Development of Tied Overlapping Shell Technique to Simulate the Path of Crack Propagation in Polymer Parts

Shigeki Kojima, Katsuya Ishibashi
TOYOTA TECHNICAL DEVELOPMENT CORPORATION

Tsuyoshi Yasuki, Hideaki Arimoto
Toyota Motor Corporation

Abstract

This paper describes a new finite element modeling technique to simulate the path of crack propagation in polymer parts. In this new technique "tied overlapping shell technique", base and overlapping elements make up the finite element model surface. The overlapping elements are rotated 45 degrees with respect to the base elements and are connected by tied contact.

Tied overlapping shell technique decreased mesh pattern dependency of FE crack propagation. Tied overlapping shell technique was applied to a polymer door trim model, and impactor crash FE analysis was performed. The result of the FE crack propagation path with the new technique correlated with the experimental result.

1. Introduction

Finite element (hereinafter referred to as "FE") analysis has been increasingly used in helping develop the crash performance of vehicles. In a crash FE analysis including occupant safety, it is useful to accurately predict not only the airbag deployment but also the deformed shape of polymer interior parts. Since polymer interior part deformation may include crack propagation in collisions, it is also useful to predict the crack propagation of polymer interior parts.

Many FE analysis techniques have been developed for simulations of crack propagation. Tabiei et al.(2002) have developed an FE analysis method with the automated fracture procedure. To predict the path of crack propagation precisely, elements need to be aligned with the crack propagation direction at the crack tip. The automated fracture procedure aligns elements with the crack propagation direction in a remesh process, and predicts the path of crack propagation by repeated remesh processes. It is not easy to apply this method to an FE crash analysis with a large full vehicle model. Instead, a more suitable method of element deletion has been used to simulate crack propagation in explicit codes such as LS-DYNA®. However, in this method, it is difficult to simulate actual crack propagation because the mesh pattern may not be aligned with the crack propagation direction (hereinafter referred to as "mesh pattern dependency of crack propagation"). Xue et al. (2006) have reported improvement of the element deletion criteria for crack propagation, but no method for the decrease of mesh pattern dependency in predicting crack propagation has been reported.

This paper describes the development of a new modeling method to decrease the mesh pattern dependency of crack propagation and the verification of the crack propagation path between a polymer door trim impact experiment and FE analysis with the new modeling method.

2. Methods

2.1 Tied Overlapping Shell Technique

To decrease mesh pattern dependency of FE crack propagation, a new modeling technique was devised. The new modeling technique consists of element groups made of base elements and overlapping elements shown in Figure 1. A pair of a base and an overlapping element represents one typical element.

The new modeling technique called "tied overlapping shell technique" has the following are characteristics:

- Base elements are regular tetragon shell elements.
- Overlapping elements are also regular tetragon shell elements that are rotated 45 degrees with respect to the normal direction of base elements' surface.
- Tied contact is defined between base elements and overlapping elements.
- Tied overlapping shell 0, 15, and 30 degrees models are defined in reference to the angle of the bottom line of base elements with respect to the horizontal axis shown in Figure 2 (hereinafter referred to as "tied overlapping shell XX deg. model").

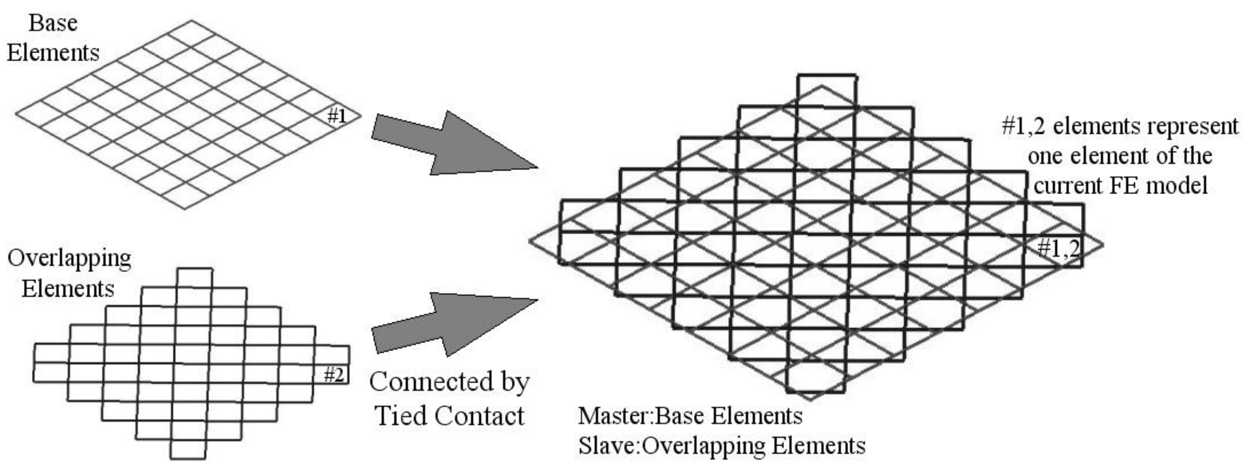

Figure 1. Tied overlapping shell technique.

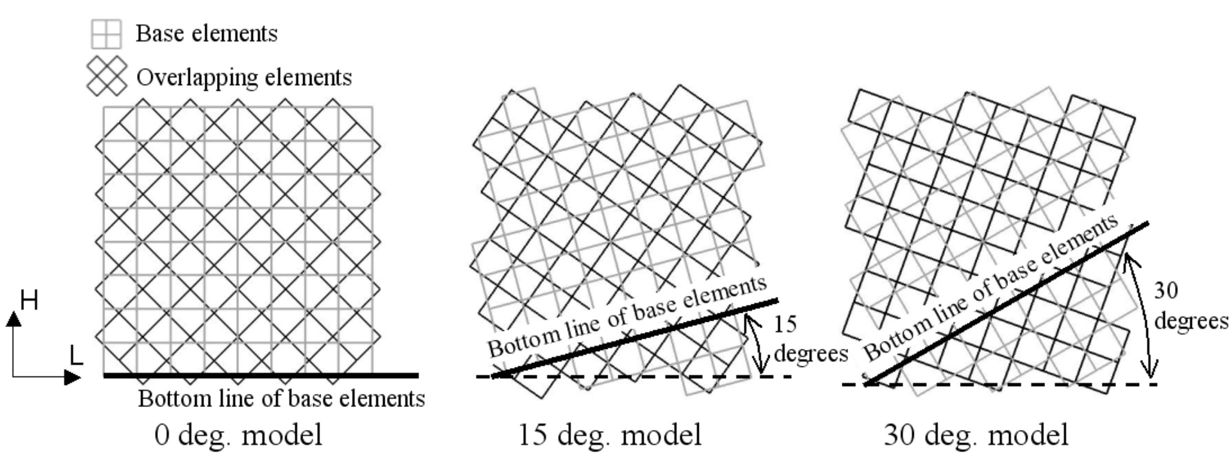

Figure 2. Tied overlapping shell 0, 15, and 30 deg. models.

2.2 Material Definition

The material definition of tied overlapping shell technique was considered in this section. A method that distributes the material property in half for base/overlapping elements was developed, and equations (1), (2), and (3) were expanded. In tied overlapping shell technique, mass density, Young's modulus and yield stress should be divided by 2.

Mass : $$S \times t \times \rho = S \times t \times \rho/2 + S \times t \times \rho/2 \quad (1)$$

Time step : $$\frac{L}{\sqrt{E/\rho}} = \frac{L}{\sqrt{\frac{E/2}{\rho/2}}} \quad (2)$$

Bending stiffness : $$\frac{E \times t^3}{12 \times (1 - pr^2)} = \frac{E/2 \times t^3}{12 \times (1 - pr^2)} + \frac{E/2 \times t^3}{12 \times (1 - pr^2)} \quad (3)$$

Current FE Model
Tied Overlapping Shell Base Elements
Tied Overlapping Shell Overlapping Elements

S : Area of a shell element
t : Thickness of a shell element
ρ : Mass density of a real plate
L : Length of a shell element
E : Young's modulus of a real plate
pr : Poisson's ratio of a real plate

3. Results

3.1 Validation of the Material Definition

We first wanted to validate the tied overlapping shell model before crack starts. To validate the material definition of the new method, a simple polymer plate impactor model was developed. This simple model generates a force-deflection curve for comparison against the current model. The boundary conditions are shown in Figure 3. Impactor crash FE analyses were performed on the following two polymer plate models:

- Tied overlapping shell 0 deg. model.
- Current FE model.

Figure 4 shows the time history of the impactor force. The result using tied overlapping shell model showed good correlation with the current FE model. Therefore tied overlapping shell element pairs produce the same force-deflection curve as the single elements of the current FE model.

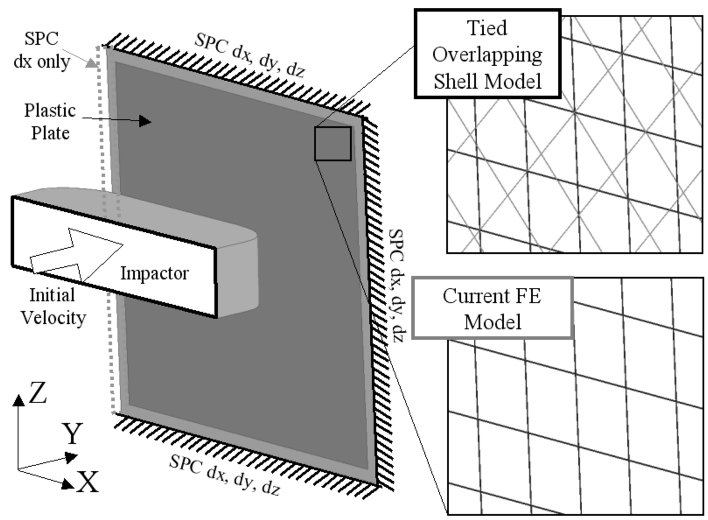

Figure 3. Polymer plate impact FE model.

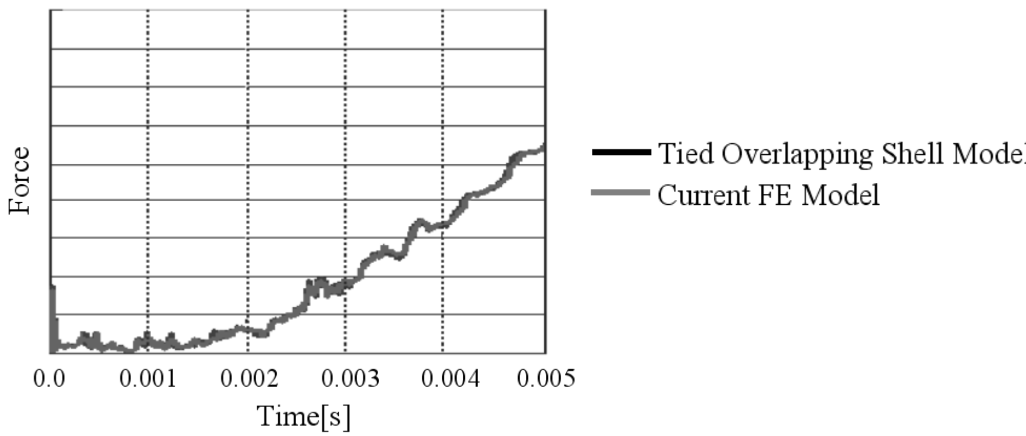

Figure 4. Time history of the impactor force.

3.2 Validation of the Mesh Pattern Dependency of the FE Crack Propagation

To validate the mesh pattern dependency of the FE crack propagation, tied overlapping shell technique was applied to the tensile polymer plate model shown in Figure 5. FE analyses were performed on the following seven FE models with different mesh patterns:

- Tied overlapping shell 0, 15, and 30 deg. models.
- Current FE models with the mesh pattern rotated 0, 15, 30, and 45 degrees with respect to the horizontal axis (hereinafter referred to as "Current 0, 15, 30, and 45 deg. model").

Figure 6 shows the force-stroke curves of each FE model. From these curves, the average force level during crack propagation was calculated, shown in Figure 7. For the current FE model, the average force during crack propagation of the current 15, 30, and 45 deg. models was larger than that of the current 0 deg. model. The force was largest for the current 45 deg. model at 113% of the force for the current 0 deg. model. On the other hand, in the result of tied overlapping shell model, the average crack propagation force of each model is approximately the same. This indicates that the FE crack can progress in any direction with almost the same force. These results validate that tied overlapping shell technique decreases mesh pattern dependency of FE crack propagation.

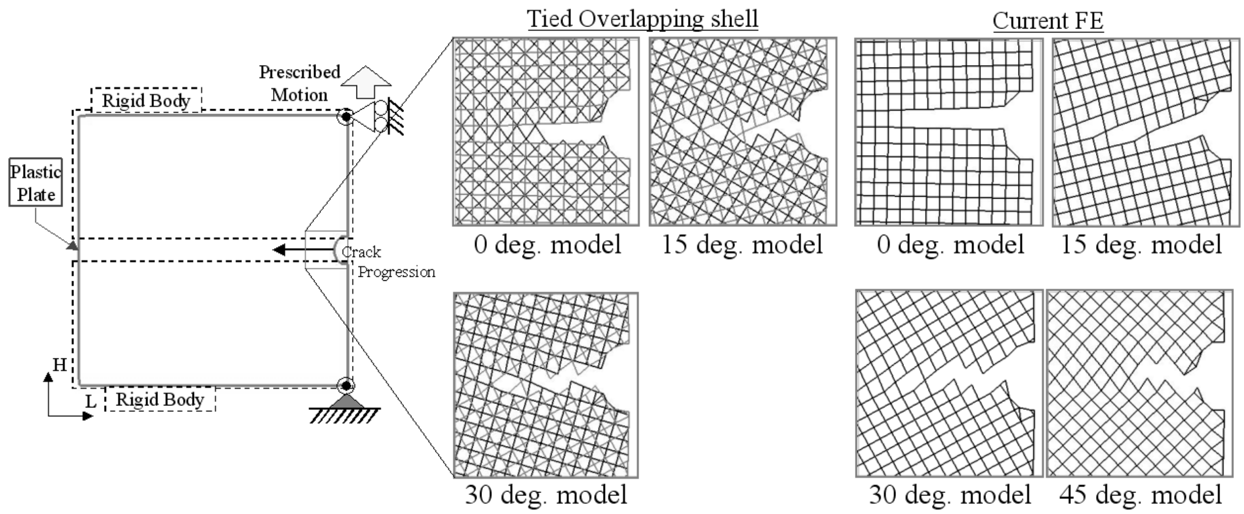

Figure 5.Tensile polymer plate models.

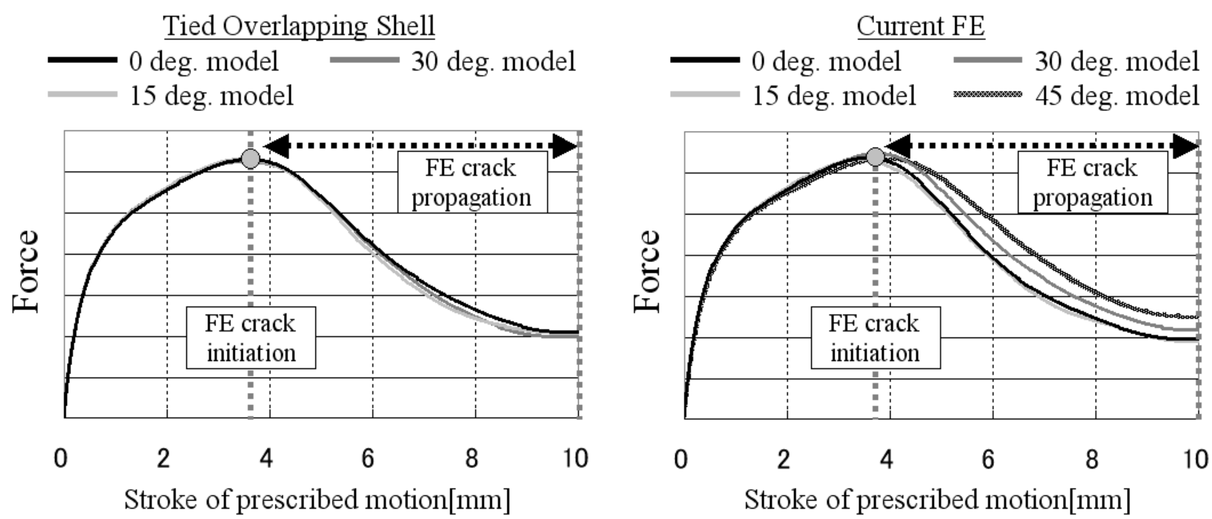

Figure 6a. Force-stroke curves of tied overlapping shell models.

Figure 6b. Force-stroke curves of the current FE models.

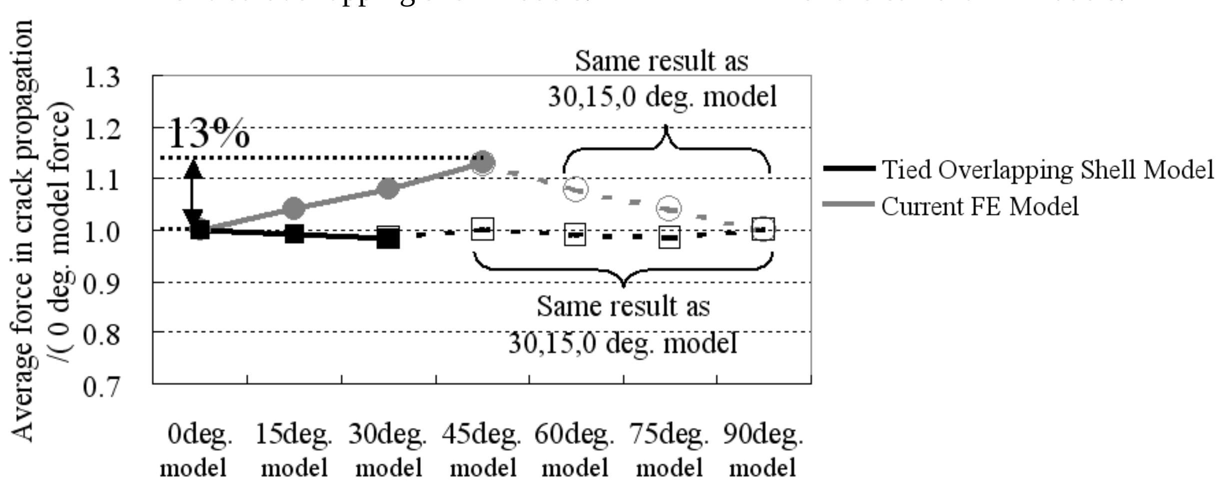

Figure 7. Comparison of the average force during crack propagation between tied overlapping shell model and the current FE model.

3.3 Verification of the FE Analysis using Tied Overlapping Shell Technique

The result of the previous sections confirm that tied overlapping shell technique decreases mesh pattern dependency of FE crack propagation and that the force-deflection curve correlates with the current FE model. To verify the effectiveness of tied overlapping shell technique, the result of the FE analysis using tied overlapping shell technique was compared to experimental results. Tied overlapping shell technique was applied to the door trim model shown in Figure 8a, and impactor crash FE analysis was performed. For purpose of comparison, the impactor crash FE analysis using our current detailed door trim model shown in Figure 8b was also performed. The following are characteristics of the door trim model using tied overlapping shell technique:

- Tied overlapping shell elements were applied to the impacted area.
- Minimum length of shell elements in the impacted area is 2.0mm.
- Four jigs were set up behind the door trim according to the experimental condition.
- Initial velocity was applied to the impactor in the direction of the door trim model.
- *MAT_123 stress-strain curve for the door trim material property was defined with the element deletion using principal strain criteria from tensile experimental results.

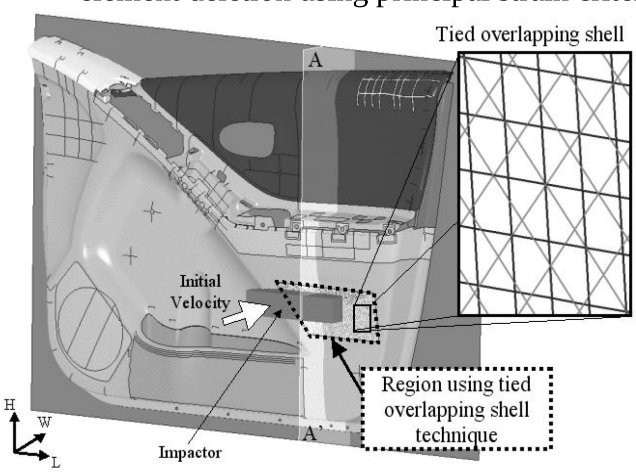

Figure 8a. Door trim impact FE model using tied overlapping shell technique.

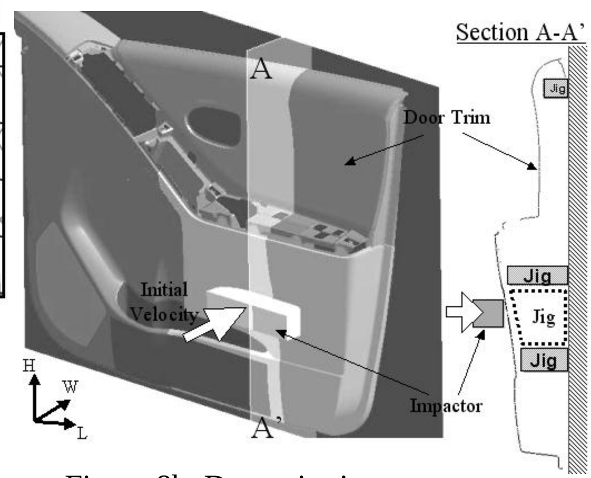

Figure 8b. Door trim impact our current detailed FE model.

Figure 9 shows the comparison of the crack propagation path between the experiment and the FE analyses. Figure 9a shows the experimental result. Two crack propagations occurred during the impactor stroke. Experimental crack #1 progressed toward the front direction from point B at the corner of the impactor. Experimental crack #2 progressed toward the lower right from point B.

Figure 9b shows the FE result using the current detailed model. One crack propagation occurred during the impactor stroke. FE crack #1 progressed toward the front direction from point B' at the corner of the impactor model initially. After FE crack #1 propagation past point C, the crack propagation path changed direction to the lower left direction, away from the path of the experimental crack. The crack propagation corresponding to experimental crack #2 did not occur in the FE analysis.

On the other hand, Figure 9c shows the result of the FE analysis using tied overlapping shell technique. Two crack propagations occurred during the impactor stroke. FE crack #1 progressed toward the front direction from point B' at the corner of the impactor, the same direction as the experimental crack path. FE crack #2 progressed toward the lower right from point B', also the same direction as the experimental crack path.

The crack propagation path of the FE analysis using tied overlapping shell technique correlated well with the experiment.

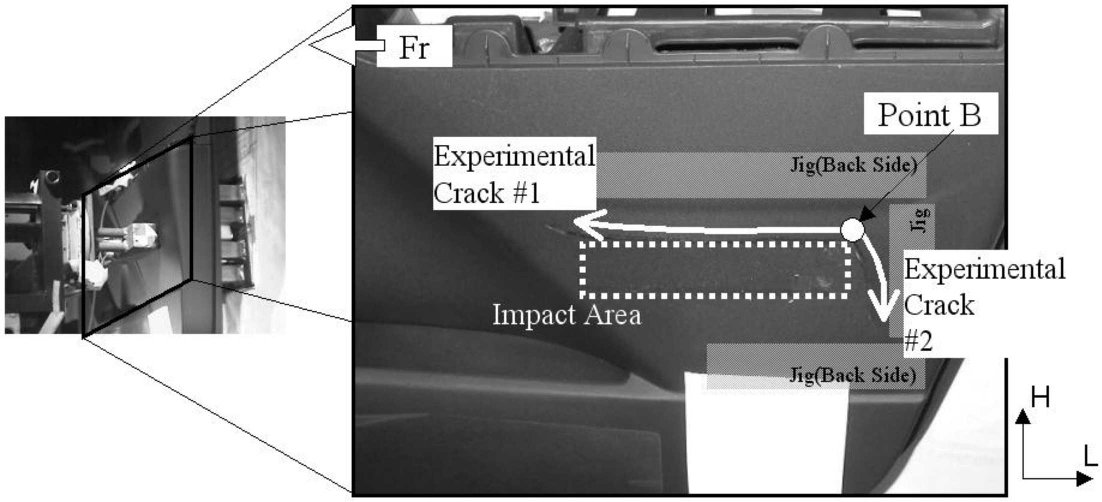

Figure 9a.The crack propagation path of the experiment.

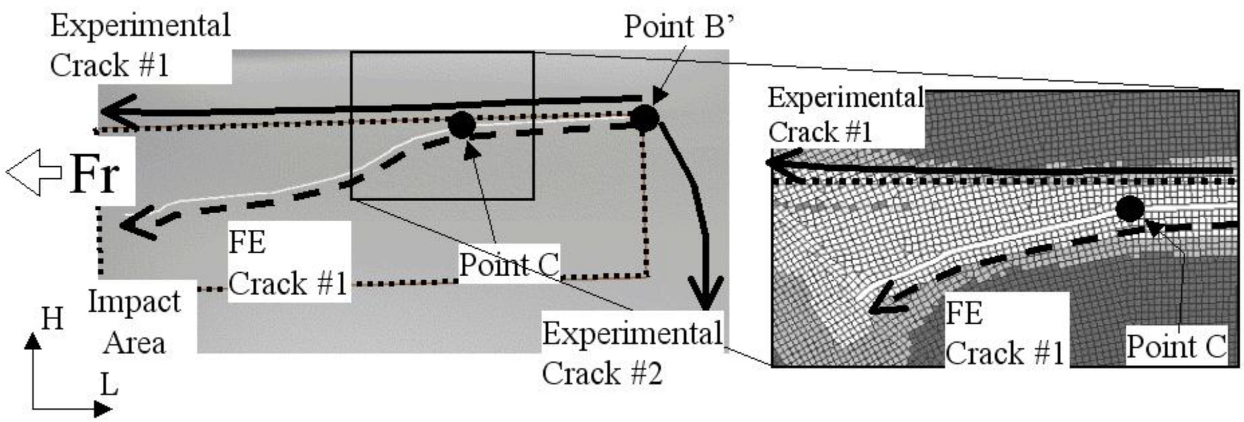

Figure 9b.The crack propagation path of the current FE model.

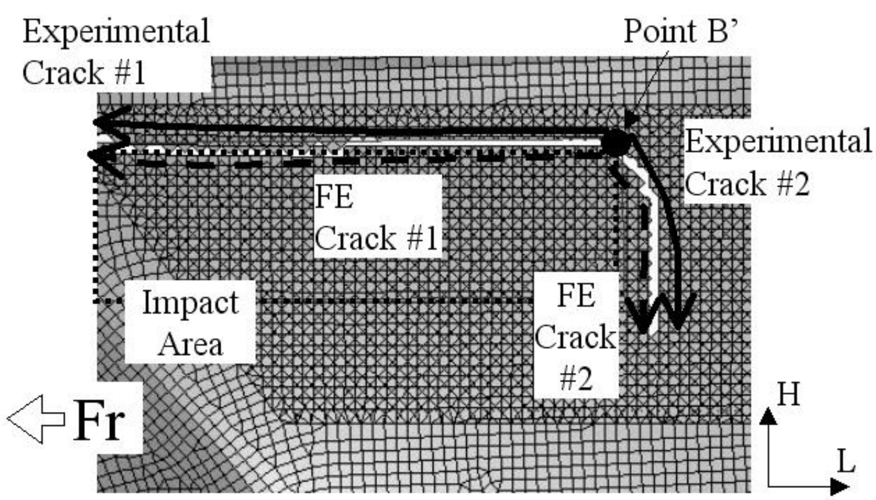

Figure 9c.The crack propagation path of tied overlapping shell model.

Figure 10 shows impactor force-stroke curves. In the experimental result, the force level increased until impactor stroke 40mm and then decreased. The force level of our current FE analysis correlated well with the experiment until the impactor stroke 34mm. After that, the path of FE crack #1 was changed and turned away from the experimental result. The force-stroke curve of the our current FE analysis did not correlate well with the experiment after the impactor stroke 34mm.

On the other hand, in the FE result using tied overlapping shell technique, the force level correlated well with the experiment until maximum stroke 50mm. These results confirm that tied overlapping shell technique improved the accuracy of an FE analysis including crack propagation.

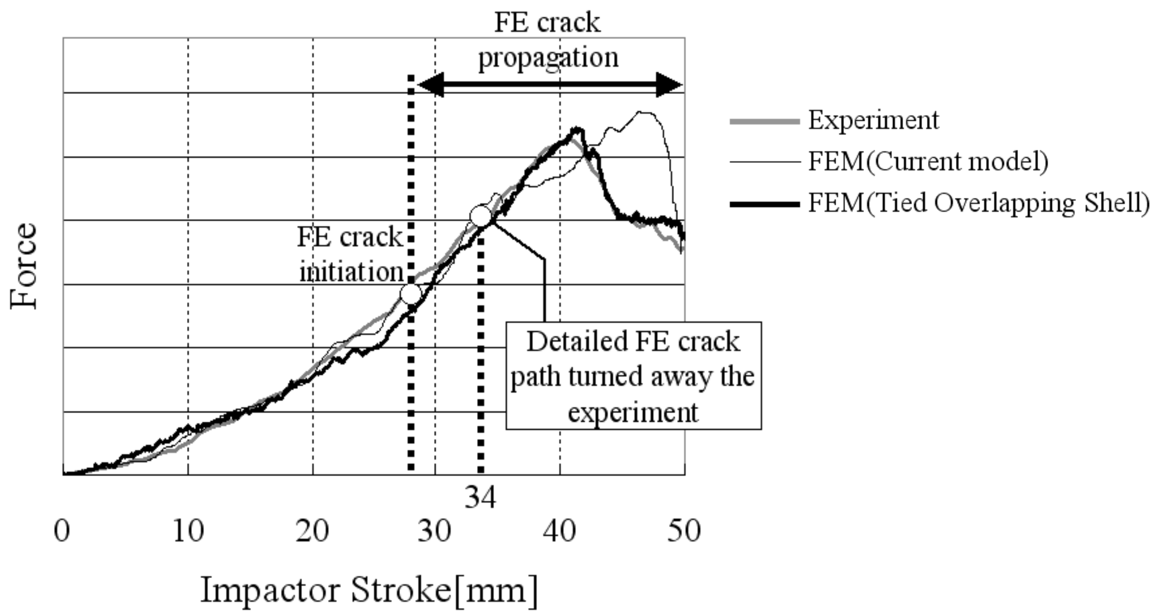

Figure 10. The impactor force-stroke curves in the door trim impact.

4. Discussion

The door trim impact FE analysis using tied overlapping shell technique shows a similar crack propagation path to the experimental result. The reason why is discussed in this section. First, element deletions were investigated at the crack tip corresponding to experimental crack #2 which progressed toward the lower right and downward directions.

Figure 11 shows the principal strain on each element around crack tip elements at impactor strokes 43 and 48 mm. In Figure 11a, the crack progressed toward the lower right direction. Dotted element #1, an overlapping element, was deleted first. Next, dotted element #2, a base element, was deleted and the crack progressed.

In Figure 11b, the crack progressed downward. Dotted element #3, a base element, was deleted first. Next, dotted element #4, an overlapping element, was deleted and the crack progressed. According to the change of load direction, the order of element deletion was changed.

In general, an element of the base/overlapping element that the mesh pattern was aligned to the direction of the crack propagation was first deleted, secondarily an element of the other base/overlapping element was then deleted. This process decreases mesh pattern dependency of the FE crack propagation for the tied overlapping shell technique.

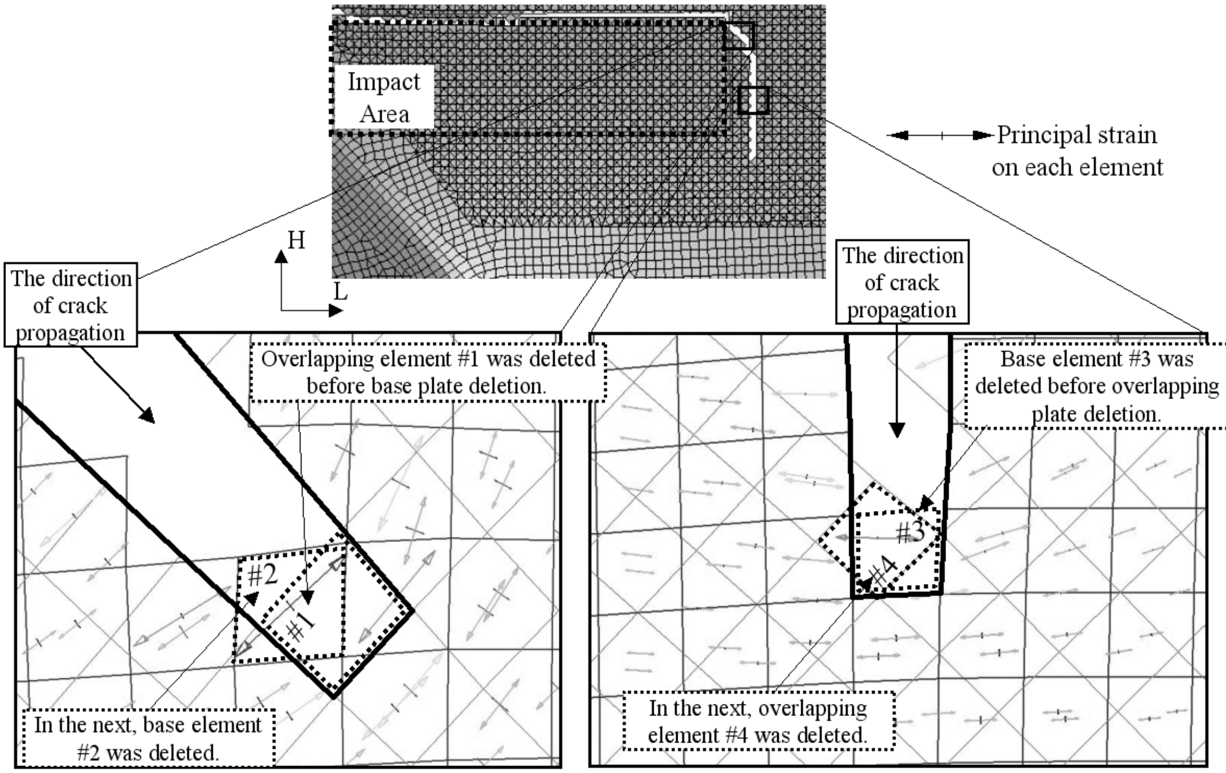

Figure 11a. Lower right crack propagation at impactor stroke 43mm.

Figure 11b. Downward crack propagation at impactor stroke 48mm.

5. Conclusions

To decrease mesh pattern dependency of FE crack propagation, the new modeling technique "tied overlapping shell technique" was devised. The material properties of the mesh for tied overlapping shell technique were validated against the current mesh model. In test piece models, it was confirmed that using tied overlapping shell technique decreased mesh pattern dependency of the FE crack propagation by requiring the same force for crack propagation in several directions.

Tied overlapping shell technique was applied to the door trim impact model and FE analysis was performed. The crack propagation path in FE analysis using tied overlapping shell technique correlated well with the experiment including a curved crack propagation path. Correlation was achieved because the order of base/overlapping element deletion could be changed based on element alignment in the case of load direction change.

References

LS-DYNA user manual V971, Livermore Software Technology Corporation.

Tabiei, A., Wu, J.(2002), Development of The DYNA3D Simulation Code with Automated Fracture Procedure for Brick Elements, 7th International LS-DYNA Users Conference, Dearborn.

Xue, L., Wierzbicki, T.(2006), Verification of a New Fracture Criterion Using LS-DYNA, 9th International LS-DYNA Users Conference, Dearborn.