J-Composites/Compression Molding Version 2.0: New Simulation Tool for CFRP Composites

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1 Abstract

Composite materials like fiber reinforced plastics (FRP) are becoming more widely used in the automotive industry and have been found very effective in reducing vehicle weight. Recently, discontinuous long carbon fiber reinforced plastics are increasingly used for lightweight structural parts with high stiffness, strength and energy absorption performance. Compression molding is considered one of the most efficient manufacturing processes to mass produce FRP parts for automotive applications. Compression molding can form discontinuous long fiber reinforced plastics into complex shapes with relatively low manufacturing cost and short process time. LST and JSOL developed new compression molding simulation techniques for discontinuous long fiber reinforced plastics using a beam-in-adaptive EFG coupling function in LS-DYNA®. Then JSOL developed a modelling tool called J-Composites®/Compression Molding to generate an input deck for this new compression molding simulation. In this paper, new functions of J-Composites/Compression Molding Version 2.0 are introduced and two compression molding simulations using hybrid lay-up composites are presented.

2 Introduction

Automotive manufacturers are considering using discontinuous long carbon fiber reinforced thermoplastics as a high strength car body material to satisfy strict crash safety performance requirements as well as for weight reduction for fuel efficiency. Compression molding has been proven to be an efficient manufacturing process and capable of forming complicated shapes in this material [1]. To predict fiber orientation, filling timing and other aspects required for compression molding, in January 2017 a new simulation technology for compression molding of discontinuous long fiber reinforced plastics was developed in LS-DYNA [2][3]. The main features of this new technology are fibers modelled by beam elements and matrix resin modelled by tetrahedral solid elements with a 3D r-adaptive re-meshing function based on an Element-Free-Galerkin (EFG) formulation.

In the first part of this paper, an overview of a modelling tool called J-Composites/Compression Molding is provided. This tool has been developed by JSOL and released worldwide [4]. This compression molding simulation needs a complex input deck consisting of fibers modelled by beam elements, matrix resin modelled by tetrahedral solid elements, 3D r-adaptive re-meshing parameters, contact definitions, resistive coupling forces and so on. This tool generates such complicated data easily.

In the second part of this paper, some new functions of the Ver.2.0 of J-Composites/Compression Molding released in March 2021 are introduced.

In the third part, two compression molding simulations with hybrid lay-up using ROS (Randomly-Oriented Strands) and CUD (Chopped Unidirectional Fiber) thermoplastic composites to form a part with single-rib geometry are presented. Here, two different shapes of matrix resin model are used; one a flat shaped model and the other a convex shaped model. The convex shaped model can be applied by a new function in Ver.2.0.

In the final part, future development plans of J-Composites/Compression Molding are presented.

3 Overview of J-Composites/Compression Molding

As shown in Fig.1, J-Composites is a set of tools that work in conjunction with LS-DYNA to facilitate the complex manufacturing processes and process-chain simulations of fiber reinforced plastic composites [5] [6]. JSOL has released the software products: “Form Modeler (FoM)”, for setting up a press forming analysis model; “Fiber Mapper (FiM)”, for mapping resin flow simulation results onto a structural mesh and “Compression Molding (CoM)”, for creating a compression molding analysis model.

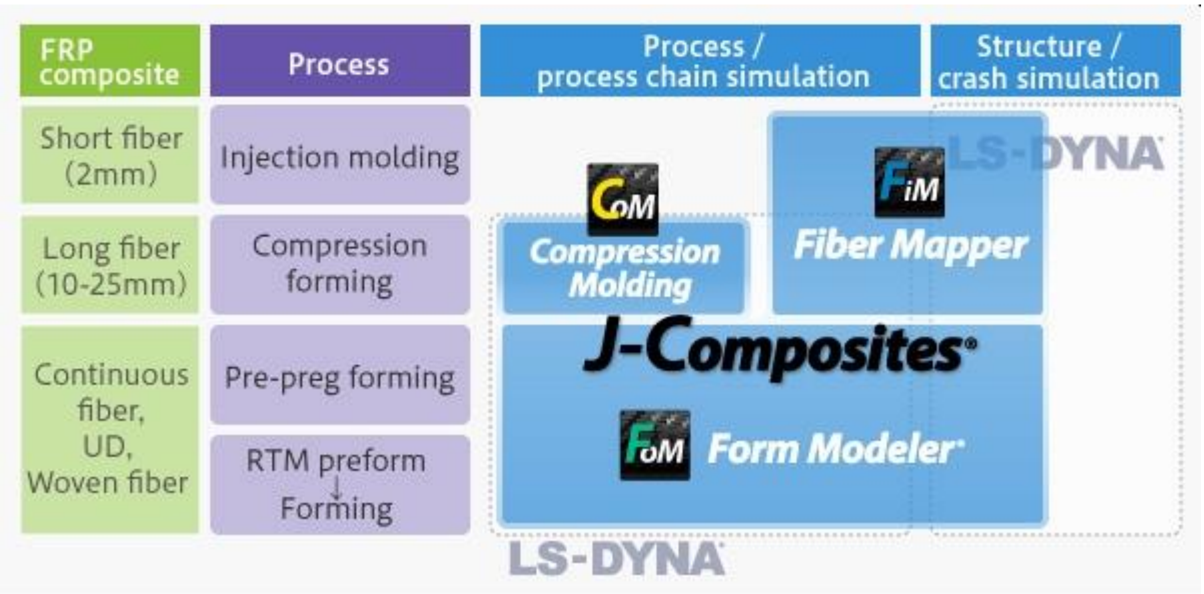

Fig.1: The set of tools in J-Composites

S. Hayashi et al. [7] have performed compression molding simulations of discontinuous long carbon fiber reinforced thermoplastics using a beam-in-solid coupling method and 3D adaptive EFG. Beam and solid elements are coupled by **`*CONSTRAINED_BEAM_IN_SOLID`** (CBIS) [8]. CBIS constrains both accelerations and velocities between beam and solid elements (constraint based method). With the option CDIR=1, coupling is applied only in the beam normal direction, thereby releasing constraint in the beam axial direction. In addition, an axial coupling force function AXFOR can be used to calculate resistive forces based on the slip between beam nodes and solid elements. In this work, resistive forces are calculated using a friction model in a proprietary user-subroutine developed by JSOL. The 3D adaptive EFG is calculated with r-adaptive remeshing capability using a 3D Element-Free-Galerkin (EFG) formulation [9]. Fig.2 shows the modelling method using the beam-in-solid coupling function and the 3D adaptive EFG function. This new function was implemented in LS-DYNA R10 [2].

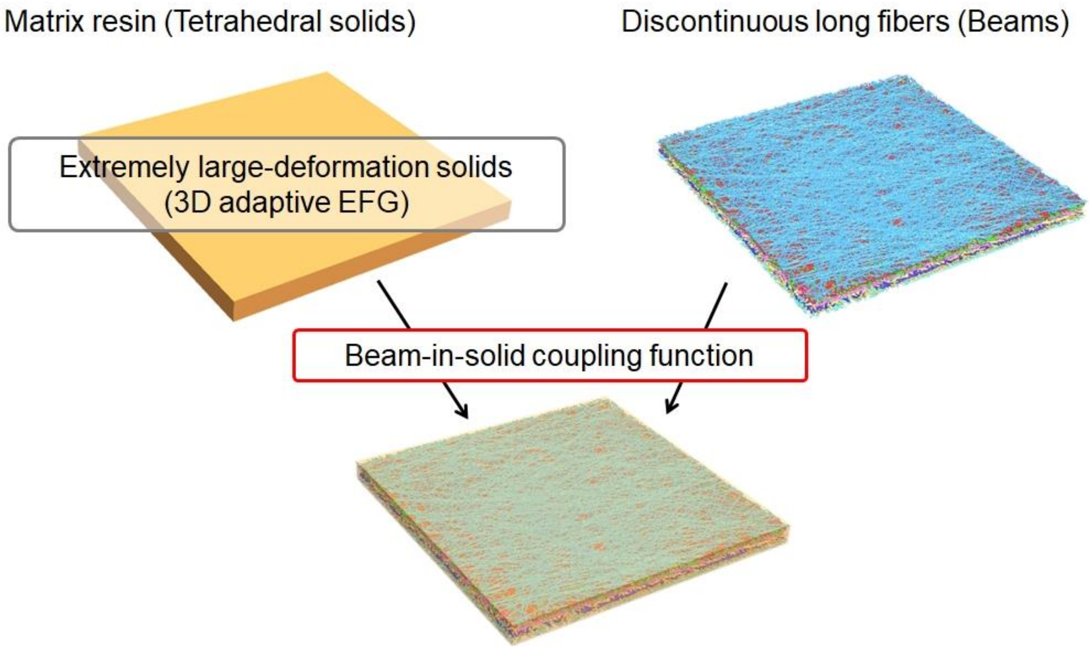

Fig.2: Matrix resin by tetrahedral solids and discontinuous long fibers modelled by beams

The compression molding simulation needs a complex input deck comprising beam elements that model fibers, tetrahedral solid elements for the matrix resin, 3D r-adaptive re-meshing parameters, contact definitions, resistive coupling forces and so on. If such data is not set up carefully and accurately the simulation result often becomes unstable. To easily generate the complex input deck JSOL has developed a simulation tool called J-Composites/Compression Molding. First, we read a template model containing a workpiece (sheet) and tools (punch and die) then input material parameters to construct the FRP composites. Next, the fiber model (beams) and matrix resin model (tetrahedral solids) are made by a mesh generator and other input parameters set up automatically. The fiber model generator developed by JSOL generates a fiber model with quasi-isotropic fiber orientation and achieves homogeneous fiber distribution [10]. Finally, a complete input deck for the compression molding simulation is output.

4 New functions of J-Composites/Compression Molding Version 2.0

4.1 New fiber orientation types

In the previous Ver.1.0, two types of 2D randomly-oriented discontinuous fiber orientations, “Randomly Oriented Fiber (ROF)” and “Randomly Oriented Strand (ROS)” were supported [4]. In the new Ver.2.0, new types of orthotropic fiber orientation types, “Unidirectional Fiber (UD)“ and “Chopped Unidirectional Fiber (CUD)“ are added. The UD type is categorized as a continuous fiber orientation composite and has the big advantage of high strength. However it does not readily deform into complex shapes like ribs because of the continuous fibers. Therefore, when UD layers are used in a composite part, careful consideration is needed to deform it into the final molded shape. On the other hand, the CUD type is made by chopping continuous fibers of a UD composite so it is categorized as a discontinuous fiber composite. Therefore it has as the same high formability as the ROS and ROF types which can deform to complex shapes. Fig.3 shows each input panel to define UD and CUD types. Input parameters to generate the UD type are “Beam Length” and “Fiber Spacing“. For the CUD type, “Fiber Length”, “Cut Angle“, “Gap Length“, “Beams per Fiber“ and “Fiber Spacing“ are input.

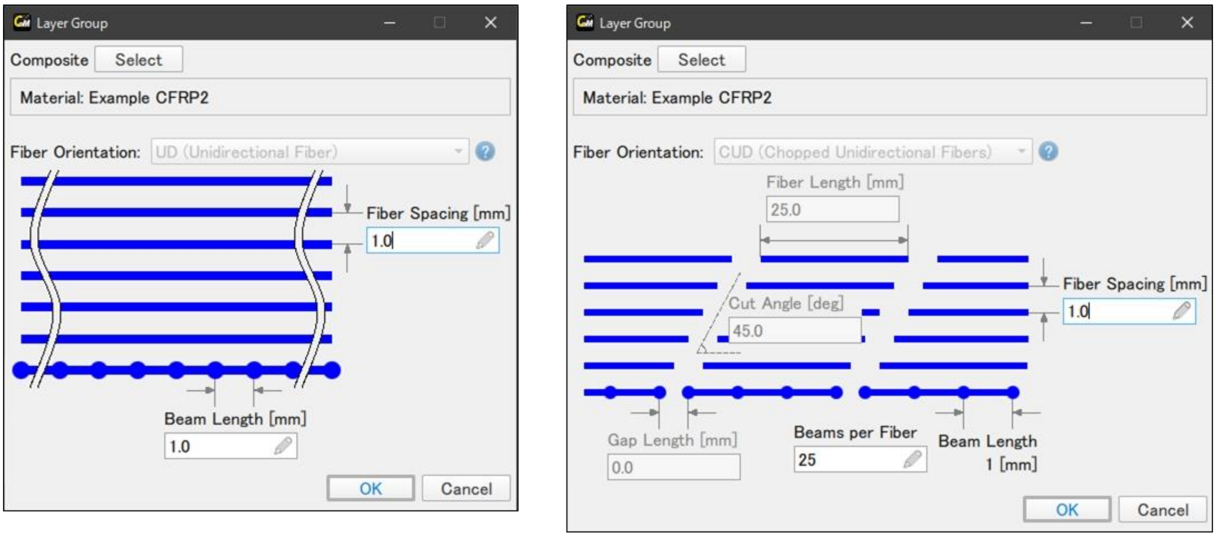

Fig.3: Input panels to define UD (left) and CUD (right)

For the UD and CUD composites, fiber orientation angles have to be defined on each layer and are often described by the layer pattern description method. For example, the layer pattern, “0/45/90/135“ consists of a total of four layers, 0, 45, 90 and 135 (equal to -45) degree angles such that the composite has a quasi-isotropic property. Fig.4 shows the menu to input layer patterns. This standard description method for layer patterns like “0/45/90/135“ can be entered directly into the tool.

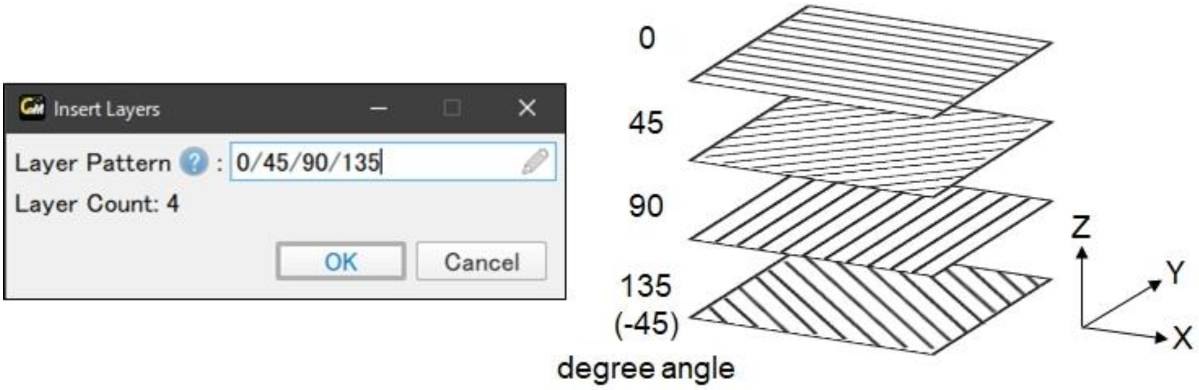

Fig.4: Input panel to enter layer pattern

4.2 Hybrid lay-up composites consisting of different fiber orientation type layers

In Ver.2.0, hybrid lay-up composites are supported to have a different fiber orientation type for each layer. Fig.5 shows an example of a hybrid lay-up composite of ROS and CUD types. This composite has a total of eight layers. The upper four layers consist of ROS composite and the lower four layers CUD composite with layer pattern "0/45/90/135". The same matrix resin material data has to be used for all layers, which is one condition of hybrid lay-up composites.

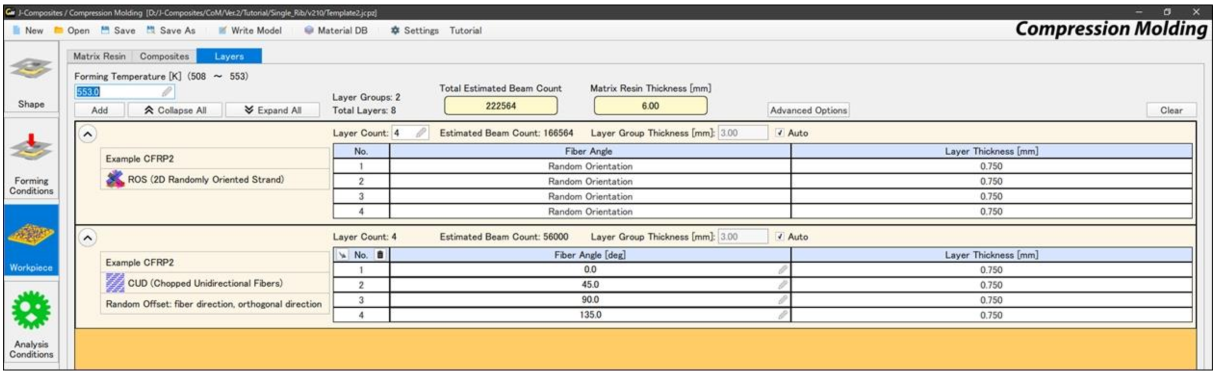

Fig.5: Operation panel to create lay-up composites

Fig.6 shows the fiber model generated from the above hybrid lay-up. CoM automatically defined different part IDs for each strand and chopped fiber to see easily how they are moved during the simulation.

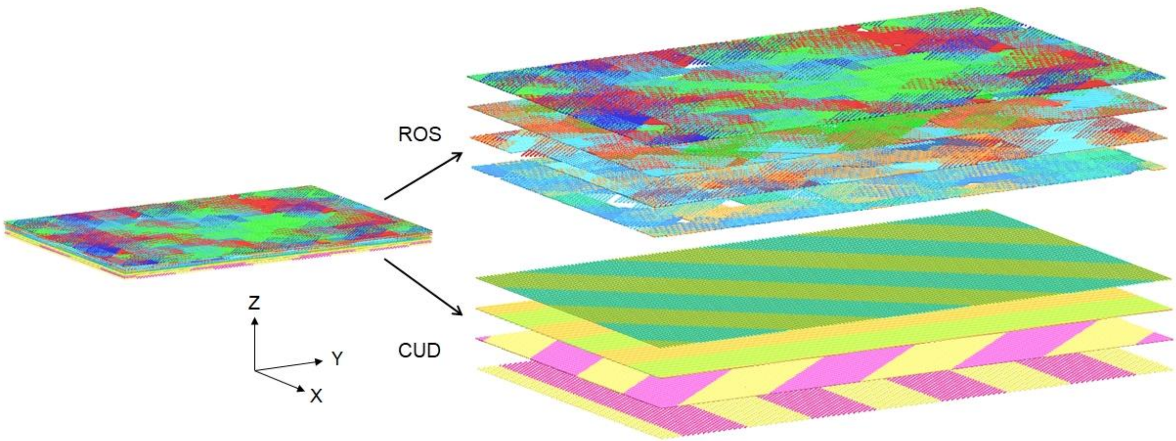

Fig.6: Hybrid lay-up fiber model: upper layers ROS type and lower layers CUD type

4.3 More complex matrix resin geometries of arbitrary shape

Ver.1.0 supported only rectangular and cylindrical geometries. In Ver.2.0, arbitrary geometries including convex shapes can be input.

As shown in Fig.7, when a matrix resin model of arbitrary shape is input to CoM as shell elements, tetrahedral solid elements with a constant thickness are generated.

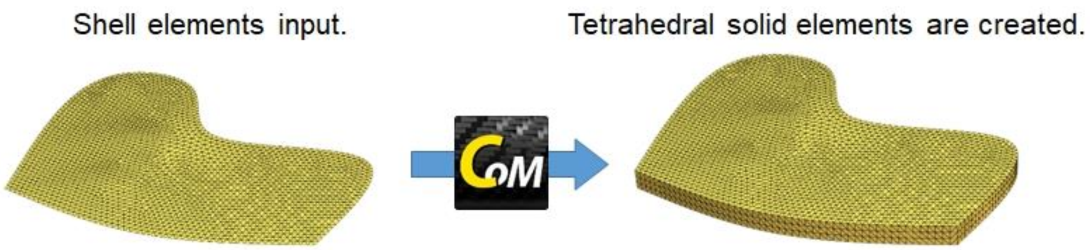

Fig.7: Matrix resin sheet with arbitrary shape (constant thickness)

As shown in Fig.8, when a matrix resin model using tetrahedral solid elements is input, the original elements are used as is. CoM automatically detects the thickness of the matrix resin model including a convex shape and generates a fiber model filling inside it. In this case, if the matrix resin element mesh size is uneven, the simulation often becomes unstable and terminates with an error. Therefore, the matrix resin model has to be meshed carefully. In a future version, an auto-meshing function to make a matrix resin model including a convex shape will be implemented. This function will create optimized tetrahedral solid elements for stable calculations.

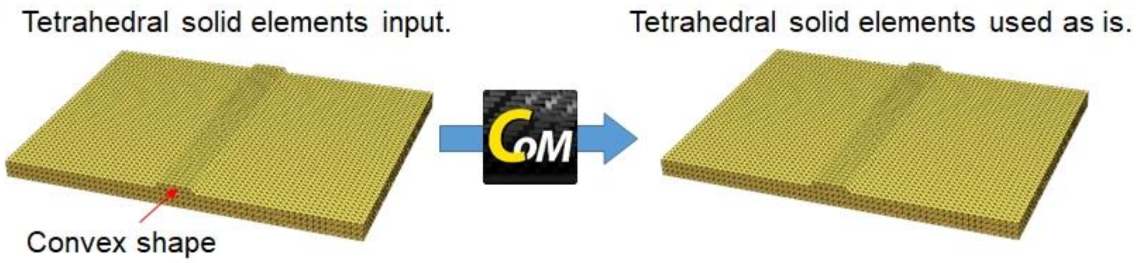

Fig.8: Matrix resin sheet with convex shape

4.4 New commercial CFRP material data in Material Database

In Ver.2.0, the commercial ROS thermoplastic composite sheet Flexcarbon® [11] developed by Suncorona Oda Co., Ltd. has been added to the Material Database. CoM users can access this material data free of charge. Each strand is made up of carbon fiber / thermoplastic epoxy resin, 25mm long and 12mm wide. Macroscopic mechanical properties of composite materials are often measured using squeeze flow tests [12]. Squeeze flow tests of Flexcarbon were performed by The Innovative Composite Center (ICC) at Kanazawa Institute of Technology in Japan. The material input data was developed from squeeze flow test results by reverse engineering. Fig.9 shows contact forces from squeeze flow tests at three different deformation velocities, 0.1, 1 and 10 mm/sec. Each test was conducted at a temperature of 200 degrees Celsius inside a high temperature chamber. The LS-DYNA results show good agreement to the tests.

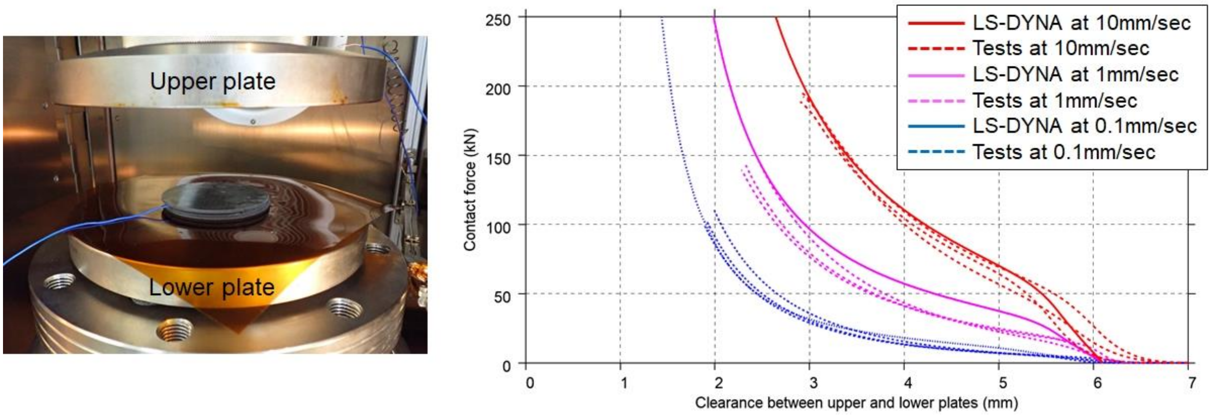

Fig.9: Squeeze flow test results of LS-DYNA and tests

4.5 Upgraded contact definitions for more stable calculation

During the development of Ver.2.0 many investigation simulations were performed to refine the modelling methods to make compression molding simulation more stable and accurate. In the investigations it was found that the friction coefficient between the matrix resin and tools has a large influence on the accuracy and stability of the simulation. As a result of the investigations, a friction coefficient of 0.01 to 0.03 is recommended as this represents the lubricant applied to tools before the real compression molding process. In accordance with that, the default friction coefficient in Ver.2.0 was changed to 0.03. Furthermore, if an instability problem occurs, a lower friction coefficient 0.01 is recommended to avoid this problem. It was found that the lower the friction coefficient, the more stable the simulation. The latest Ver.2.1 released in August 2021 has further upgraded contact definitions.

The takeaway here is that contact definitions are very important for compression molding simulation stability. JSOL will continue to investigate and upgrade contact definitions in future versions.

4.6 Enhanced set-up system for analysis and forming conditions

Ver.2.0 has new functions to adjust some analysis conditions:
- Set the time when the deformation mode switches from the press forming phase to the compression molding phase
- User-defined curves for time step and adaptive remeshing interval
- Adjustable function for the deletion of uncoupled beam elements
- Optional function to apply mass scaling to all elements for faster calculation time (sometimes for more stable simulation)
- Preview tool movement animation (available in Forming Conditions panel)

5 Examples of Compression Molding Simulation

5.1 Tutorial manual using single rib molding model

CoM provides a tutorial manual for training new CoM users. Fig.10 shows the compression molding simulation model created in the tutorial manual. The mold tool has one single rib shape and the matrix resin sheet is a hybrid lay-up composite of the ROS and CUD types shown in Fig.6. In the tutorial manual, all operation procedures for setting up this model are described in detail so that the users can learn how to use CoM easily.

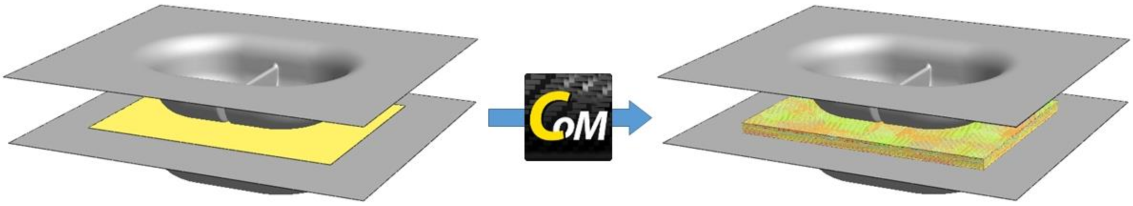

Fig.10: Compression molding simulation model using hybrid lay-up composite

Fig.11 shows the deformation behavior of this simulation model. The calculation took about 5 hours on 64 cores of an MPP machine.

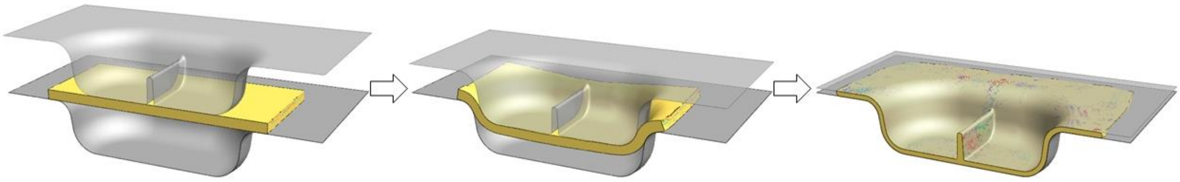

Fig.11: Compression molding simulation result of hybrid lay-up composite model

In this composite model, the CUD type is defined in the lower four layers. Fig.12 shows the initial and final deformation behavior of the 90 degree angle fiber orientation layer (third layer in the lower four layers). Since these fibers are chopped at a 45 degree angle, each of the chopped fibers moves apart.

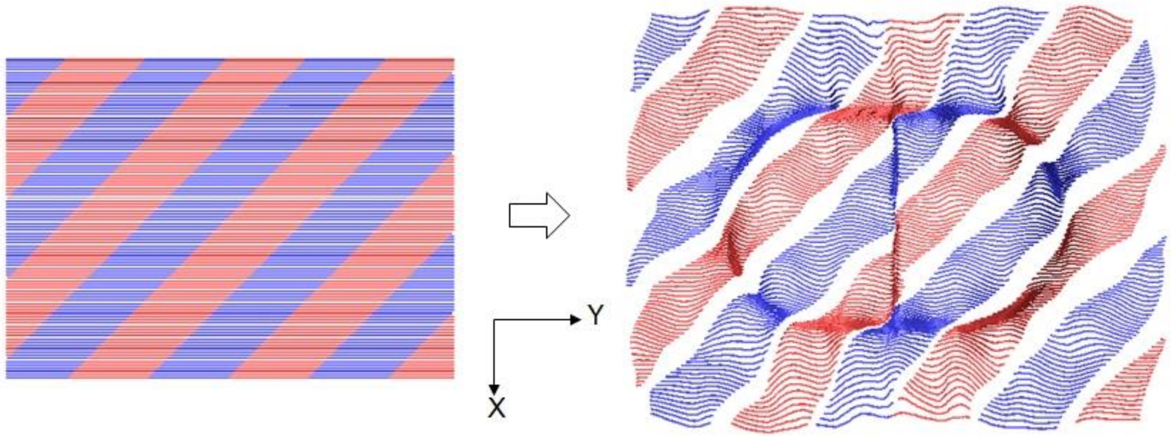

Fig.12: Initial and final deformation behavior of 90 degree angle fiber orientation layer

5.2 Convex shaped matrix resin model

Next, compression molding simulation was performed using a convex shaped matrix resin model. The mold tools are the same as the tutorial model. As described in the previous section, users have to prepare the convex shaped matrix resin modelled by tetrahedral solid elements. Fig.13 shows the template model using the convex shaped matrix resin model (on the left) and the compression molding simulation model (on the right) generated in CoM.

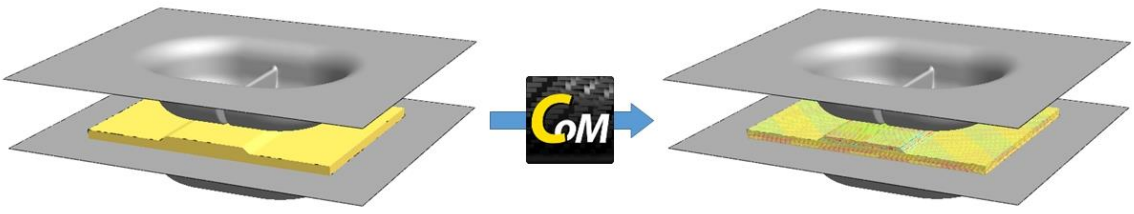

Fig.13: Compression molding simulation model using convex shaped matrix resin model

Fig.14 shows the dimensions of the convex shape matrix resin model and fiber orientations. The upper four layers are modelled using the ROS type with 3mm thickness and the lower four layers using the CUD type with 5mm thickness.

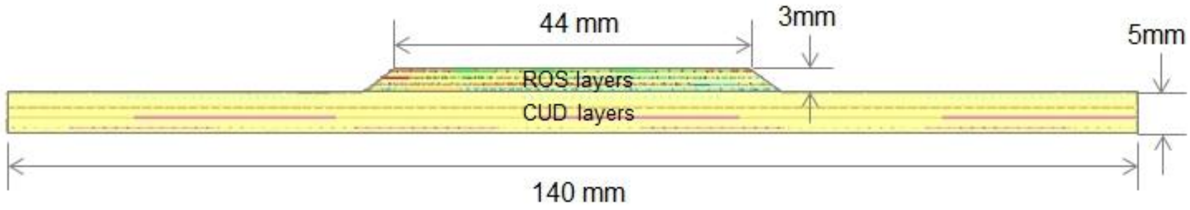

Fig.14: Dimensions of convex shape matrix resin model and fiber orientations

Fig.15 shows the deformation behavior of the composite model. The convex shape was compressed and flattened completely. The molding simulation was successful in that matrix resin and fibers have completely filled the single-rib voids.

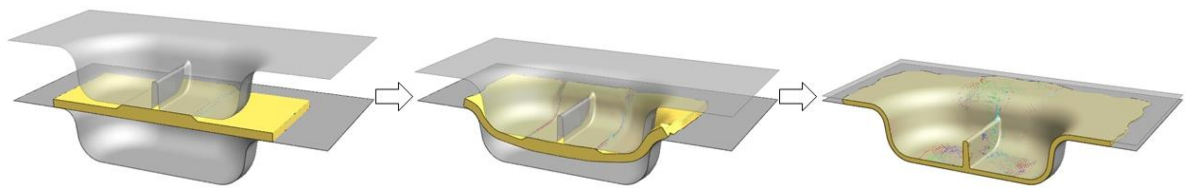

Fig.15: Compression molding simulation result of convex shaped matrix resin model

6 Summary

A modelling tool for compression molding simulations, J-Composites/Compression Molding has been developed by JSOL and Ver.2.0 was released worldwide in March 2021. In this new version, the following new functions were implemented:

1. Generates new fiber orientation types
   - Unidirectional Fiber type (UD)
   - Chopped Unidirectional Fiber type (CUD)
   - Hybrid lay-up composites consisting of ROS, ROF, UD and CUD types
2. Supports more complex matrix resin geometries of arbitrary shape
   - Arbitrary shape with contact thickness
   - Convex shape
3. Adds new commercial CFRP material data into Material Database
   - Flexcarbon (ROS type) from Suncorona Oda Co., Ltd.
4. Upgrades contact definitions for more stable calculation
5. Enhances set-up system for analysis and forming conditions

- Set time when the deformation mode switches from the press forming phase to the compression molding phase
- User-defined curves for time step and adaptive remeshing interval
- Adjustable function for deletion of uncoupled beam elements
- Optional function to apply mass scaling to all elements for faster calculation time (sometimes for more stable simulation)
- Preview tool movement animation (available in Forming Conditions panel)

7 Future development plan of J-Composites/Compression Molding

Development of the following new functions is on-going for the next Ver.3:

1. New fiber orientation type
   - Unidirectional Arrayed Chopped Strand (UACS)
2. Enhance Material Database system
   - New data management system which can save fiber orientation with material data
3. New commercial CFRP material data
4. Improve tool motion setting capabilities
   - Auto-positioning of tool initial location

In future versions JSOL will continue to develop J-Composites/Compression Molding capabilities according to technical accumulation and requests from users:

1. New penalty-based beam-in-solid coupling function to have more accurate simulation
2. Thermal-structural coupling simulation for cold molding process
3. Thermoset matrix resin composites (compatible with curing reaction calculations)
4. Mesh generator to make complex matrix resin geometries like convex shapes
5. Auto-fitting function to generate material parameters from squeeze flow test results
6. New fiber orientation types:
   - 3D Randomly-Oriented Fibers type
   - Other types requested by users
7. More complex matrix resin geometries:
   - Separated parts
   - Other geometries requested by users
8. New matrix resin model using incompressible SPG elements
   - Improving stability of calculation and keeping volume of matrix resin constant

8 Acknowledgments

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9 Literature

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