

New Methods for Compression Molding Simulation and Component Strength Validation for Long Carbon Fiber Reinforced Thermoplastics

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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, long carbon fiber reinforced thermoplastics are increasingly being 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 FRP into complex shapes with relatively low manufacturing cost and short process time. However, this often generates unwanted fiber orientation, uneven distribution of fibers and fillers, weld lines and matrix rich regions. These forming effects strongly affect mechanical strength. To analyze these complex phenomena, LSTC and JSOL developed new compression molding simulation techniques for long fiber reinforced plastics using a beam-in-adaptive EFG coupling function in LS-DYNA®. In this paper, a compression molding simulation for long carbon fiber reinforced thermoplastics is introduced and new component strength analysis method with a beam-in-SPG coupling model using deformed beams calculated in the compression molding simulation is presented.

2 Introduction

Automotive manufacturers are considering the use of long carbon fiber reinforced thermoplastics as a material with high strength for satisfying strict crash safety performance as well as weight reduction for fuel efficiency. Compression molding has been proven to be an efficient manufacturing process to form a complicated shape in a short time [1]. However, currently there are a very limited number of high-accuracy simulation technologies available that can predict long fiber orientation, filling timing and other aspects required for compression molding. Therefore, in January 2017 a new simulation technology for compression molding of long fiber reinforced plastics was developed in LS-DYNA [2].

In the first part of this paper the new simulation technology for compression molding of long fiber reinforced plastics is introduced. The main features of this new technology are fibers modelled by beam elements and matrix modelled by tetrahedron solid elements with r-adaptive remeshing function based on an Element-Free-Galerkin (EFG) formulation. Relative motion of beams in the solid elements is simulated by coupling momentum along the normal direction of each beam element. This coupling method transfers load from beam to solid and vice-versa; a so-called strong coupling interaction. Solid elements for the matrix are adequately remeshed with an r-adaptive function which enables large deformations and can generate complex shapes.

In the second step an investigation to apply this new simulation technology to Randomly-Oriented Strand (ROS) thermoplastic composites is presented. Simple compression tests using the ROS thermoplastic composites were performed at various high temperatures and macroscopic mechanical properties during compression molding were measured. This new simulation technology has the capability for beam elements to slide along the beam axial direction with some resistive force from the solid elements. Macroscopic mechanical properties are controlled by both mechanical properties of the fiber and the matrix and the resistive forces against fibers sliding axially in the matrix.

In the third step a compression molding simulation of the ROS thermoplastic composites is performed to form a complex shaped part with one cross-rib geometry and compared to the real component. 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 static compression strength analysis with a beam-in-SPG coupling model using deformed beams calculated in a compression molding simulation is presented and compared to test results.

3 Introduction of Capabilities used in New Compression Molding Analysis

Beam and solid elements are coupled by `*CONSTRAINED_BEAM_IN_SOLID` (CBIS), which has been implemented since LS-DYNA R8 [3]. CBIS constrains both accelerations and velocities between beam and solid elements (constraint based method). CBIS has a coupling option which applies only in the beam normal direction, thereby releasing constraint in the beam axial direction. As an additional function, an axial coupling force function has also been implemented. The beam and solid axial debonding processes can be modelled with a user-subroutine giving the axial shear force based on the slip between beam nodes and solid elements.

A 3D Element-Free-Galerkin (EFG) formulation based on a Mesh-free Galerkin Method was implemented in LS-DYNA 970 during 2001-2002. Following that, a 3D adaptive EFG including r-adaptive remeshing capability was developed to simulate extremely large deformation of metals like 3D forging, extrusion, cold forming, metal cutting, friction stir welding, riveting, etc. [4].

In May 2016 the idea was conceived in JSOL Corporation (JSOL) to combine the new axial beam coupling function in CBIS with 3D adaptive EFG to simulate compression molding of long fiber reinforced plastics. In this method CBIS continues to constrain the beam elements to the tetrahedral solid elements even during the re-meshing process. Livermore Software Technology Corporation (LSTC) improved the code to enable the simultaneous use of these two functions with the aid of JSOL's testing and feedback. Fig.1 shows the modelling method using the beam-in-solid coupling function. This new function was implemented in LS-DYNA R10 [5].

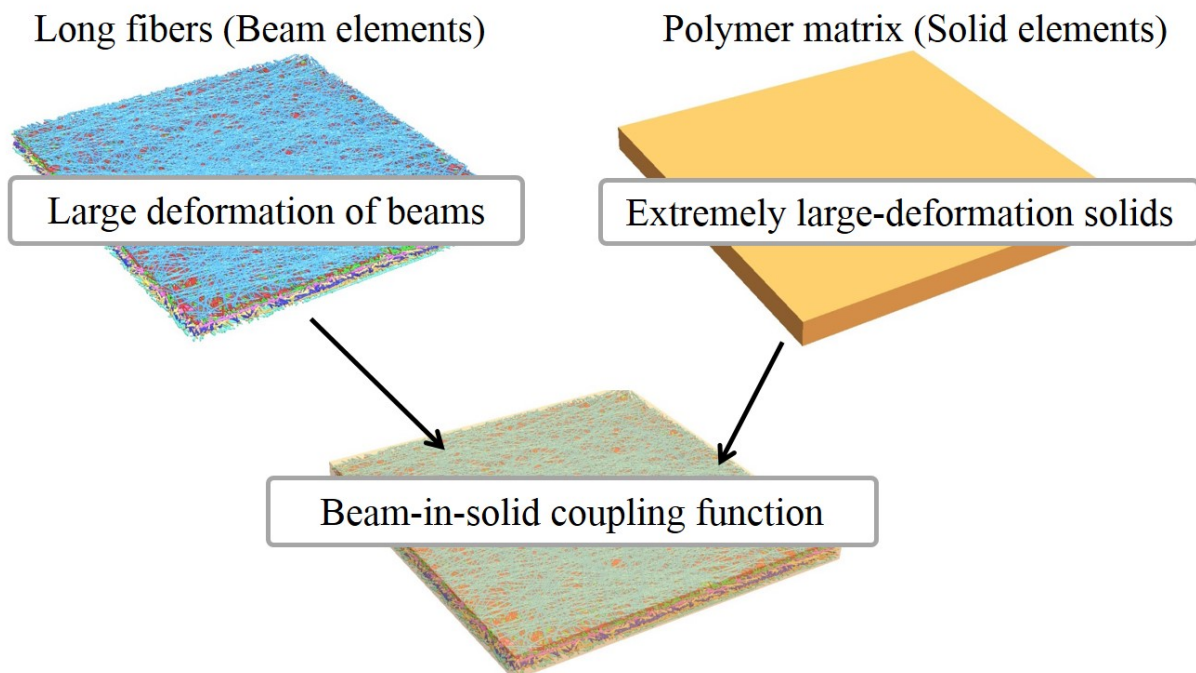


Fig.1: Long fibers modelled by beam elements and polymer matrix by solid elements

S. Hayashi et al. [2] applied these new simulation technologies to a compression molding of long glass fiber reinforced thermoplastics (Tepex® flowcore from Bond-Laminates GmbH) and compared results for complex shaped part. Fig.2 (left) shows deformations mid-way through the compression molding test of the long glass fiber reinforced thermoplastic sheet. Large wrinkles occur around the edge of the sheet. The simulation result seen in Fig.2 (right) shows good agreement to the test.

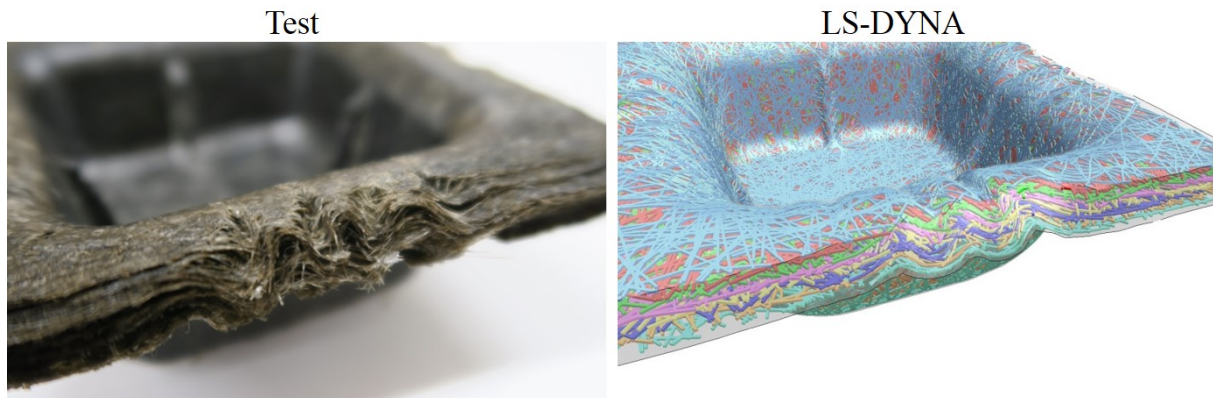


Fig.2: Charge wrinkling mid-way through the punching process

4 Simple Compression Test to Identify Macroscopic Mechanical properties

Simple compression tests were performed to measure macroscopic mechanical properties of Randomly-Oriented Strand (ROS) thermoplastic composites (Flexcarbon® from Suncorona Oda Co., Ltd.). The ROS thermoplastic composites comprise many strands in 2D random orientation. Each strand is a chopped piece of unidirectional (UD) prepreg composite tape made up of carbon fiber / thermoplastic epoxy resin with fiber volume fraction (V_f) 40%. One strand is 25mm long and 12mm wide.

Fig.3 shows a simple compression test using a disc-shaped test specimen in diameter 75mm and thickness 6mm of the ROS thermoplastic composites. The simple compression tests were performed at low velocity 0.1 mm/sec inside a high temperature chamber, each at constant temperature of 125, 150, 175 and 200 degrees. The melting temperature of the thermoplastic epoxy resin was 100 degrees. A lubricant was applied to the loading surfaces to reduce friction against the test specimen.

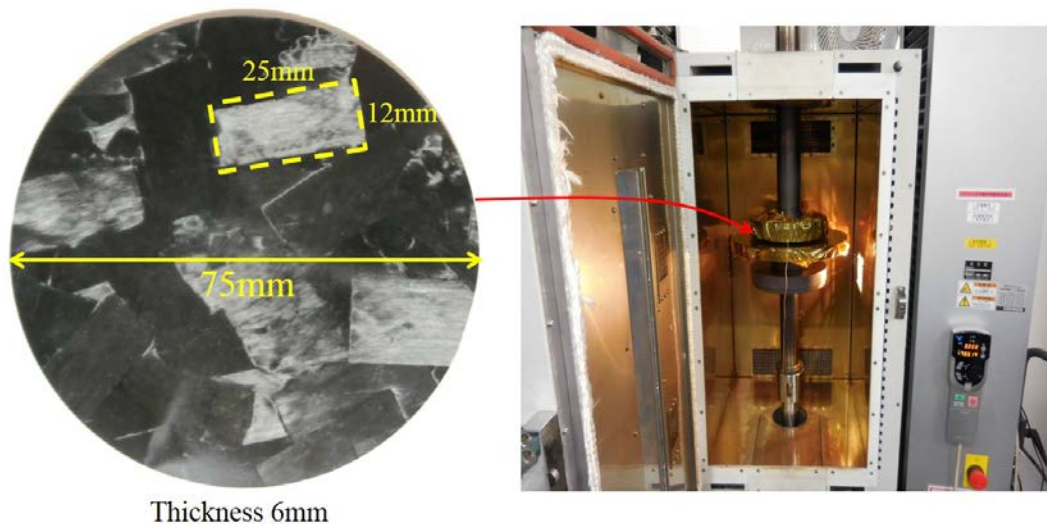


Fig.3: Test specimen and compression test machine with high temperature chamber

Fig.4 shows a full-scale model of the test specimen of the ROS thermoplastic composite. Carbon fibers in one strand are modelled by multiple elastic truss beam elements in a row. The matrix is modelled using tetrahedron solid elements with elastic-viscous or elasto-plastic material. The specimen simulation model consists of eight layers of 2D randomly oriented strands. The very large number of fibers in the real composite must be represented by a much smaller number of beams in the model; however the beam cross-sectional area is adjusted to ensure the same 40% V_f .

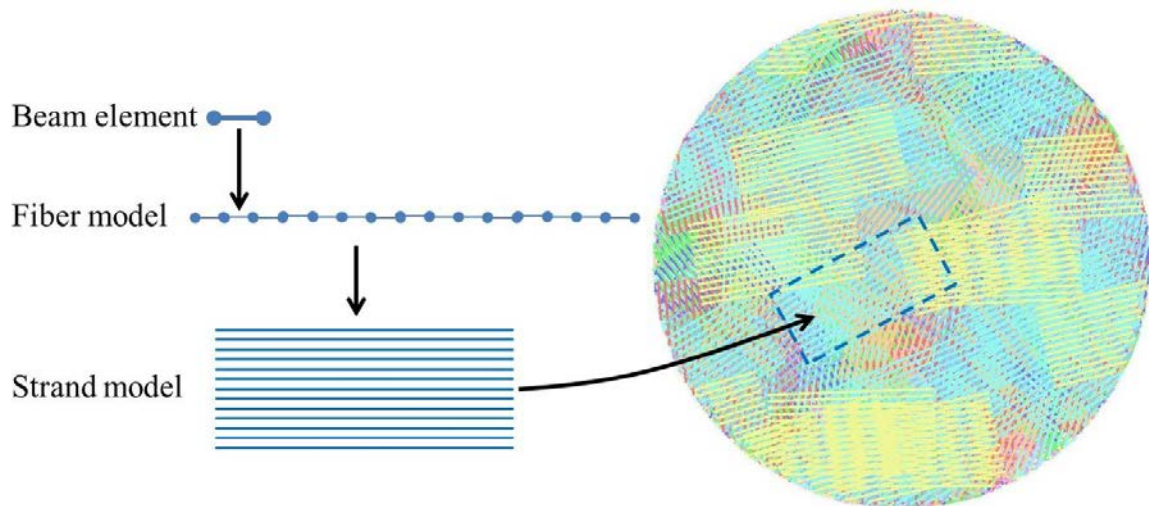


Fig.4: Test specimen simulation model

Macroscopic mechanical properties during compression molding are controlled by the combination of mechanical properties of the carbon fiber and matrix (Young's modulus, Poisson ratio and viscosity or work hardening) and resistive forces against fibers sliding axially in the matrix. The resistive forces are defined by a user-subroutine coupling option and calculated as elastic-perfectly plastic with a maximum resistive force in a proprietary user-subroutine developed by JSOL. In the first step realistic mechanical properties of the carbon fiber and the matrix scaled by V_f were entered in the simulation model. Next the resistive force was tuned to match contact forces from the tests.

Fig.5 shows the final shapes of the test and the simulation formed by simple compression at temperature 200 degrees. Fig.6 shows contact forces of the simple compression tests at four different temperatures. The simulation results show good agreement to the tests.

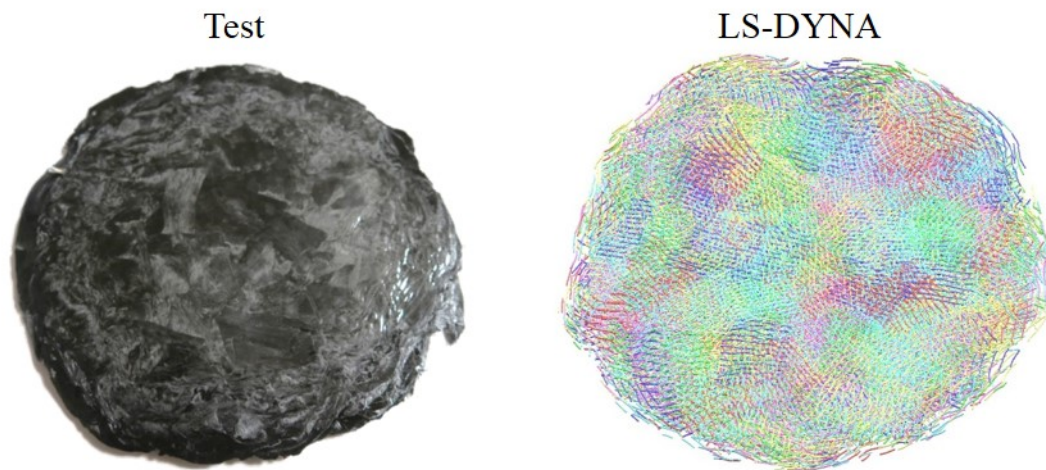


Fig.5: Final shapes formed by simple compression at temperature 200 degrees

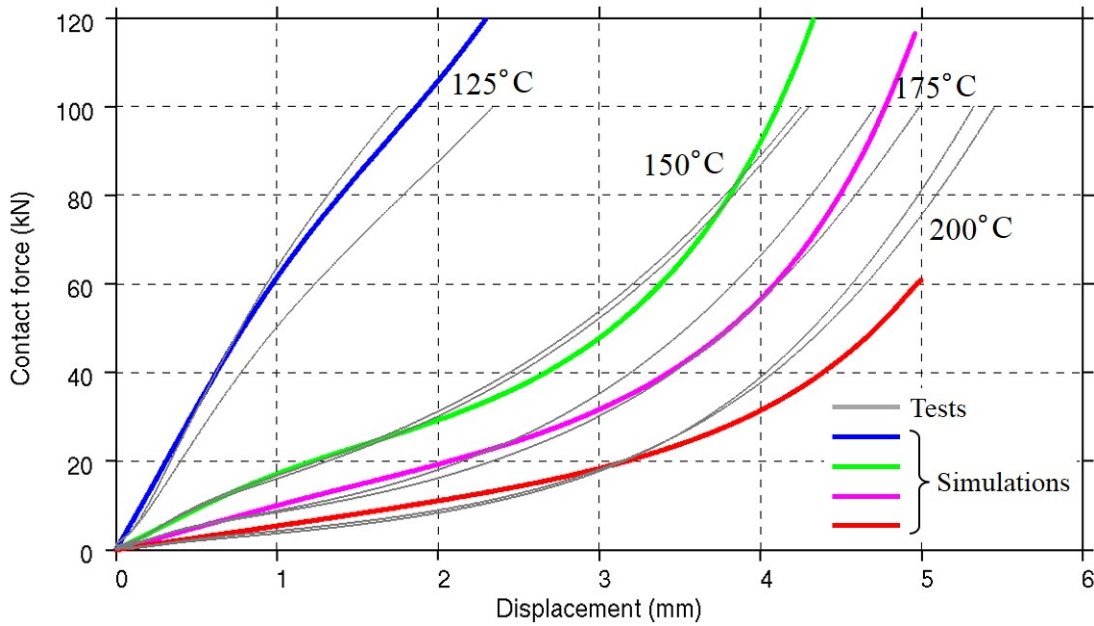


Fig.6: Contact forces at four different temperatures

5 Compression Molding Test and Simulation to Form Cross-Ribbed Component

A compression molding test was performed to evaluate this new simulation technology. Fig.7 shows the ROS thermoplastic composite sheet (Flexcarbon® from Suncorona Oda Co., Ltd.) and the simulation model used in the compression molding. The sheet is square shape, 100mm x 100mm and thickness 8mm. The simulation model is made by the same modelling method as that developed in the simple compression simulation at temperature 200 degrees.

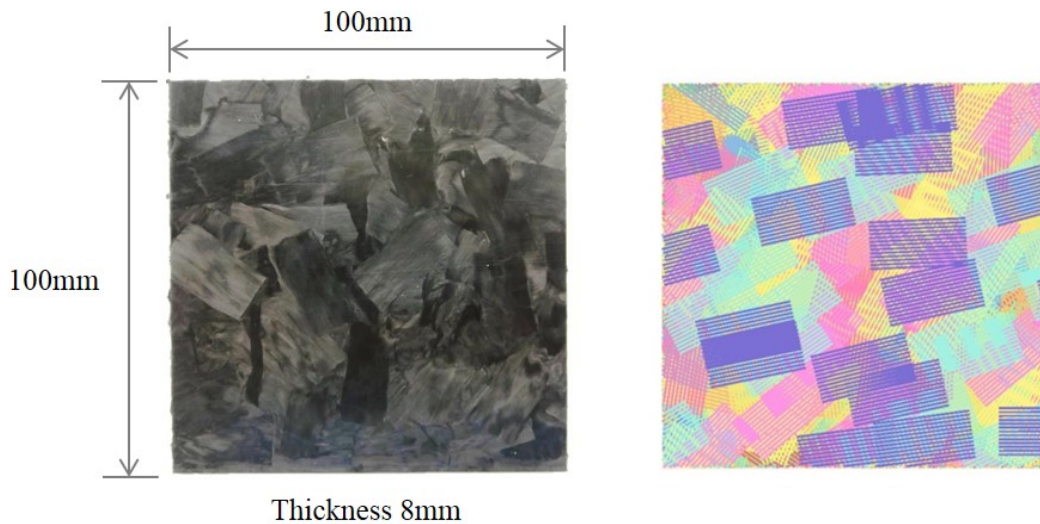


Fig.7: ROS thermoplastic sheet and simulation model

Fig.8 shows the punch and die used in the test and the simulation. The compression molding test was performed by a heat and cool molding method. The ROS thermoplastic composite sheet is heated in an oven until the temperature reaches 200 degrees. The punch and the die are also heated to the same temperature. The heated sheet is moved from the oven to the die and formed in several seconds at temperature 200 degrees. Then the formed sheet is solidified by gradually cooling the punch and the die to a temperature of 90 degrees over a period of several minutes. The molded sheet was then released from the molding system.

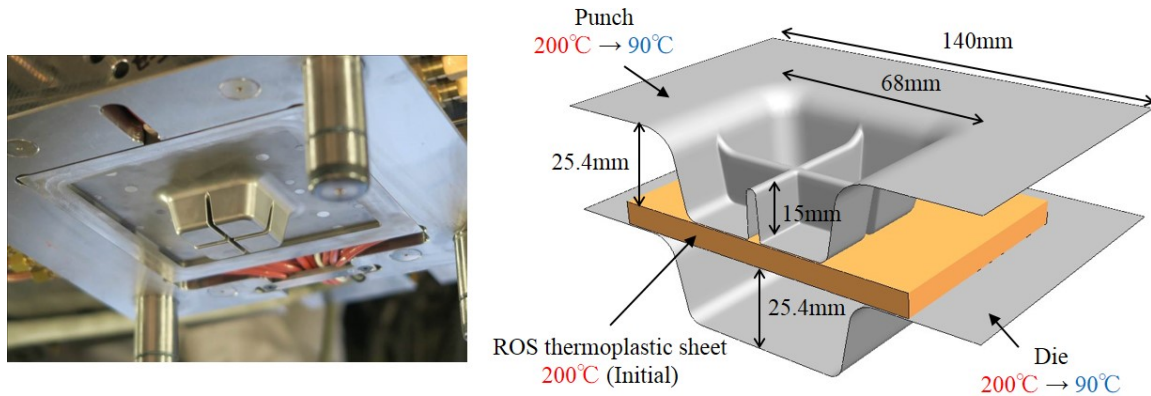


Fig.8: Compression molding to form cross-rib shaped component

Fig.9 shows the final forming shapes from the test and the simulation. The total footprint of expanded material is predicted to be the same as seen in the test.

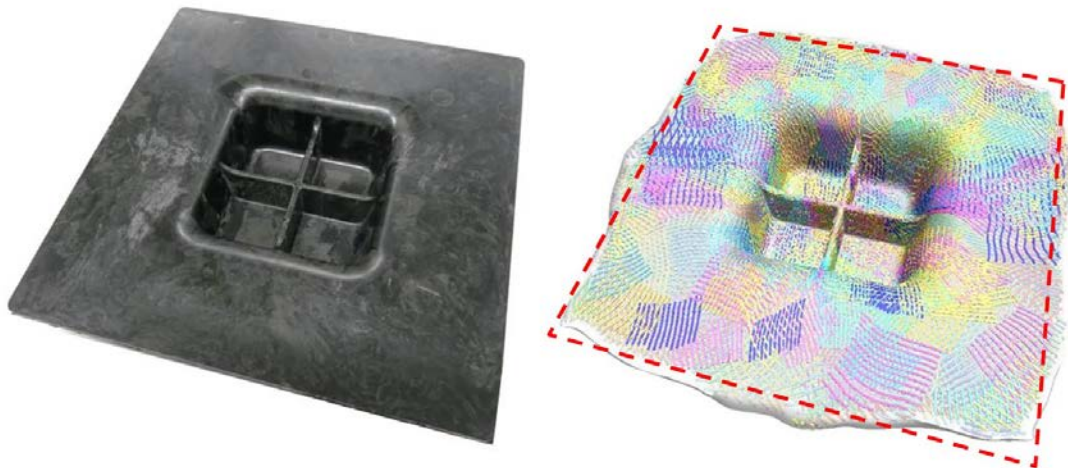


Fig.9: Final shapes formed by compression molding

6 Mechanical Strength Test and Simulation

After the compression molding, mechanical strength test and simulation were performed. Fig.10 shows a static compressive strength test using the component part made of the carbon ROS thermoplastic composite.

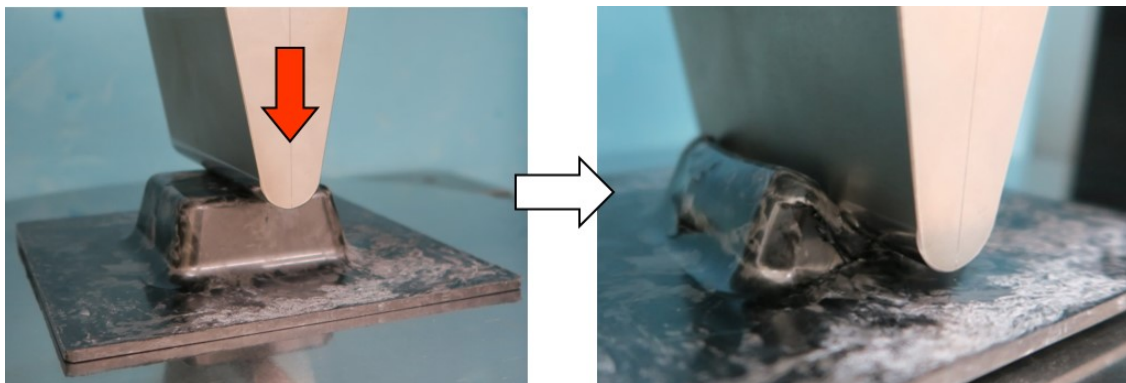


Fig.10: Static compression strength test of carbon ROS thermoplastic composite

Fig.11 shows a simulation model of the component part using the Beam in SPG coupling method `*CONSTRAINED_IMMERSSED_IN_SPG` in LS-DYNA [6]. Beam elements were carried over from the previous compression molding simulation. Polymer matrix was modelled using new meshless Smoothed Particle Galerkin (SPG) elements. SPG elements were given elasto-plastic material properties and rupture simulated by bonding failure between SPG elements, not element deletion [7].

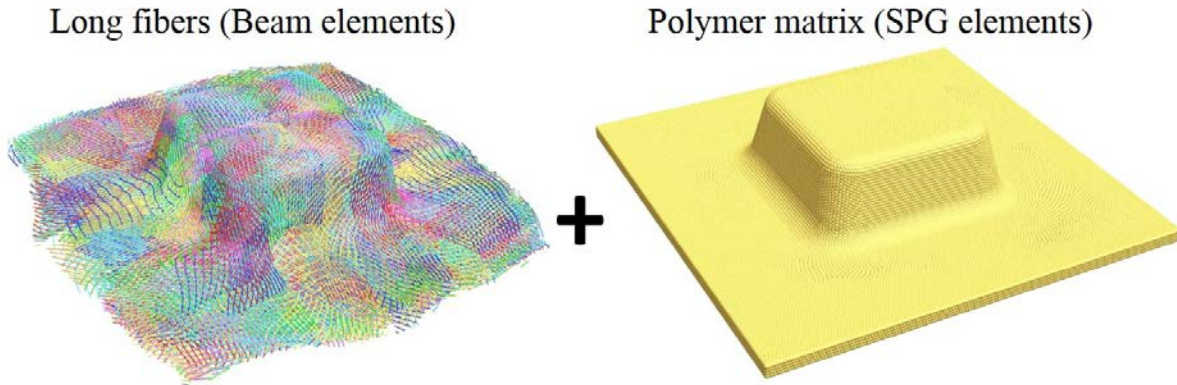


Fig.11: Beam in SPG coupling model

Fig.12 shows a matrix polymer failure behaviour of the test and the simulation. Deformation behaviour of this simulation is very similar to the test result.

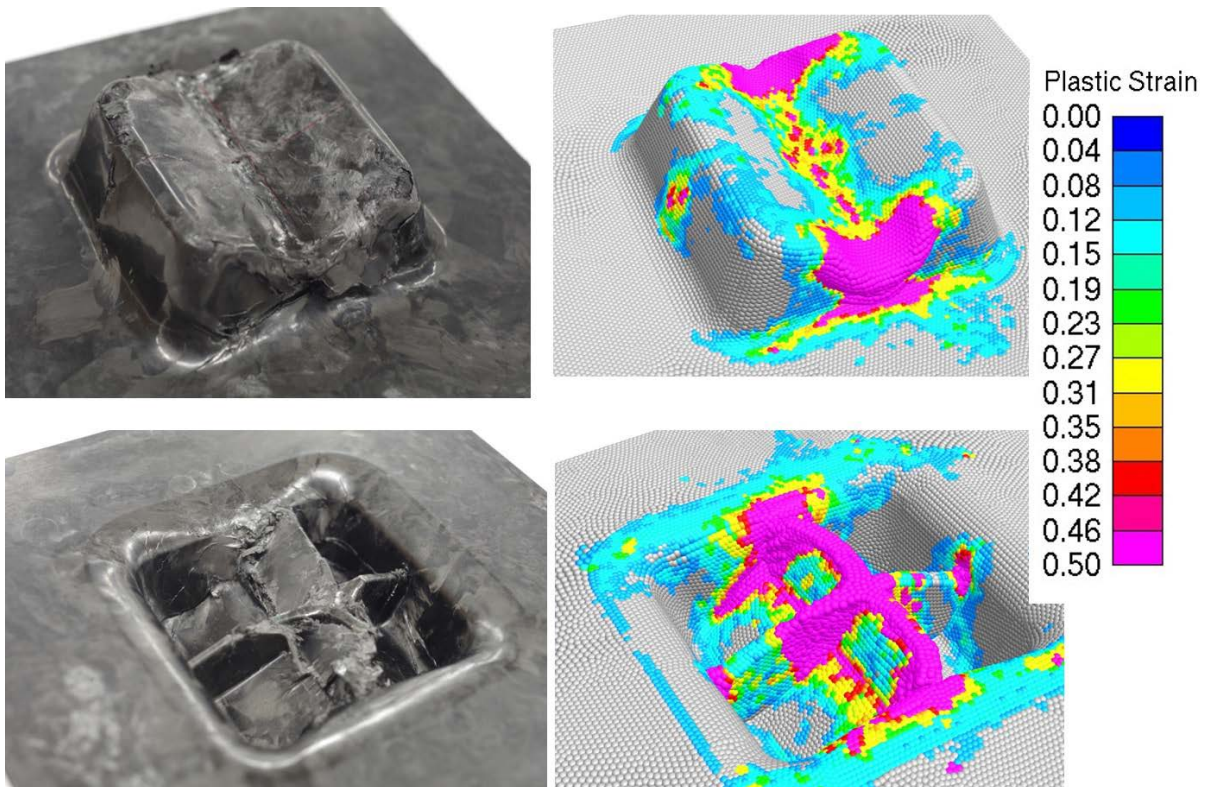


Fig.12: Failure behaviors of test and simulation

Fig.13 shows beam axial force distribution. Beam failure occurred at stresses exceeding the tensile strength of carbon fibers.

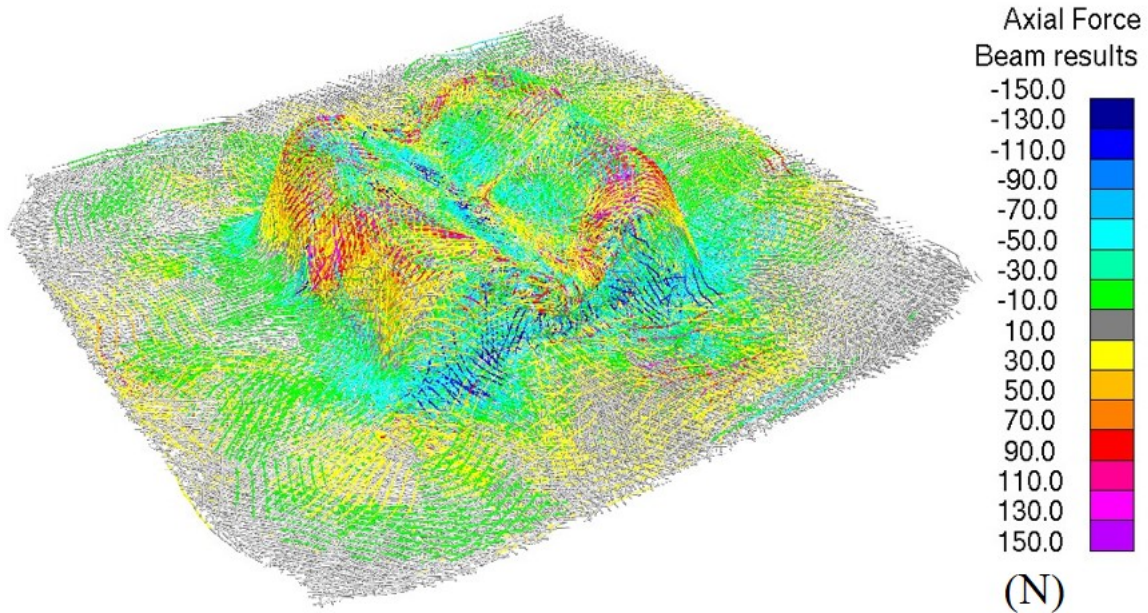


Fig.13: Beam axial force distribution of simulation

Fig.14 shows reaction forces of the test and the simulation. Reaction force of the simulation predicted the first peak well and was close match to the tests overall.

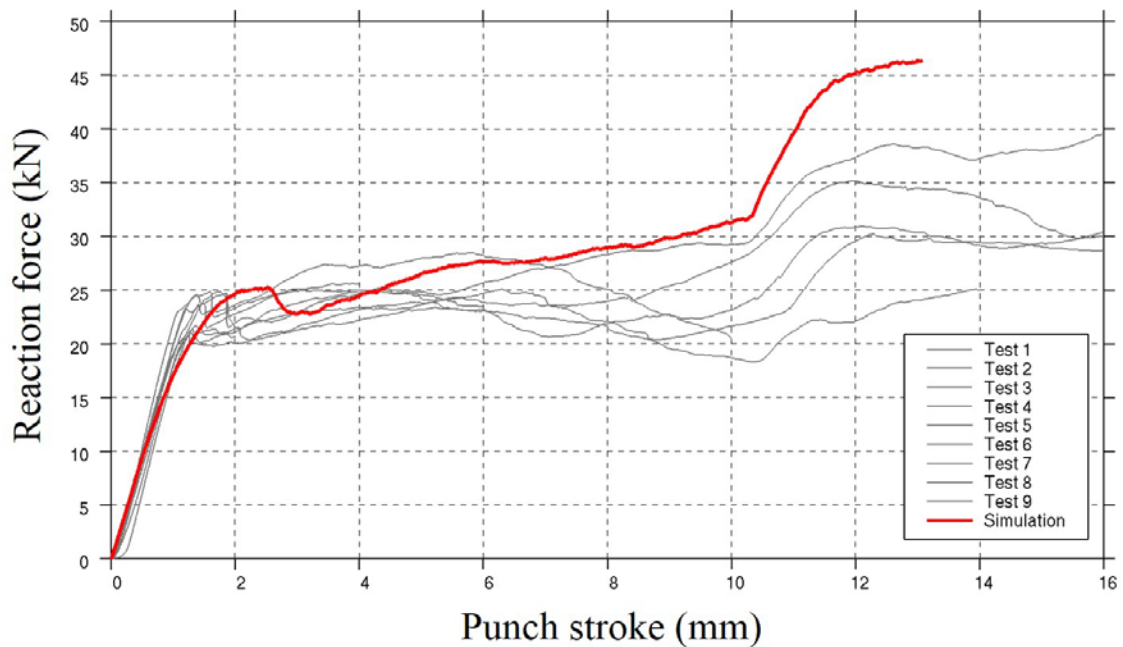


Fig.14: Reaction forces of tests and simulation

7 Conclusion

This new simulation technology has great potential to simulate compression molding of long carbon fiber reinforced thermoplastics with high accuracy and provides much valuable data in analysis results:

- Filling behavior and timing
- Fiber orientation and deformation
- Axial force of fiber
- Stress occurring in matrix
- Identification of weld line locations and matrix rich region
- Distribution of fiber volume fraction (Vf)
- Punch reaction force
- Heat transfer and temperature distribution
- Other measureable values

Strength analysis using the result of compression molding simulation for a long carbon fiber reinforced thermoplastic component was performed successfully and deemed to have great potential to predict mechanical strength with high accuracy.

8 Acknowledgments

We would like to show grateful appreciation to Suncorona Oda Co., Ltd. who supplied the ROS thermoplastic composites. We also would like to thank JAPAN TESTING LABORATORIES, Inc. (simple compression and strength tests) and Asano Co., Ltd. (compression molding tests) to perform high quality tests.

9 Literature

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