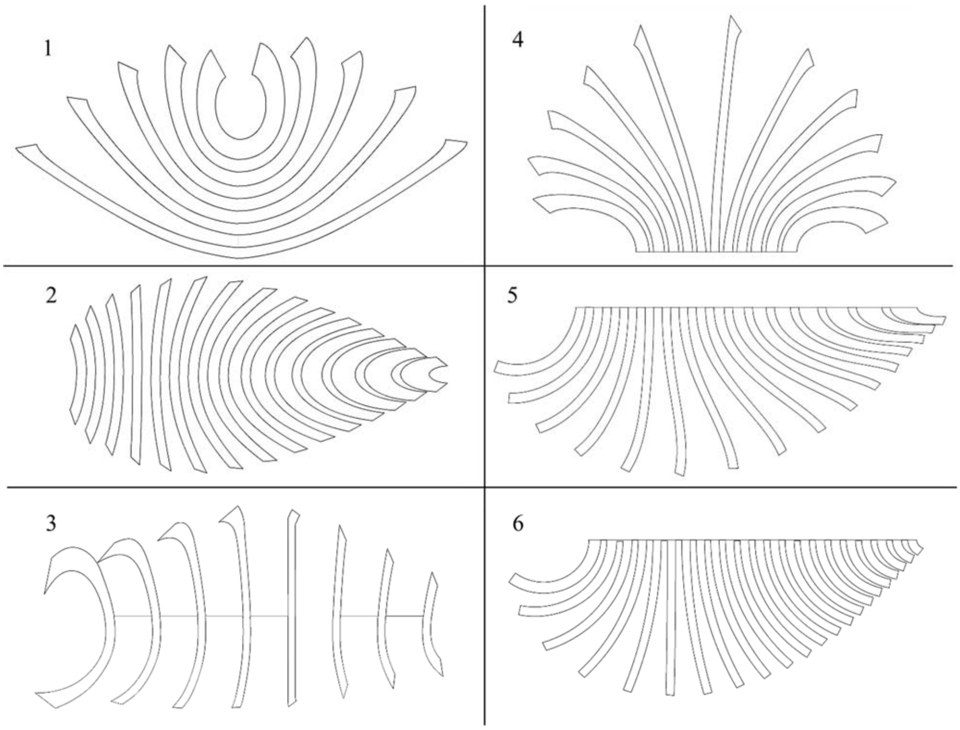


Fig. 9. Unfolded diagram of the water-drop shape.

Fig. 10. Reconstructed water-drop shape.

surface. The shape is shown in **Fig. 11**, and the unfolded diagram is shown in **Fig. 12**. The threshold of SOD is 0.15 rad. The side surface of the cylinder/cone is a developable surface, and thus bands are merged as a single surface.

5. Conclusion

In this study, a design and fabrication method for a 2D preform by using unfolded diagrams as an intermediate substrate during CFRP molding was developed. The unfolded shape of the objective shape used for the 2D preform was proposed, and software to generate an unfolded diagram from 3D CAD data was developed by using an open source CAM kernel. Additionally, the validity of the unfolded diagrams was confirmed by reconstructing the objective shape by using a papercraft.

In future, optimization of the unfolded diagram is planned by assuming the use of specific intermediate material and a molding experiment by using the 2D preform.

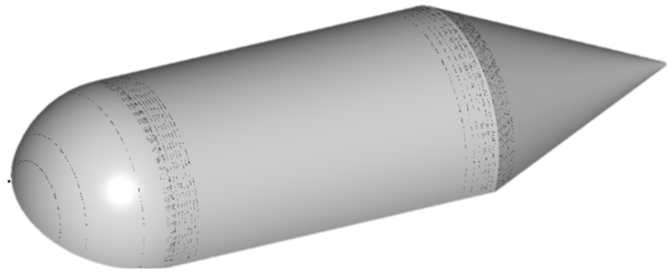


Fig. 11. Tested shape for surface segmentation by SOD.

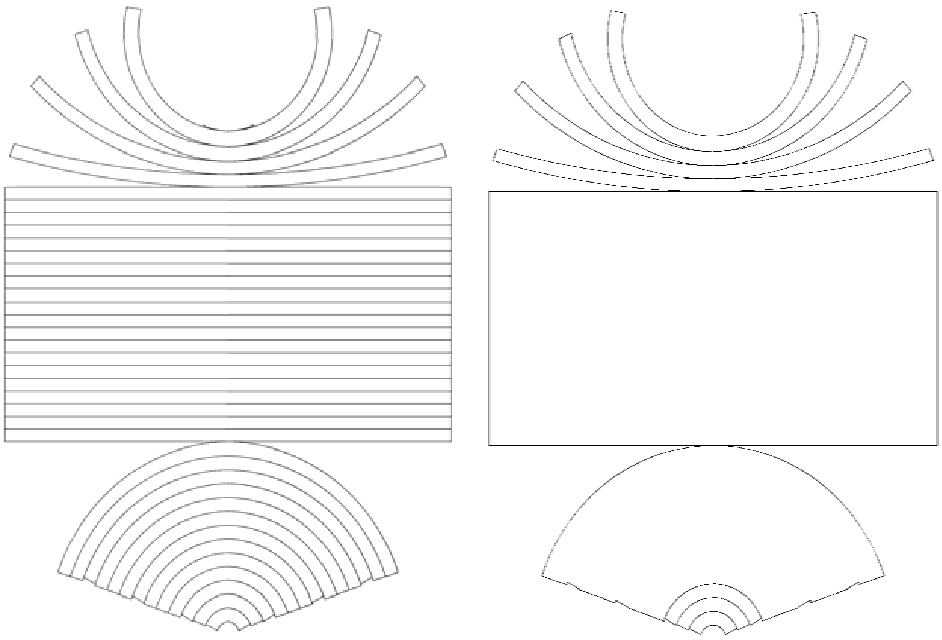


Fig. 12. Unfolded diagram using SOD.

Acknowledgements

This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in Aid for young scientist (B), 15K17948 JSPS. The authors would like to thank JXTG Nippon Oil & Energy Corporation for providing the tow prepreg.

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