Utilization of Surrogate Models for Enhanced Crash Simulation Accuracy of Fiber-Reinforced Plastic Parts

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Abstract

In recent years, the application of plastic in automotive parts has been expanding as a replacement for steel plates, aiming for greater shape flexibility and weight reduction. Among plastics, fiber-reinforced plastic with glass fibers as reinforcement exhibits anisotropy, where the strength characteristics vary depending on the orientation of the fibers. To perform highly accurate crash simulations, it is necessary to reproduce this anisotropy in the LS-DYNA model.
To reproduce this anisotropy, it is well known to conduct resin flow simulation in advance to obtain fiber orientation information and map it to the LS-DYNA model. However, performing resin flow simulation requires mastering advanced specialized software, knowledge of plastic molding, and a long working time, making it not easily accessible.
Therefore, we developed a system that allows anyone to easily and quickly reflect the anisotropy of fiber-reinforced plastic in the LS-DYNA model by using a surrogate model of resin flow simulation as the core, along with a super-fast mapping tool and an intuitive GUI. This resulted in a 99.6% reduction in man-hours compared to conventional methods.
Furthermore, the model combining this method with **`*MAT_4A_MICROMEC`** showed improved reproducibility of strength characteristics compared to the isotropic **`*MAT_SAMP-1`** model.

1 Introduction

Accurately simulating the deformation behavior of components in crash simulation is crucial for minimizing discrepancies with actual vehicle crash test results. Glass fiber-reinforced plastics (GFRP) exhibit anisotropic mechanical properties, primarily due to the orientation of the reinforcing fibers. (Fig.1)

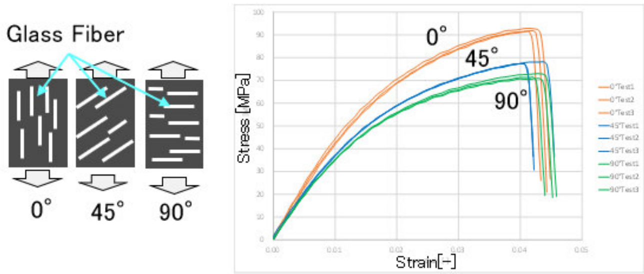

Fig.1: Anisotropy of Fiber-Reinforced Plastic

Therefore, it is essential to incorporate fiber orientation effects into crash simulation models to improve the accuracy of deformation predictions. Typically, this is accomplished by first conducting resin flow analyses to predict fiber orientation distributions during the molding process and then mapping this orientation data to the crash simulation model for subsequent analysis [1].

However, because resin flow analysis is computationally intensive and time-consuming, it is often impractical to incorporate it routinely into the vehicle development cycle. As a result, conventional crash simulations are typically performed using a representative fiber orientation angle, rather than detailed, part-specific fiber orientation data. This simplification poses challenges for both shortening the development period and improving the accuracy of crash simulation predictions.

Against this background, the adoption of surrogate models has recently been drawing growing attention [2]. The present study proposes a surrogate model for resin flow analysis that utilizes a voxel-based representation in combination with a 3D extended pix2pix algorithm [3], enabling rapid prediction of fiber orientation data.

2 Construction of the Surrogate Models

2.1 Dataset Construction

To construct the training dataset, 2,000 resin flow analysis cases were conducted per training model. Each case used a voxelized representation [4] of the component geometry, with a uniform voxel count of 8 million (200 x 200 x 200), which minimized mesh division variability and enabled consistent treatment of fiber orientation data (Fig.2). For every case, geometry data, gate positions, and flow path lengths from the gates to each voxel were assembled. These were used as input features for machine learning models, with fiber orientation data serving as target outputs.

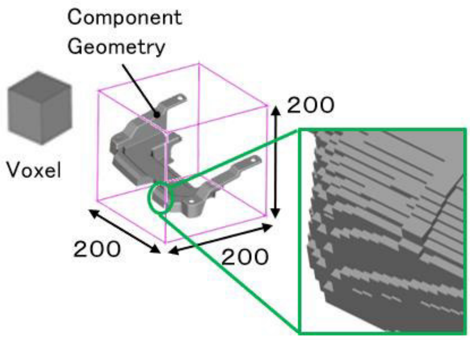

Fig.2: Voxel Conversion Model

2.2 Applied Algorithm

As shown in Fig. 3, a model was constructed by extending the pix2pix framework to three dimensions. Since pix2pix is a method based on Generative Adversarial Networks (GANs), simultaneous training was performed on two Deep Neural Networks (DNNs): a generator and a discriminator.

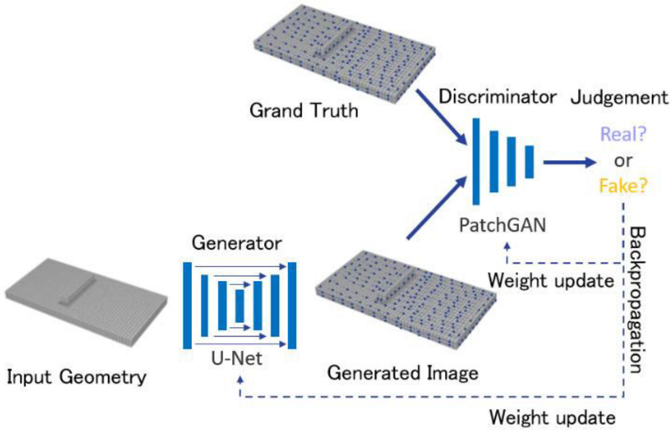

Fig.3: pix2pix Model

3 Validation of the Surrogate Models

3.1 Model Validation Workflow

New components not used during training were prepared. As a preprocessing step, the component geometry was converted from STL format to a voxel model, following the same procedure as in the training phase. Additionally, the flow path length from the gate to each voxel was calculated and provided as input. Fig.4 illustrates the overall workflow for fiber orientation estimation.

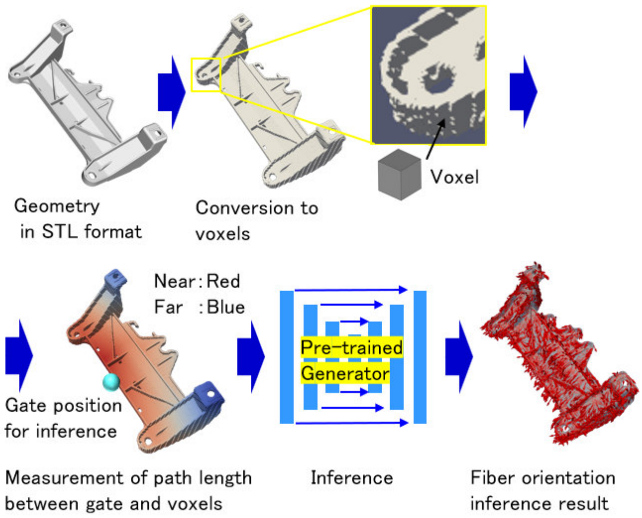

Fig.4: Model Validation Flow for Fiber Orientation Prediction

3.2 Prediction Results

To evaluate prediction accuracy, it is necessary to assess the difference between the fiber orientation obtained from actual flow analysis and that predicted by the surrogate model. In this study, the fiber orientation data from flow analysis and surrogate model predictions were compared, and the angular error was measured. The target accuracy for the model was set to be less than 45 degrees.

The prediction results are shown in Fig.5. The model successfully captured the radial flow pattern emanating from the gate. As shown in Fig.6, the average angular error across the entire component was 22 degrees. Even when the component was subdivided into a 5×5 grid for localized comparison, all regions met the target accuracy threshold, demonstrating that the model achieved high prediction accuracy.

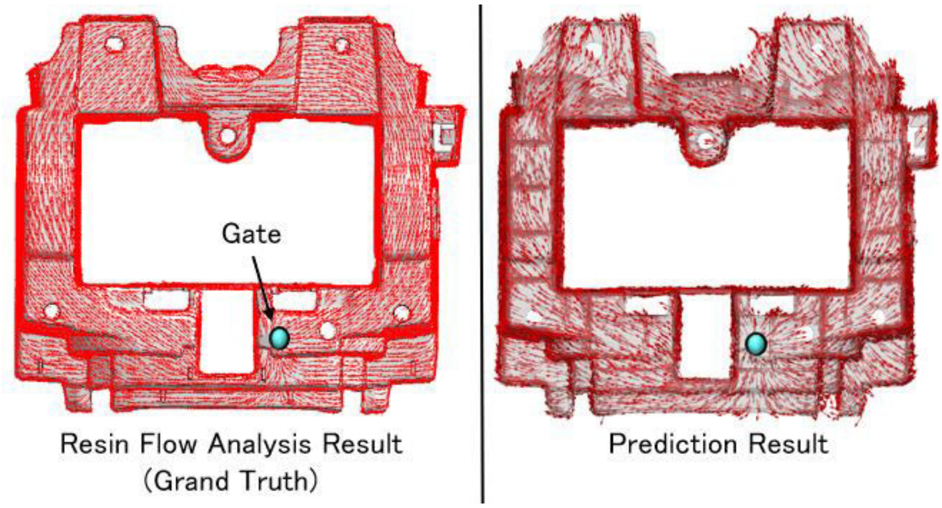

Fig.5: Comparison between Resin Flow Analysis and Prediction Result

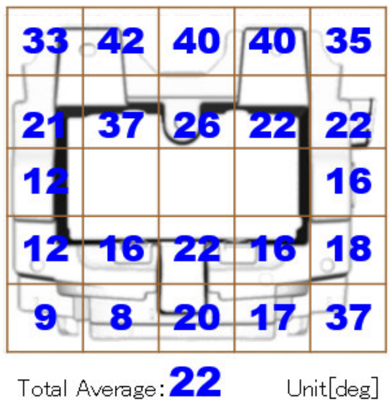

Fig.6: Fiber Orientation Angular Error

3.3 Prediction Time

Conventional flow analysis required approximately 25 hours from model creation to result evaluation. In contrast, the use of surrogate model eliminates the need for flow analysis model generation and computation. By preparing the 3D CAD data and performing preprocessing in 2 minutes, followed by 1 minute of inference, fiber orientation can be output in a total of just 3 minutes—achieving a 99.6% reduction in processing time (Fig.7).

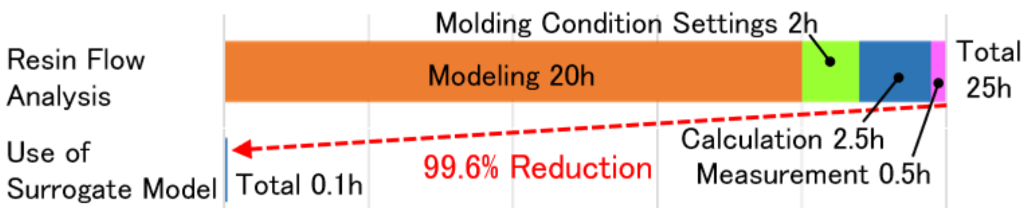

Fig.7: Comparison of Work Hours

4 Validation of Crash Simulation Prediction Accuracy

The fiber orientation data obtained from the surrogate model was applied to the crash simulation model to evaluate its impact on prediction accuracy.
Two crash tests were conducted in which a fiber-reinforced resin component was fixed in place and impacted by an adult head impactor. In both tests, cracks were observed near the left and right mounting points, specifically in regions A and B. (Fig.8)

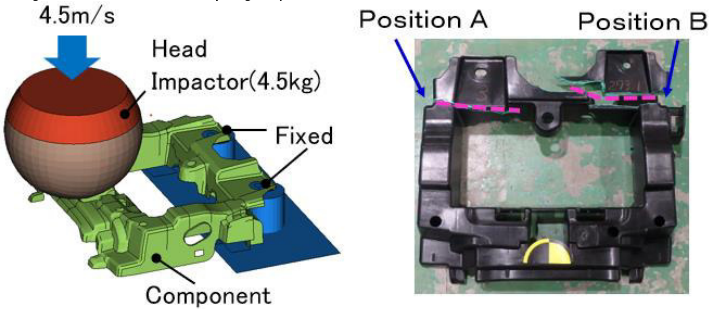

Fig.8: Test Conditions and Result

A crash simulation model corresponding to the physical test was constructed, and two cases were compared:

- Conventional model
  No reproduction of anisotropy.Using conventional representative fiber orientation angles with **`*MAT_SAMP-1`**.

- Use of surrogate model
  Incorporating fiber orientation data with **`*MAT_4A_MICROMEC`** obtained from the surrogate model to reproduce anisotropy.

The use of surrogate model successfully replicated the same fracture locations observed in the physical test. In contrast, the conventional model exhibited a tendency to overpredict fracture, with cracks appearing not only in regions A and B but also in other areas, resulting in deformation behavior significantly different from the test results (Fig.9).

As a result, the impactor load progression revealed that the conventional model reached its peak earlier, whereas the use of surrogate model showed improved alignment with the fracture timing observed in the physical test. In terms of peak load error relative to the test, the conventional model exhibited a deviation of -19%, while the surrogate model case showed a deviation of +11%, representing an 8% improvement in prediction accuracy over the conventional approach (Fig.10, Table 1).

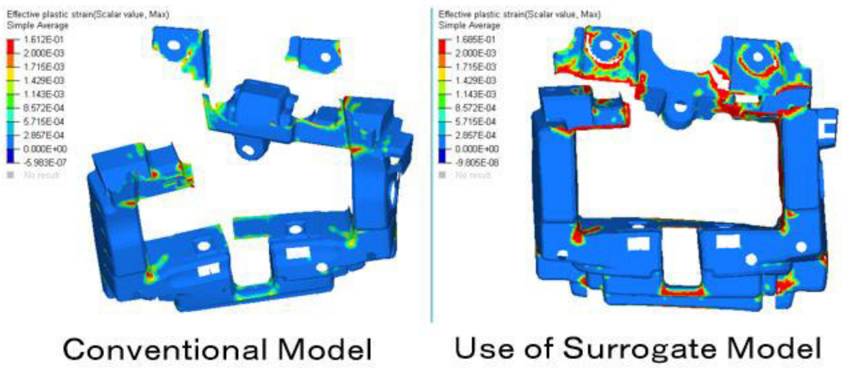

Fig.9: Comparison of Deformation in Simulation

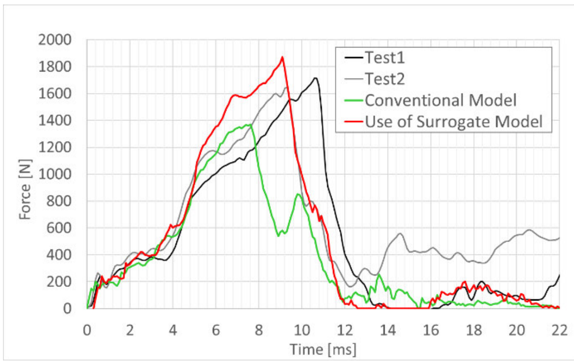

Fig.10: Impactor Force Diagram

Case	Force[N]	Error
Test Average	1682	-
Conventional Model	1370	-19%
Use of Surrogate Model	1873	+11%

Table 1: Impactor Force Maximum Value

5 Summary

In this study, a surrogate model for resin flow analysis was developed and validated to enable crash simulations that incorporate fiber orientation data within the standard vehicle development process. The following conclusions were obtained:

- The developed surrogate model accurately predicted fiber orientation, with angular errors in all evaluated regions remaining below 45 degrees.
- The time required to obtain fiber orientation data was reduced by 99.6%.
- By incorporating fiber orientation from the surrogate model into the crash simulation model, the reproducibility of fractures in component-level tests was improved, and the absolute error in the peak load of the impactor decreased by 8%.

Future research will explore the application of this method to other areas, such as predicting the properties of cast materials.

6 Literature

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