J-Composites/Compression Molding - Introducing New Simulation System for FRP Composites

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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-solid 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, main features of J-Composites/Compression Molding are introduced and the latest compression molding simulation result of a large scale component model created by J-Composites/Compression Molding is presented.

1. 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 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, simulation technology for compression molding of discontinuous long fiber reinforced plastics is introduced. One of the advantages of this method is that many fiber layers can be modelled using a smaller number of elements than more conventional methods. As the result, this method is very efficient regarding calculation cost.

In the second step, a modelling tool called J-Composites/Compression Molding Ver.1.0 is introduced. This tool has been developed by JSOL and released worldwide. The new 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 new tool generates such complicated data easily.

In the third step, a compression molding simulation of ROS (Randomly-Oriented Strands) thermoplastic composite is performed to form a very complex shaped part with lattice-rib geometry. This is then compared to the real component part. The simulation can provide valuable information regarding fiber orientations, areas prone to fiber failure, filling timing, weld line locations, maximum pressing force and so on. In the final step, the future development plan of J-Composites/Compression Molding is presented.

2. Compression molding simulation using beam-in-solid coupling method

2.1 Coupling function to constrain beam and solid

S. Hayashi et al. [4] have performed compression molding simulations of discontinuous long carbon fiber reinforced thermoplastics using a beam-in-solid coupling method. Figure 1 shows the compression molding test and simulation results that form a component with cross-rib geometry. The simulation result shows good agreement to the real component.

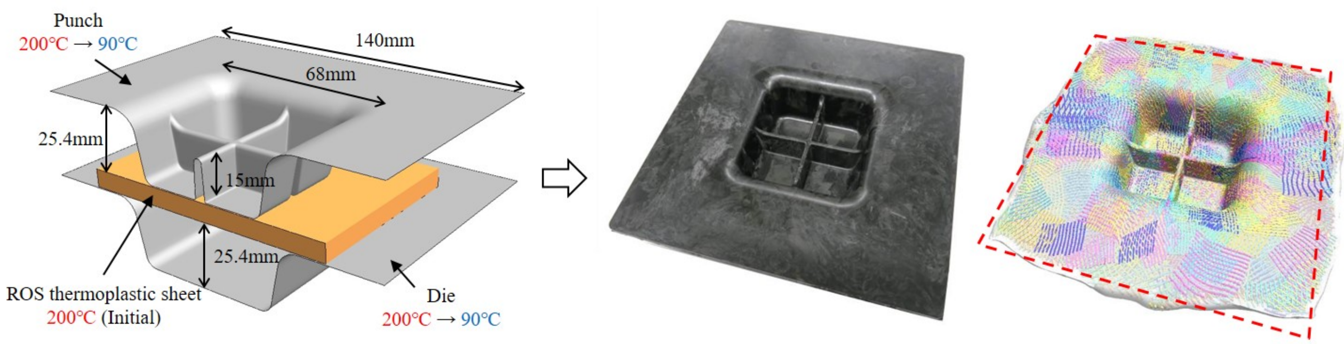

Figure 1: Final shapes formed by compression molding test and simulation

Beam and solid elements are coupled by *CONSTRAINED_BEAM_IN_SOLID (CBIS), which has been implemented since LS-DYNA R8 [5]. 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. One important feature of this beam-in-solid coupling function is that it can constrain multiple beam elements in one solid element as shown in Figure 2.

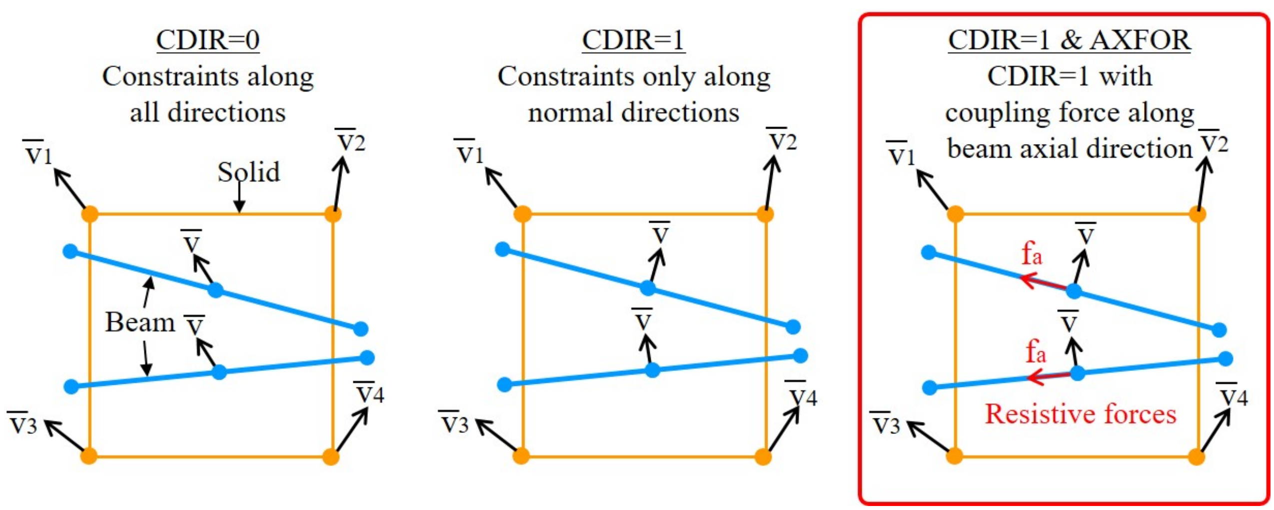

Figure 2: 3 types of coupling option in CBIS

2.2 Advantage of beam-in-solid coupling method regarding calculation cost

In this beam-in-solid simulation approach, the fiber is modelled by beam elements and calculations predict deformation and axial forces within the beam elements. As highlighted in [6], it could be thought that this method is a mesoscopic modelling approach which needs much higher computational resources than a fiber orientation model like Folgar-Tucker. However, this is not correct. In the fiber orientation model, each fiber orientation tensor must be mapped at each solid element respectively. As shown in Figure 3, generating many layers of tetra solids requires a very small mesh in all directions, so the number of tetra solids increases exponentially with the number of layers. Because of this, the fiber orientation model with many layers must be modelled by an extremely large number of solids which incurs a very large calculation cost. On the other hand, the fiber layers in the beam-in-solid coupling model are represented by beams, and the number of beams only increases in proportion to the number of layers.

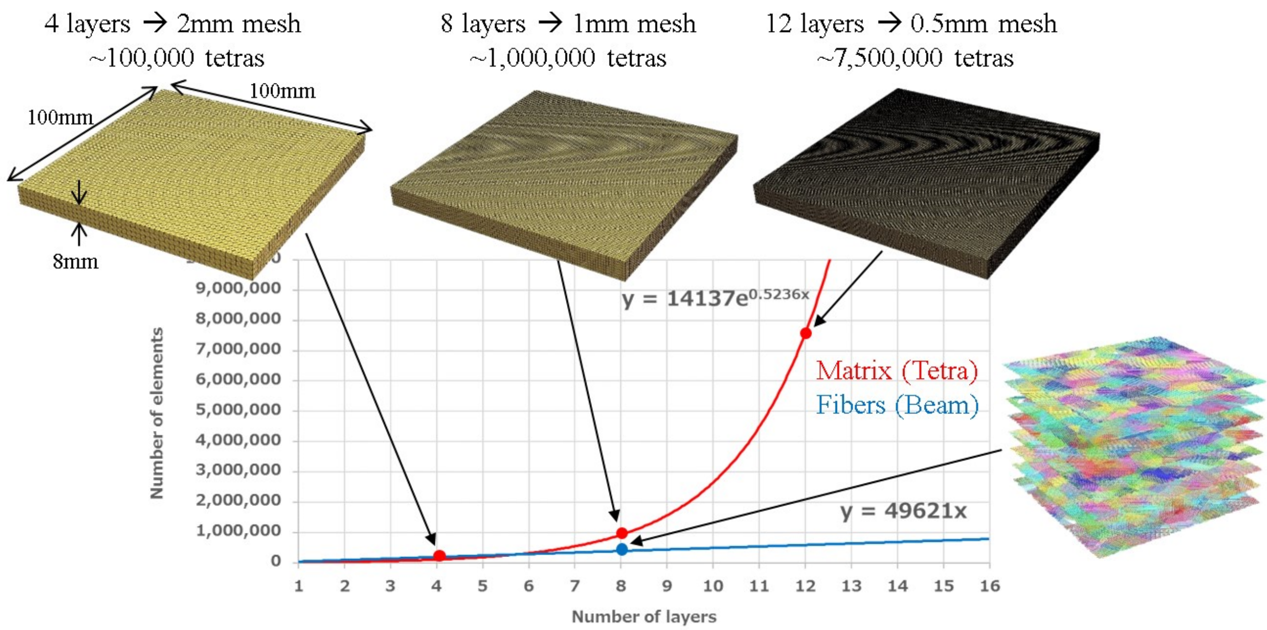

Figure 3: Increase of number of solids and beams with the number of fiber layers

In the beam-in-solid coupling model shown in Figure 4, there are 8 layers of fibers but the matrix resin is meshed by only 4 layers. Such an unmatched condition can be analyzed because the beam-in-solid coupling function can constrain multiple beam elements in one solid element. This is the reason why the beam-in-solid coupling model is very efficient at modelling many layers of fibers.

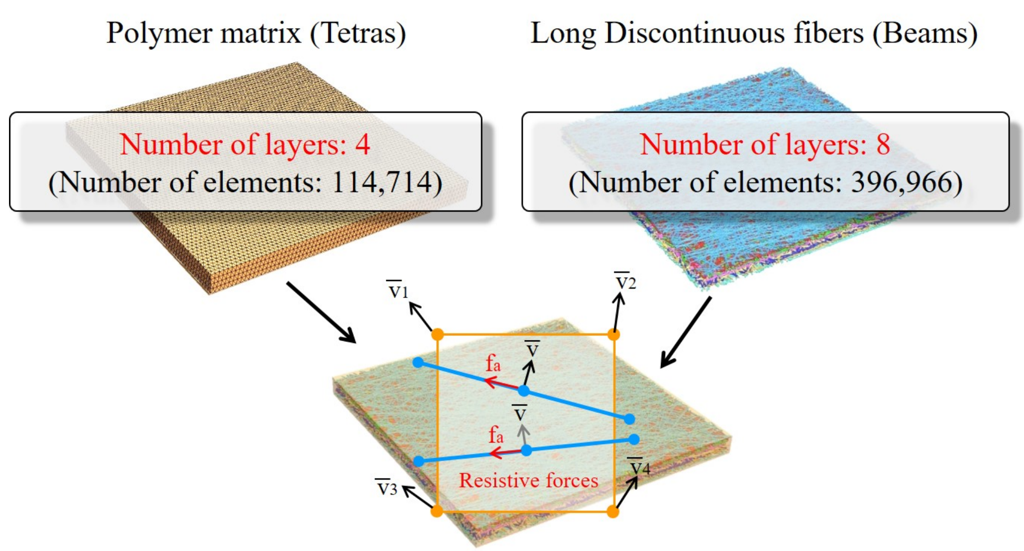

Figure 4: Constraint of multiple beam elements in one solid element

3 Introducing J-Composites/Compression Molding

3.1 Overview of J-Composites/Compression Molding

This new compression molding simulation model needs a complex input deck which consists 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. If such data is not set up carefully and accurately the simulation result can become unstable. To generate the complex input deck easily, JSOL developed a modelling tool called J-Composites/Compression Molding. First, we read a template model for press forming simulation which has a representative model of the workpiece (composite sheet) and tools (punch and die) into J-Composites/Compression Molding and then input material parameters to construct the FRP composite. Next, the fiber model (beam elements) and matrix resin model (tetrahedral solid elements) are made by a mesh generator and some input parameters are set up automatically. Finally, a complete input deck for the compression molding simulation is output.

J-Composites is a set of tools which work in conjunction with LS-DYNA to facilitate the complex manufacturing process and process-chain simulation of fiber reinforced plastic composites [7]. JSOL has already released the software products “Form Modeler” for setting up a press forming analysis model and “Fiber Mapper” for mapping a resin flow simulation results on to a structural mesh. Now “Compression Molding” (CoM) is added to the J-Composites series.

3.2 Generating a fiber model

The CoM software automatically measures the size of the matrix resin from the workpiece sheet in the template model and generates beam elements for the fiber filling the matrix resin. In CoM Ver.1.0, two simple geometries of matrix resin are supported “cylinder” or “cuboid”. Fiber composition can be defined as either “Randomly Oriented Fiber (ROF)” or “Randomly Oriented Strand (ROS)”. Figure 5 shows the examples of the fiber model generated in CoM. In the future versions, more types of fiber composition and complicated matrix resin shapes including convex geometries will be added.

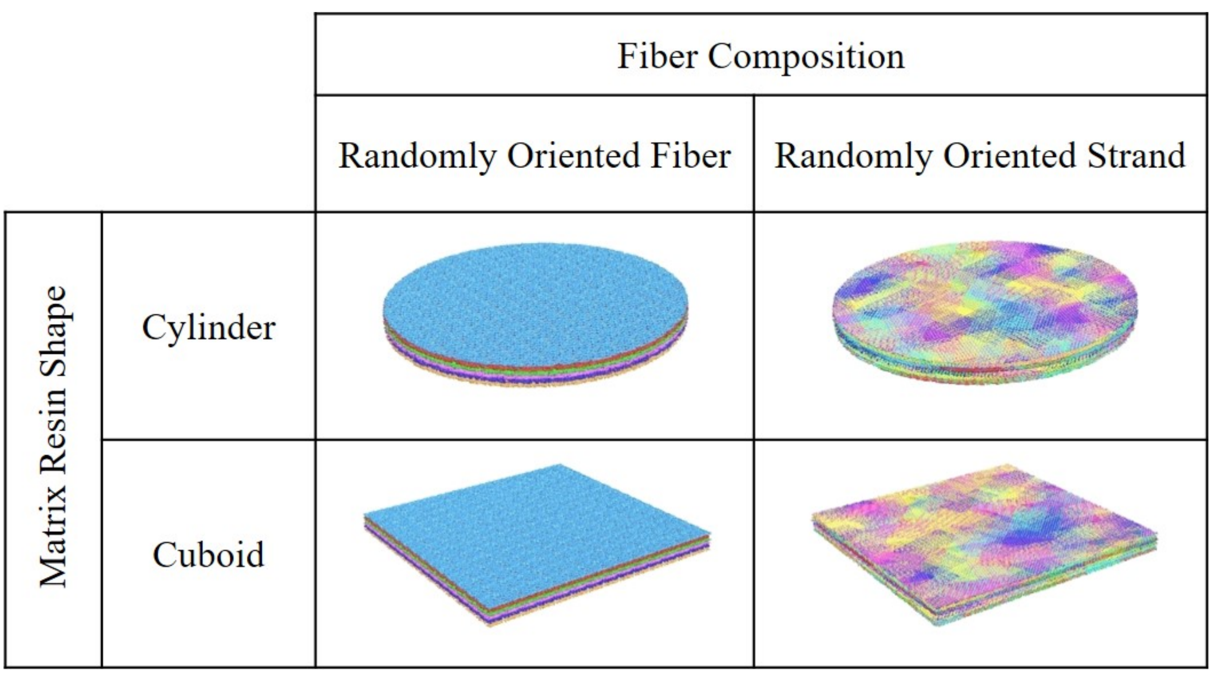

Figure 5: Fiber Composition type and matrix resin shape

Figure 6 shows the operation panel to generate a fiber model for an ROS type composite. Input parameters to generate the strand model are "Fiber length", "Beams per Fiber", "Width", "Fibers Across Width" and "Beam Length". "Layer Count" must also be entered according to thickness of the matrix resin. "Strands per Cluster Radially" and "Cluster Unit Width" are the input parameters for the Cluster Overlapping Method. This method developed by JSOL generates a fiber model with quasi-isotropic fiber orientation and achieves homogeneous fiber distribution in a cluster unit area using a small number of beam elements [8]. An estimate of the number of beam elements is displayed before the they are generated. If this estimate is larger than desired, the "Layer Count" or fiber model clustering parameters can be adjusted to reduce the number of beam elements.

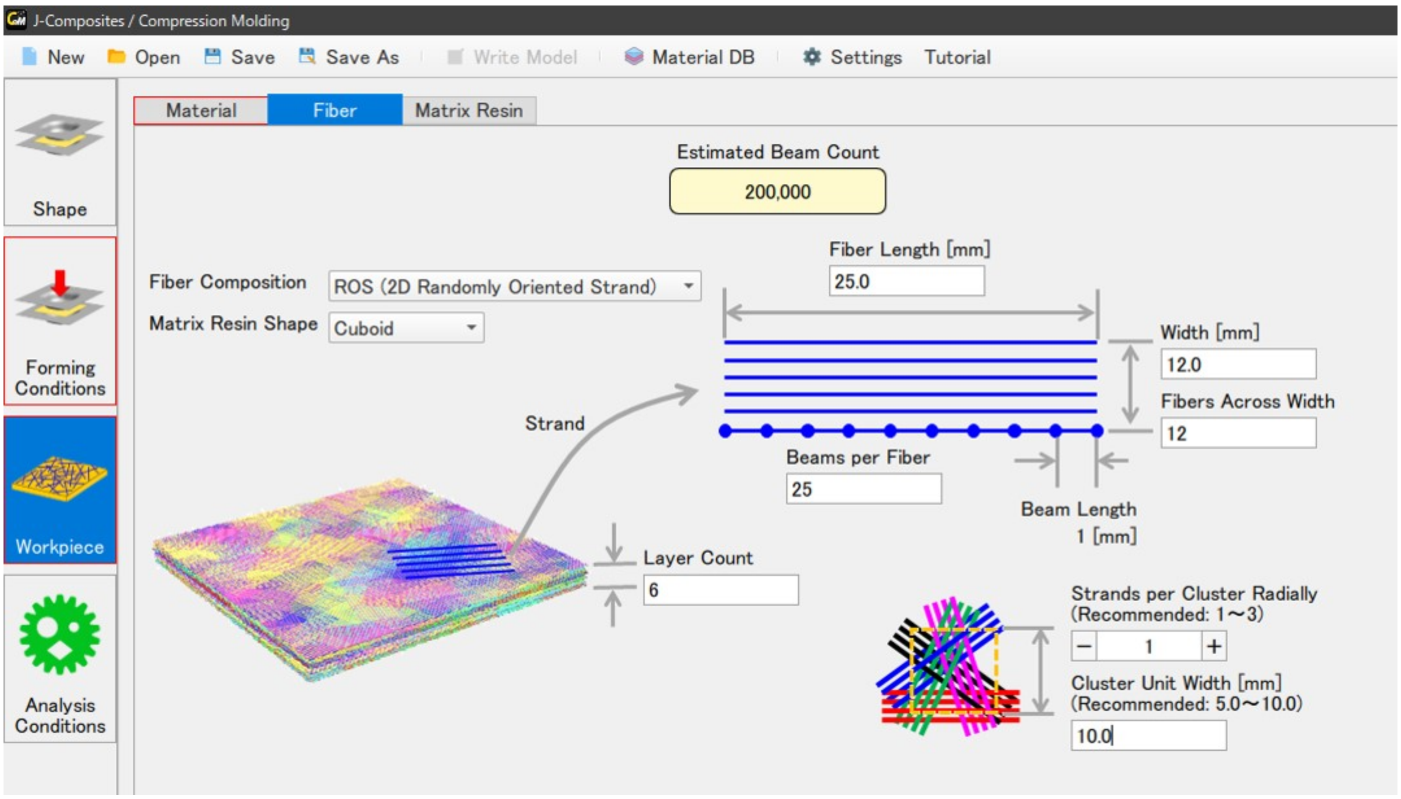

Figure 6: Fiber Composition type and matrix resin shape

3.3 Automeshing a matrix resin model

If the workpiece sheet in the template model has been modelled by triangular shells, the CoM generates tetrahedral solids from the shells and uses them for the matrix resin model as shown in Figure 7. The mesh size in the thickness direction is set automatically to a reasonable value. If the workpiece sheet is modelled by tetrahedral solids, they are used as-is for the matrix resin model.

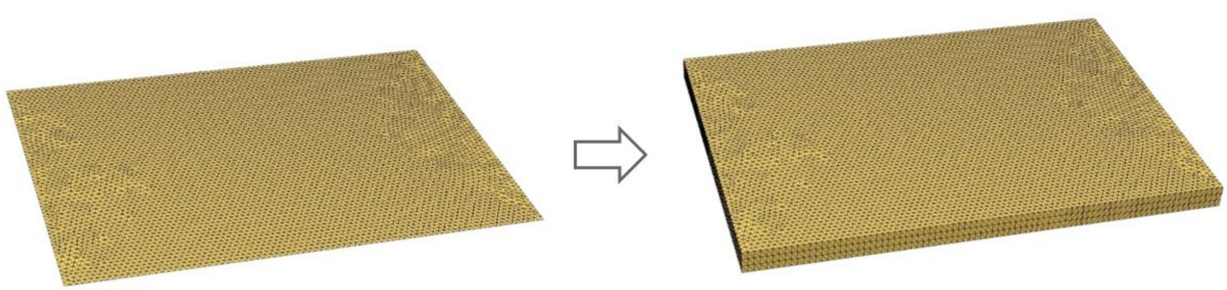

Figure 7: Automeshing tetrahedral solids from triangular shells

3.4 Automatically setting optimized input parameters

This new simulation method uses two highly complex functions for beam-in-solid coupling and 3D r-adaptive re-meshing calculations, so it requires technical skill and experience to define input parameters which achieve both efficient calculation times and stable simulations. To help with this problem, the CoM automatically sets optimal parameters based on JSOL's know-how and experience. These include ideal contact definitions, time step and 3D r-adaptive re-meshing parameters. The compression molding process consists of two phases: a press forming phase followed by a compression molding phase. In the press forming phase, a relatively large re-meshing time interval is acceptable, but in the compression molding phase, a smaller time interval must be used for stable simulation. There are two presets to deal with these phases available in Ver.1.0 and in most cases the preset input can be used without modification.

3.5 Composite material database

Composite material data for compression molding simulation is managed in a database in the CoM. Figure 8 shows an example CFRP material saved in the database. The data consists of three components: "Fiber material", "Matrix Resin material" and "Fiber-Matrix Resin Interaction". In the database, each component and various composite material data can be managed, and new composite material data can be created by combining three other components. Master composite material data supplied from material suppliers and public papers is saved in read-only mode in the material database. In Ver.1.0, one example provided by JSOL is available.

"Matrix Resin material" and "Fiber-Matrix Resin Interaction" can be defined as temperature dependent data. In Ver.1.0, heat & cool press simulations which perform compression molding at a constant temperature are supported and a constant forming temperature must be specified. In future versions, cold press simulations with variable temperatures are planned to be supported. Cold pressing is simulated by coupling thermal and structural analysis.

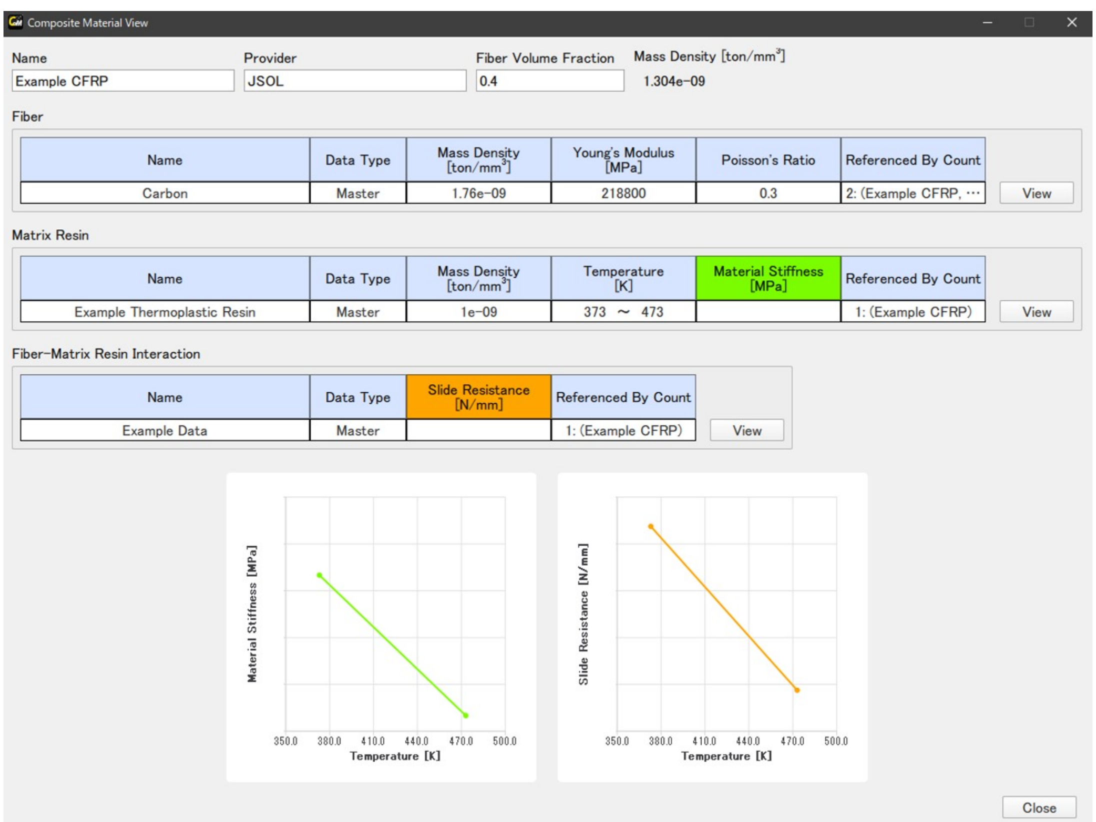

Figure 8: Composite material database panel

Squeeze flow tests are performed to measure macroscopic mechanical properties of composite materials [9]. Figure 9 shows the final shapes of the test and simulation results from a squeeze flow test. Figure 10 shows compression forces of a squeeze flow test at four different temperatures. Input parameters for "Matrix Resin material" and "Fiber-Matrix Resin Interaction" are identified from results of squeeze flow tests by reverse engineering. The simulation results using correlated material data are in good agreement with the tests.

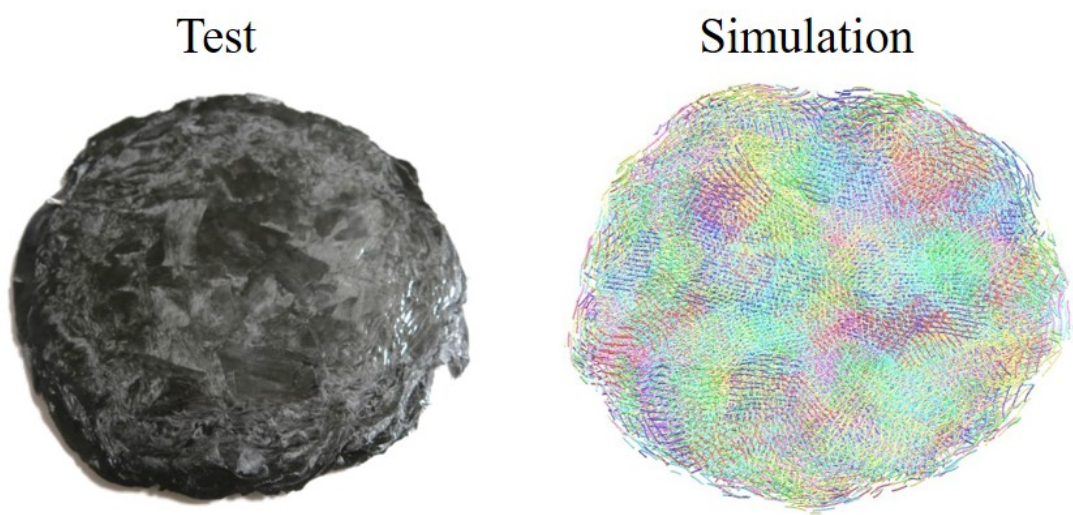

Figure 9: Final shapes formed by squeeze flow test and simulation results

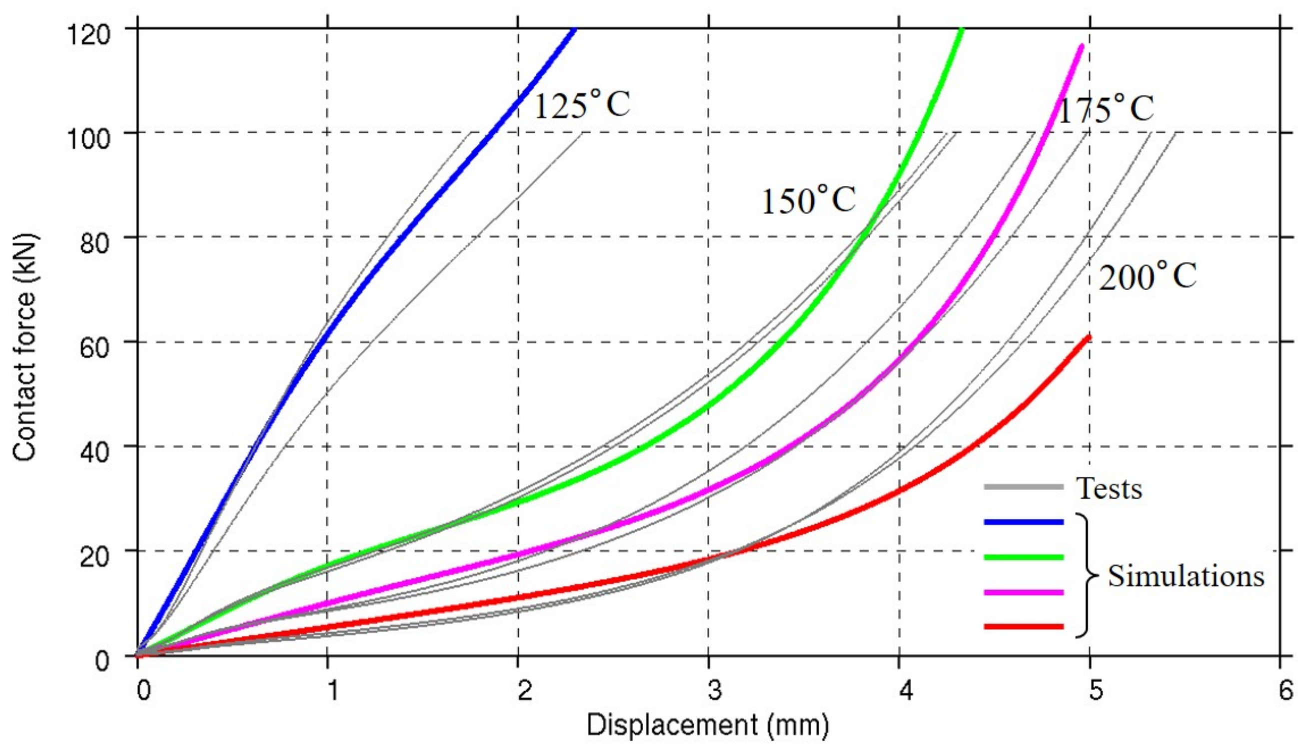

Figure 10: Compression forces at four different temperatures

4 Application of Large Scale Component Model

A compression molding process to form a complex part with a lattice-rib geometry was performed by the Innovative Composite Center (ICC) at Kanazawa Institute of Technology, using ROS thermoplastic composites (Flexcarbon® from Suncorona Oda Co., Ltd.). Figure 11 (on the left) shows the final shape of the compression molding performed under heat & cool press processes. The molding was successful in that matrix and fibers have completely filled the lattice-rib voids. Figure 11 (center and right) shows the matrix resin and discontinuous long fibers predicted by the simulation, which used the same tool geometries as the real process. The calculation took about 24 hours on 64 cores of an MPP machine.

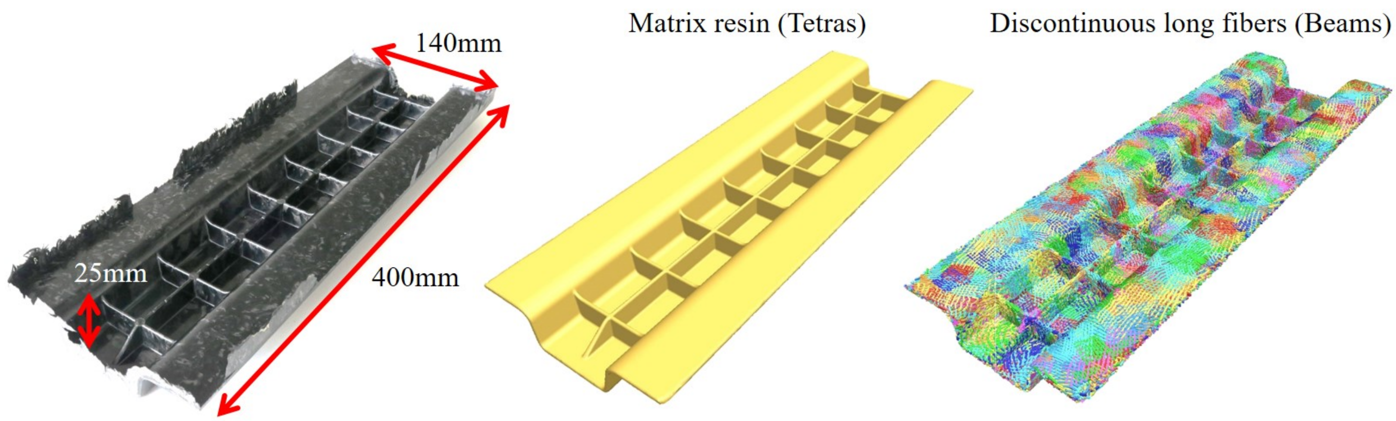

Figure 11: Compression molding test and simulations of a lattice-rib shape

Figure 12 shows enlarged views of the formed structure from the real pressing (on the left) and simulation (center and right). Weld lines are correctly predicted to form at the top edges of ribs and fibers are realistically oriented along the weld lines. The weld line deformation in the matrix model disappeared in the final shape, unlike the real component, however locations of these weld lines can be determined from fiber orientations.

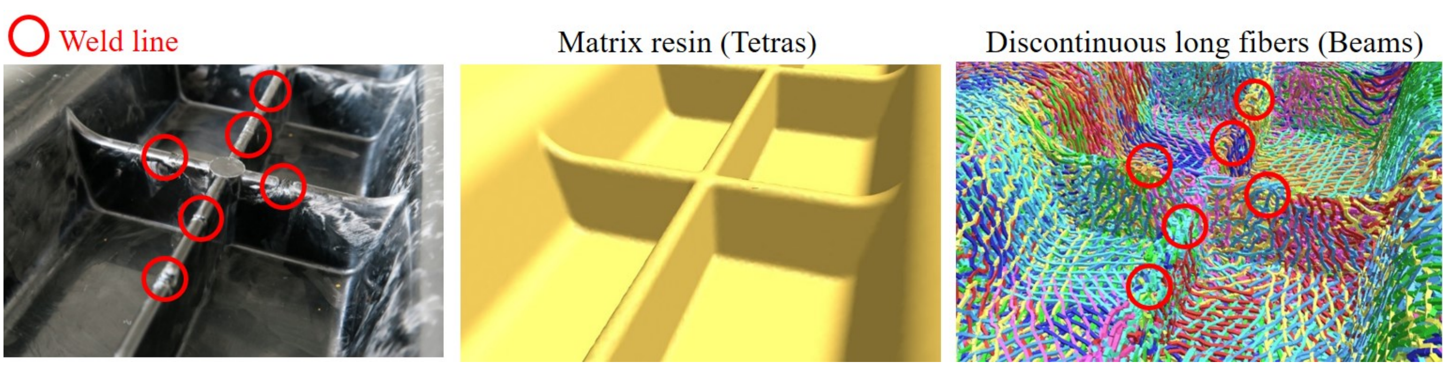

Figure 12: Predicting locations of weld lines

5 Summary

A modelling tool for compression molding simulations, J-Composites/Compression Molding (CoM) Ver.1.0 has been developed by JSOL and released worldwide in the spring of 2020. The CoM has a user-friendly GUI and can create the complex input data required for beam-in-solid coupling and 3D r-adaptive re-meshing functions. Many functions are developed based on JSOL's extensive CAE know-how, making compression molding simulations both stable and calculation cost efficient. A compression molding simulation of a large-scale component with lattice-rib geometry was performed and compared well to the real part. It is considered that the CoM can successfully be applied to a design study of such a complex component part. Comparisons of tetrahedral mesh suggest the beam-in-solid coupling approach has relatively smaller calculation cost than more conventional methods like the fiber orientation model. Moreover, LST and JSOL plan to develop more efficient simulation methods to further reduce calculation cost.

6 Future development plan of J-Composites/Compression Molding

JSOL will continue to develop J-Composites/Compression Molding capabilities. The following new functions are planned to be implemented in future versions:

- Generate other fiber orientation types
  - Hybrid lay-up of discontinuous fiber ply and continuous fiber ply
  - Quasi-isotropic laminate of chopped UD fiber ply
  - 3D Randomly-Oriented Fibers
- Support more complex matrix resin geometries
  - Convex shape
  - Separated parts
- Enhance material database system
  - Fitting function to generate material parameters from squeeze flow test results
- Improve tool motion setting capabilities
  - Auto-positioning of tool initial location
  - Auto-setting of tool motion
- Add new functions requested by users
- Implement new simulation capabilities into LS-DYNA
  - Development of more stable and faster simulation method in cooperation with LST

Acknowledgments

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