

Composite Forming Simulation with Introduction to J-Composites/Form Modeler Version 2.0

Masato Nishi¹, Sean Wang¹, Shaun Dougherty¹, Xinhai Zhu²

¹ JSOL Corporation

²Livermore Software Technology Corporation

1 Abstract

JSOL Corporation has developed J-Composites®, a set of tools, which works in cooperation with LS-DYNA®, to facilitate the complex manufacturing process and process-chain simulation of fiber reinforced composite materials. The J-Composites series consists of “Form Modeler”, a tool to set up a press forming analysis model, and “Fiber Mapper”, a tool to map a resin flow simulation result on to a structural mesh. Additionally, “Compression Molding”, a tool for compression molding simulation is in development. This paper introduces some new capabilities of J-Composites/Form Modeler version 2.0 and demonstrates composite forming simulations.

2 Introduction

The increasing requirement for high performance and weight reduction in industry has gradually expanded the use of fiber reinforced composites. Finite element analysis as an alternative approach to experimental study is effective in designing fiber reinforced composite products because there are many design parameters. Process and process-chain simulations are especially important because the performance of the final composite part strongly depends on changes in fiber orientation during the process. In this context, JSOL Corporation has developed J-Composites [1]. J-Composites is a set of tools, which works in cooperation with LS-DYNA, to facilitate the complex manufacturing process and process-chain simulation of fiber reinforced composite materials. The motivation behind development is to be able to effectively simulate complex models, which can accurately represent material behavior during the process. The J-Composites series consists of “Form Modeler”, a tool to set up a press forming analysis model, and “Fiber Mapper”, a tool to map a resin flow simulation result on to a structural mesh. Additionally, “Compression Molding”, a tool for compression molding simulation [2] is in development.

This paper introduces some new capabilities of J-Composites/Form Modeler version 2.0 and demonstrates composite forming simulations. Form Modeler version 1.0 provided three main functions: Material-DB creates and manages material data, Lay-up Modeler creates a composite model, and Lay-up Mapper maps a fiber result to a structural model. Three major enhancements have been implemented in version 2.0. Firstly, we enhanced our standard material database included with Material-DB with data from published literatures and a collaboration with a major Japanese material maker, Mitsubishi Chemical. The second enhancement was to add to Lay-up Modeler the ability to automatically create models for thermal mechanical coupling simulation. Third was to add new functionality to take advantage of LS-DYNA’s new capability by enabling the user to set-up a model for one-step inverse simulation. In addition, four case studies including ones using the new capabilities will be shown. Firstly, prediction capability of wrinkle developments is validated for twill-weave carbon fiber fabric TORAYCA® C06347B. Second is thermoforming simulation of an automotive B-pillar by thermal-mechanical coupling analysis for Tepex® dynalite 102_RG-600 from Bond Laminates, which consists of PA6 and glass fiber fabric. Third is one-step simulation of TORAYCA C06343B, a plain-weave carbon fiber fabric provided by Toray. Finally, process chain simulation of press and injection hybrid molding simulation by linking Form Modeler with the commercial injection molding simulation software, Moldex3D® [3].

3 Introducing J-Composites/Form Modeler

J-Composites/Form Modeler is a tool for creating composite forming simulation models. There are four major functions: “Material-DB” creates and manages material data, “Lay-up Modeler” creates a composite forming model, “One Step Setup” creates one step inverse model, and “Lay-up Mapper” maps a fiber result to a structural model, so that users can easily create LS-DYNA models that will

accurately predict the behavior of dry fabric and thermoplastic/thermoset pre-preg sheets during forming and conduct process-chain simulations.

3.1 Main Strategy to Describe Bending Behavior to Accurately Predict Wrinkles

Shell elements are usually used in sheet metal forming simulation. The out-of-plane bending stiffness of a continuous material such as metal can be directly deduced from in-plane properties. However, composite forming simulation using shell elements shows that the derived bending stiffness is unrealistically high compared to experimental bending stiffness. In order to describe the very low out-of-plane bending stiffness at macroscopic scale, it is possible to use the extremely small transverse shear stiffness in a Reissner-Mindlin shell where transverse shear deformation is capable. However it is very difficult to measure the transverse shear property of a textile reinforcement by experimental approach.

Thus we propose the shell-membrane model in order to consider the bending stiffness that is independently free from any in-plane properties [4, 5]. Fig.1 shows the composition of our proposed model.

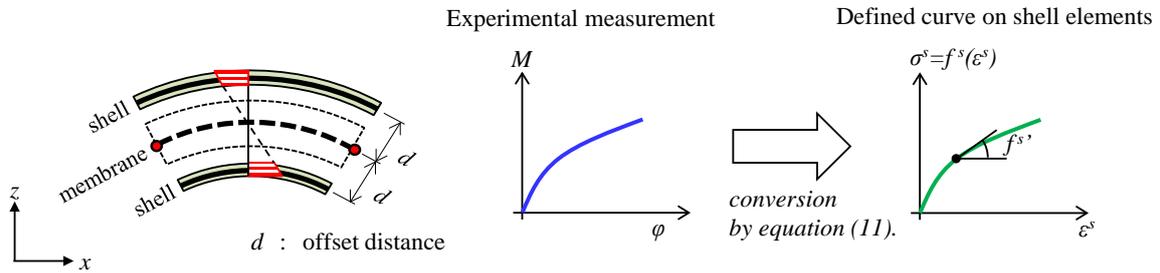


Fig.1: Shell-membrane model considering out-of-plane properties decoupled from in-plane properties.

Let z be the normal direction of the shell element and let $z=0$ be the thickness center position (neutral plane). In the proposed model, when computing the strain of the shell element from the rotational displacement of the node, it is assumed that two shell elements are arranged on opposite sides of the node position of the membrane element. In the shell element assuming the plane stress, the strain increment $\Delta \boldsymbol{\varepsilon}^s$ caused by the rotational displacement increment $\Delta \boldsymbol{\theta}$ of the node can be described by the Eq. (1). Also, assuming that the distance from the neutral plane of the shell element is d , and the plate thickness given to the shell element is $t/2$, z takes the range of the Eq. (2), so that strain of the shell element with respect to rotational displacement is calculated largely according to the value of d . Incidentally, the suffix "s" indicates the shell element added to the membrane element.

$$\Delta \boldsymbol{\varepsilon}^s = \begin{Bmatrix} \Delta \varepsilon_x^s \\ \Delta \varepsilon_y^s \\ \Delta \varepsilon_{xy}^s \end{Bmatrix} = z \begin{Bmatrix} \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial y} \\ \frac{\partial}{2\partial y} & \frac{\partial}{2\partial x} \end{Bmatrix} \begin{Bmatrix} \Delta \theta_y \\ \Delta \theta_x \end{Bmatrix} \quad (1)$$

$$-d - \frac{t}{4} \leq z \leq -d + \frac{t}{4}, \quad d - \frac{t}{4} \leq z \leq d + \frac{t}{4} \quad (2)$$

Here, $\Delta \theta_y$ and $\Delta \theta_x$ are rotation angle increments around the y axis and around the x axis, respectively. Assuming a small deformation increment, the bending moment increment $\Delta \mathbf{M}$ of the shell element of this model can be expressed as follows;

$$\Delta \mathbf{M} = \left\{ \Delta M_y \quad \Delta M_x \quad \Delta M_{xy} \right\}^T \quad (3)$$

$$\Delta M_y = \int_{-d-t/4}^{-d+t/4} \Delta \sigma_x^s z dz + \int_{d-t/4}^{d+t/4} \Delta \sigma_x^s z dz, \quad \Delta M_x = \int_{-d-t/4}^{-d+t/4} \Delta \sigma_y^s z dz + \int_{d-t/4}^{d+t/4} \Delta \sigma_y^s z dz \quad (4)$$

$$\Delta M_{xy} = \int_{-d-t/4}^{-d+t/4} \Delta \sigma_{xy}^s z dz + \int_{d-t/4}^{d+t/4} \Delta \sigma_{xy}^s z dz \quad (5)$$

Here, ΔM_y and ΔM_x are moment increments about the y-axis and x-axis, respectively, and ΔM_{xy} is a torsional moment increment.

$\Delta \sigma^s$ is the stress increment of the shell element. Assuming that the gradient of the stress-strain characteristic given to the shell element is f^s , Eq. (4) and Eq. (5) are transformed as follows;

$$\Delta M_y = \int_{-d-t/4}^{-d+t/4} f_x^s \Delta \varepsilon_x^s z dz + \int_{d-t/4}^{d+t/4} f_x^s \Delta \varepsilon_x^s z dz, \quad \Delta M_x = \int_{-d-t/4}^{-d+t/4} f_y^s \Delta \varepsilon_y^s z dz + \int_{d-t/4}^{d+t/4} f_y^s \Delta \varepsilon_y^s z dz \quad (6)$$

$$\Delta M_{xy} = \int_{-d-t/4}^{-d+t/4} f_{xy}^s \Delta \varepsilon_{xy}^s z dz + \int_{d-t/4}^{d+t/4} f_{xy}^s \Delta \varepsilon_{xy}^s z dz \quad (7)$$

In addition to calculating strain from node rotation, the moment force of the node is also calculated greatly in proportion to the moving distance d of the reference surface. Basically, the offset of the shell reference surface is applied to increases the effect of bending stiffness. As a result, we can give a small stiffness to the duplicated shell elements. It is enough not to affect the in-plane properties, but get effective bending stiffness. In addition, Eq. (6) and Eq. (7) are transformed as follows using Eq. (1).

$$\Delta M_y = f_x^s \Delta \left(\frac{\partial \theta_y}{\partial x} \right) t \left(d^2 + \frac{t^2}{48} \right), \quad \Delta M_x = f_y^s \Delta \left(\frac{\partial \theta_x}{\partial y} \right) t \left(d^2 + \frac{t^2}{48} \right) \quad (8)$$

$$\Delta M_{xy} = \frac{1}{2} f_{xy}^s \Delta \left(\frac{\partial \theta_y}{\partial y} + \frac{\partial \theta_x}{\partial x} \right) t \left(d^2 + \frac{t^2}{48} \right) \quad (9)$$

The increment $\Delta \phi$ of curvature ϕ_y about the y axis, the curvature around the x axis ϕ_x and the torsion rate ϕ_{xy} are expressed by Eq. (10). So substituting this into the Eq. (8) and Eq. (9), the gradients f_x^s and f_y^s of the stress-strain properties in the x and y directions, and the gradient f_{xy}^s of the shear stress-strain property can be expressed by t , d , and the slope ($\Delta \mathbf{M} / \Delta \phi$) of the moment curvature curves observed in the bending experiment and the torsional moments observed in the torsional experiment as Eq. (11).

$$\Delta \phi = \begin{Bmatrix} \Delta \phi_y \\ \Delta \phi_x \\ \Delta \phi_{xy} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{Bmatrix} \begin{Bmatrix} \Delta \theta_y \\ \Delta \theta_x \end{Bmatrix} \quad (10)$$

$$f_x^s = \frac{\Delta M_y}{\Delta \phi_y} \frac{48}{t(48d^2 + t^2)}, \quad f_y^s = \frac{\Delta M_x}{\Delta \phi_x} \frac{48}{t(48d^2 + t^2)}, \quad f_{xy}^s = 2 \frac{\Delta M_{xy}}{\Delta \phi_{xy}} \frac{48}{t(48d^2 + t^2)} \quad (11)$$

As shown in Fig. 1 (b), bending properties with nonlinearity obtained by bending experiments and torsion experiment can also be expressed by using Eq. (11). Even if it is extended to a model that takes non-linear characteristics into consideration, in this model, it is assumed that the out-of-plane moment is decoupled from the in-plane stress

3.2 New Features in J-Composites / Form Modeler Version 2.0

In version 2.0 of Form Modeler, new features, including the enhancement of the material database, automated model creation for thermal-mechanical coupling analysis and one-step quick simulation, and other UI usability improvements are announced. Details about each item are explained below.

3.2.1 Enhancement of Standard Material Database

Since version 2.0, 10 material grades, shown in Table 1, with data from dry fabric, thermoset, and thermoplastic prepregs are registered and available as part of the standard database. The data was collected through experimentation or cited from public papers. Because thermal mechanical coupling analysis is now supported, the UI of Material DB was also updated for users to be able to input thermal and temperature-dependent mechanical properties easily.

Grade Name	Manufacturer	Matrix	Fiber	Pattern
Cetex [®] _8HSatin	TenCate	PPS	Glass	8 Harness-Satin
Cetex [®] _TC1200	TenCate	PEEK	Carbon	UD
Cycom [®] HTS-977-2	Cytec	Epoxy	Carbon	UD
HexForce [®] _G1151	Hexcel	-	Carbon	3X formable weave
HexPly [®] _T700-M21	Hexcel	Epoxy	Carbon	UD
Pipreg [®] _5HSatin	Porcher	PEEK	Carbon	5 Harness-Satin
PYROFIL [™] _TR3110 360GMP	Mitsubishi Chemical	-	Carbon	Plain weave
Tepex [®] dynalite_102-RG600	Bond-Laminate	PA6	Glass	Twill weave
Tepex [®] dynalite_202-C200	Bond-Laminate	PA6	Carbon	Twill weave
TORAYCA [®] _C06343B	Toray	-	Carbon	Plain weave
TORAYCA [®] _C06347B	Toray	-	Carbon	Twill weave

Table 1: Standard Mateirla Database List in Version 2.0

3.2.2 Ability to Automatically Create Models for Thermal Mechanical Coupling Simulation.

In some cases with specific materials and processing, such as a thermal-plastic prepreg prepared through a hot stamping process, the mechanical properties of a blank material can change dramatically with temperature variation. Matrix resin’s high sensitivity to temperature contributes to this kind of temperature dependency.

It is usually tedious and time consuming to setup a keyword model for thermal mechanical coupling simulation. The ***DEFINE_TABLE_2D** keyword is used to describe temperature-dependent mechanical properties. Moreover, in the case of scaling-up to processing speed, all thermal physical parameters with time related units also needed to be scaled to create consistency in the thermal phenomena.

By using Form Modeler version 2.0, all the tedious work described above can be avoided. Only temperature-dependent experimental data, thermal properties, mold temperature, and scale factor for processing speed are inputted. The model for thermal mechanical coupling will be generated automatically. Fig.2 shows a GUI example of input for temperature-dependent data of 3-point bending test.



Fig.2: GUI for the input of temperature dependent mechanical properties

3.2.3 Ability to Create Models for Composites Forming One-step Simulation.

This feature allows users to create a model for a quick analysis to evaluate the shear deformation during composite forming process. As a new function in LS-DYNA R11, One-step analysis for composites can be accomplished by setting up the keywords ***DEFINE_FIBERS** and ***CONTROL_FORMING_ONESTEP**, which is extended from metal forming [6]. Skipping the tedious

keyword setup, users just need to specify an FEM model of the final geometry, the material, and initial fiber orientation via the GUI shown as Fig. 3, and then the key file will be generated automatically.

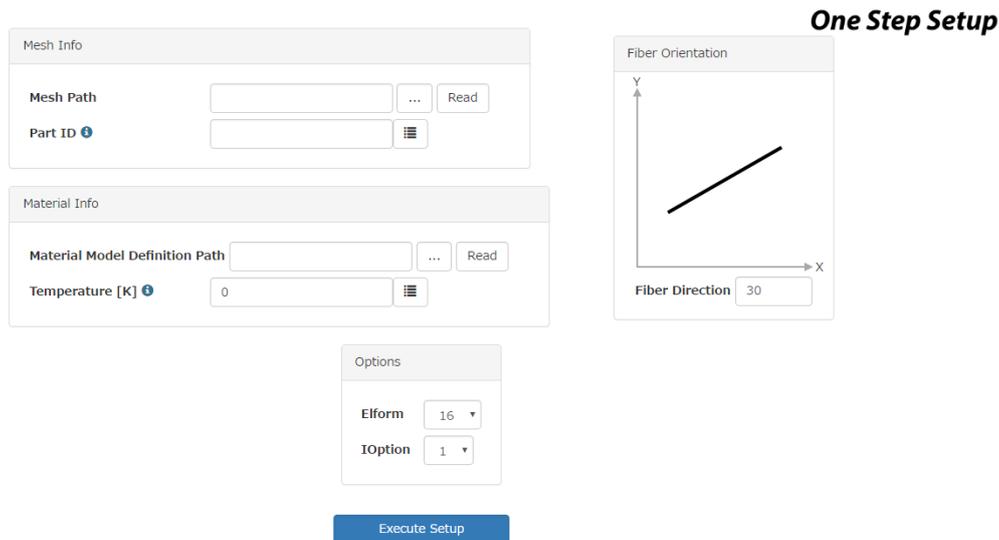


Fig.3: GUI for Composites Forming One-Step Simulation

4 Composite Forming Example with J-Composites/Form Modeler and LS-DYNA

4.1 Case Study 1: Prediction of Wrinkles for Carbon Fiber Fabric

Forming simulation of twill-weave carbon fiber fabric, TORAYCA C06347B, included in the standard material database in J-Composites/Form Modeler is performed, and compared to the experimental deformations including the wrinkling during the forming process.

The blank size is 280x280 mm. It is meshed with 313,600 elements. The surfaces of upper and lower forming tools are modeled as rigid bodies. The carbon fiber fabric is in tension during the forming process by gripping it at 4 corners. The downward movement of upper tool is 20 mm.

Fig. 4 shows the top view of the deformation of the blank during the forming experiment. Wrinkles both in the experiment and the simulation are observed around the corners and develop along with the movement of tool.

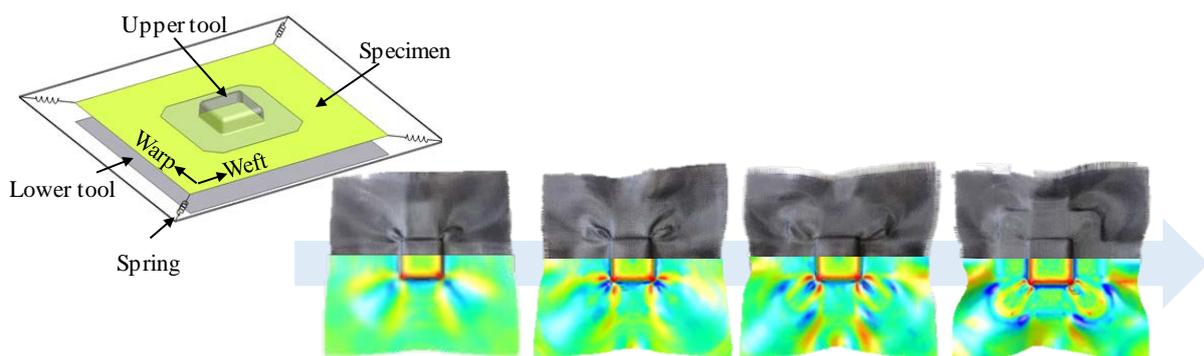


Fig.4: Comparison of wrinkle development process of twill-weave carbon textile reinforcement during forming between experiment and simulation using J-Composites/Form Modeler.

4.2 Case Study 2: Thermoforming Simulation of Automotive B-pillar

Automotive B-pillar forming simulation for simple laminates of Tepex dynalite 102-RG600, which consists of a polyamide 6 (PA6) thermoplastic matrix and twill woven glass fiber fabric, with [(0/90)]₄ and [(45/-45)]₄ lay-ups is performed by thermal-mechanical coupling analysis. The material model,

which is included in the standard material database in J-Composites/Form Modeler, considers the temperature dependent mechanical properties.

As shown in Fig. 5 (a), the laminate is modeled as multiple PARTs, in which each ply consists of a shell-membrane model, and contacts with the COMPOSITE option are created to consider the slippage between neighboring layers. The total number of elements to model the laminate sums up to 1,000,920 over four plies. The die and punch are modeled as rigid bodies.

Before the non-isothermal forming simulation, an isothermal self-gravity simulation of the laminate heated at 250°C is performed by mechanical analysis because we observed the blank sheet was deflected by self-gravity when it was set on the tool in the experiment as shown in Fig. 5(b). After the self-gravity simulation, the non-isothermal forming simulation is conducted by thermal-mechanical coupling analysis. The initial temperatures of the laminate and tools in the non-isothermal forming simulation are set at 250°C and 25°C respectively.

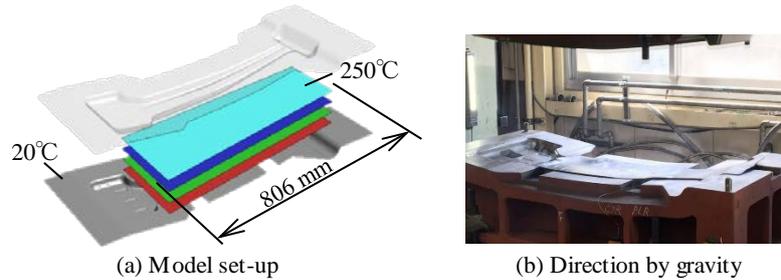


Fig.5: Automotive B-pillar Thermoforming Simulation and Forming Experiment. Pre-consolidated laminates consist of four textile thermoplastic pre-preg layers with simple laminates with $[(0/90)]_4$ and $[(45/-45)]_4$ lay-ups.

Fig. 6 shows the comparison of the deformation after forming of the automotive B-pillar of $[(0/90)]_4$ and $[(45/-45)]_4$ lay-ups to the experiments. Simulated outline for both fiber orientations show good agreement with the experimental deformations.

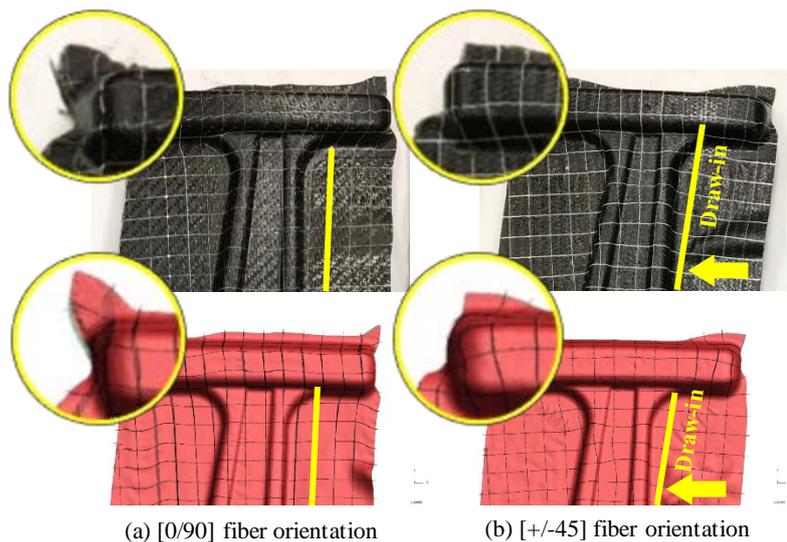


Fig.6: Thermoforming Simulation of Automotive B-pillar considering change in temperature and mechanical properties of glass reinforced thermoplastic during forming process.

4.3 Case Study 3: One-step Inverse Simulation

One-step analysis is applied to a plain-weave carbon fiber fabric, TORAYCA C06343B, and compared to incremental simulation by shell-membrane model and experiment. A material model from the standard material database is used in both incremental and one-step simulations.

Fig. 7 shows the comparisons of deformation, predicted yarn angle and initial blank shape between experiments, incremental simulation and one-step simulation, for two different lay-ups, [0/90] and [+/-45]. These results show that the one-step simulation is capable of accurately predicting shear angle distribution and initial blank shape. Computational cost for incremental simulation (size of element is 1.0 mm) is about 45 minutes using 64 cores with MPP. On the other hand, one-step simulation (size of element is 3.0 mm) can be done in 13 minutes using 1 core with SMP.

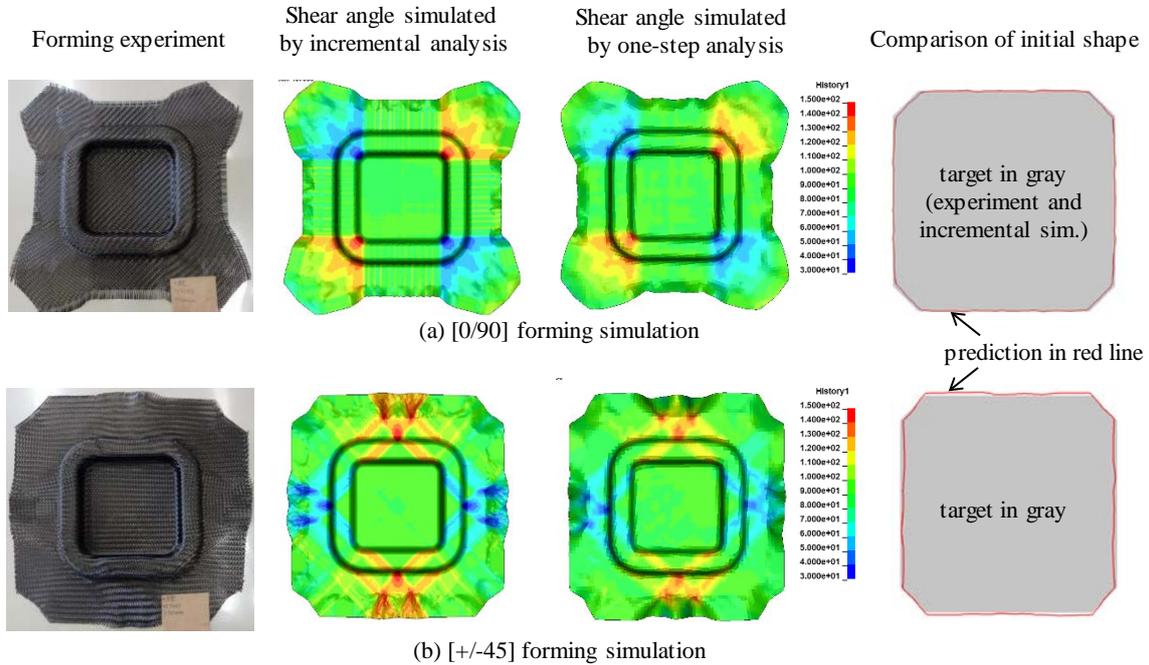


Fig.7: Comparisons of deformation, predicted yarn angle and initial blank shape between experiments, incremental and one-step simulations.

4.4 Case Study 4: Press and Injection Hybrid Molding Simulation

With the growth of demand for lightweight parts, CFRP materials are applied to products with more complicated geometry. Hybrid molding is one process that uses continuous and discontinuous fiber materials to increase its strength. At the same time as press molding for a sheet part, injection molding is processed in the same mold system to form complicated parts, such as ribs.

Fig. 8 shows the image of simulation result for hybrid molding. Press simulation and structural analysis is performed by LS-DYNA, and injection simulation is done by Moldex3D.

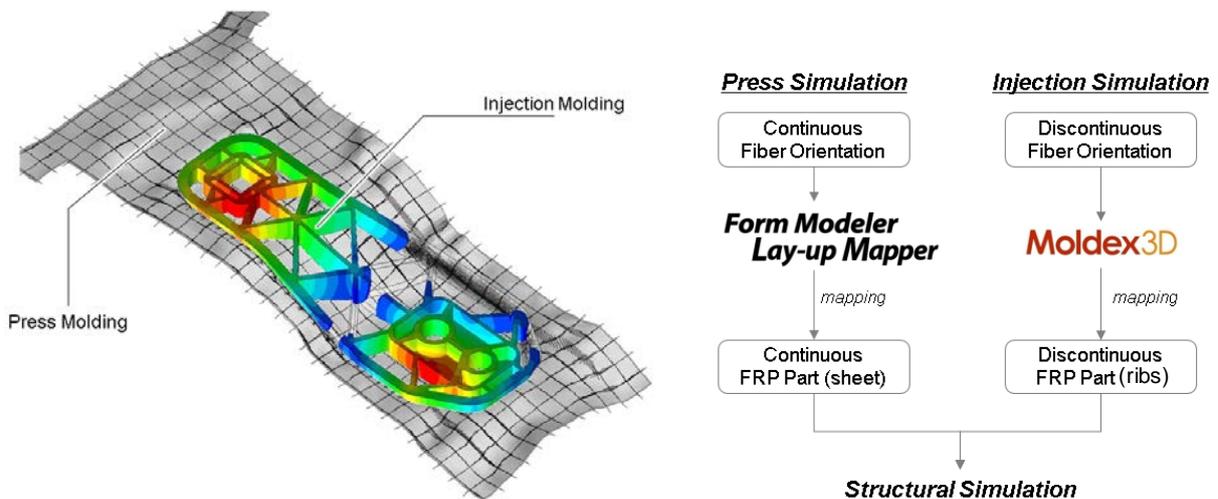


Fig.8: Image of Hybrid Molding Simulation and Mapping Workflow

Due to the anisotropic material properties, mechanical strength is strongly related to the fiber orientation after processing. Lay-up Mapper is an effective tool to map the orientation of continuous fiber, while Moldex3D-FEA Interface takes care of discontinuous ones.

5 Summary

This paper has introduced new capabilities of J-Composites/Form Modeler version 2.0, and demonstrated four case studies with J-Composites/Form Modeler and LS-DYNA to validate the prediction capability.

6 Literature

- [1] J-Composites, <https://www.jsol-cae.com/en/product/manufacturing/jcomposites/>.
- [2] S. Hayashi, H. Chen, W. Hu, "Development of New Simulation Technology for Compression Molding of Long Fiber Reinforced Plastics using LS-DYNA[®]", Proc. 15th International LS-DYNA Conference, 2018.
- [3] Moldex3D, <https://www.moldex3d.com/en/>.
- [4] M. Nishi, T. Kaburagi, M. Kurose, T. Hirashima, T. Kurashiki, "Forming Simulation of Thermoplastic Pre-impregnated Textile Reinforcement by Finite Element Method", Transactions of the JSME (in Japanese), Vol.80, No.820, 2014.
- [5] M. Nishi, T. Hirashima, Japan Patent 6182400, 2013.
- [6] D. Zeng, X. Zhu, L. Zhang, J. Dahl, H. Fan, " Development of a One-Step Analysis for Preforming of Woven Carbon Fiber Composites", Proc. 15th International LS-DYNA Conference, 2018.