

Development of Finite Element Models of Restraint System for Injury Analysis in Side Impact

Satoshi Fukushima, Koushi Kumagai, Tsuyoshi Yasuki
Toyota Motor Corporation

Yoshiharu Sonoda, Yu Setoyama
Toyota Technical Development Corporation

Abstract

The use of occupant protection simulation by finite element model is increasing for vehicle development. Finite element models of moving deformable barrier honeycomb, vehicle body, dummy, and restraint system have been developed to predict the dummy injury values. To more accurately predict the dummy injury indices in side impact analysis, this paper describes the improvement of finite element models of restraint system such as torso airbag and polyurethane pad. The improved model of polyurethane pad was able to simulate both of anisotropy and breaking. The improved model of torso airbag was able to simulate the deployment behavior from inside of seat back foam. Finally, full vehicle level FE analysis was conducted to confirm the prediction accuracy of the dummy injury indices using the improved finite element models. The results show that the dummy injury indices correlate well with actual crash testing.

1. Introduction

Finite element (hereinafter, “FE”) analysis is being increasingly used in developing the side impact performance of vehicles. Vehicle side impact performance is assessed according to various factors including vehicle body deformation and dummy injury index. Therefore, prediction of injury indices is also included in FE analysis. Recently in the US, the Insurance Institute for Highway Safety (IIHS) began to rate the side impact crashworthiness, and a vehicle safety standard, FMVSS214, was modified to add requirements for oblique pole side impact. To simultaneously design vehicles to multiple crash conditions and injury indices, enhancing the accuracy of the injury index prediction by FE analysis is desirable.

To predict side impact injury index by FE analysis, an occupant restraint system model is necessary in addition to a moving deformable barrier (MDB), vehicle body, and dummy models, all of which must accurately simulate the defined test condition. Among these models, vehicle body and MDB models with high analysis accuracies have been developed as reported by Kojima, Yasuki, and others ^[1]. Commercially available dummy FE models also have been improved over the years to provide higher analysis accuracies. Accordingly, improvements to the occupant restraint system FE models can help enhance the overall injury index prediction accuracy.

This paper discusses the results of the injury index prediction in oblique pole side impact using improved polyurethane pad and torso airbag FE models.

2. Problems Associated with Previous FE Models

2.1 Previous Modeling Method

Polyurethane pads have previously been modeled using *MAT_BILKHU_DUBOIS_FOAM, one of the material models implemented in LS-DYNA[®] [2]. For torso airbags, the Control Volume (CV) method has been used to simulate the deployment of a flat airbag unfolded in its deployment position (see Fig. 1).

2.2 Accuracy of Previous FE Models

A previous FE analysis model for oblique pole side impact is shown in Fig. 1. The maximum FE-analytic values of principal injury indices divided by the maximum test values are given in Fig. 2. This figure shows that the previous FE models yielded three thoracic rib deflections at approximately 20% less than the test values and pelvic combined force and abdominal upper rib deflection at approximately 10% above the test values.

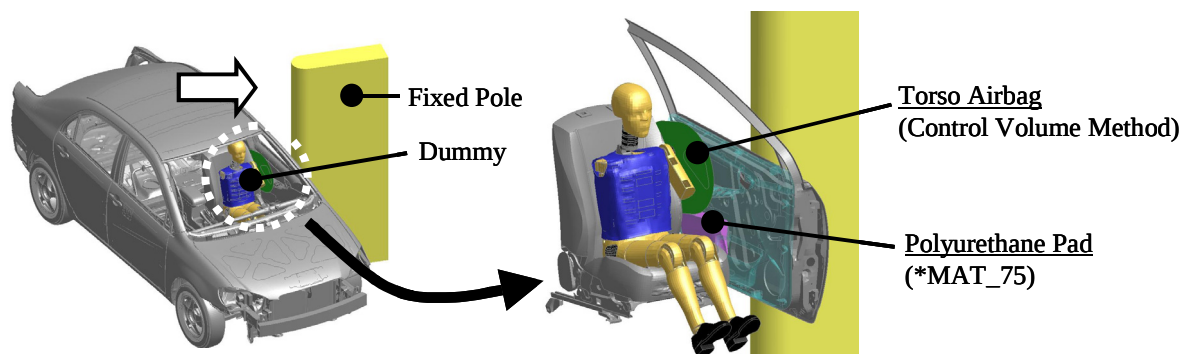


Fig. 1 Models in FE Analysis of Oblique Pole Side Impact

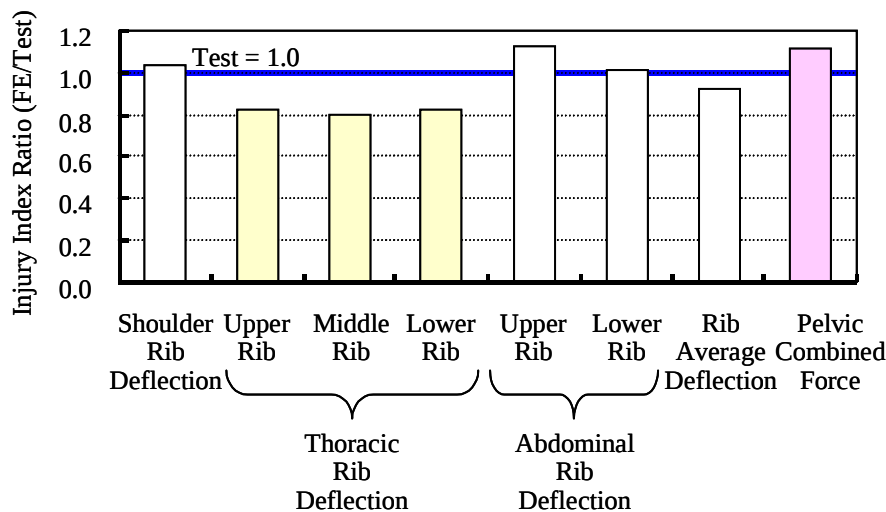


Fig. 2 Comparison of Dummy Injury Indices between Test and FE Analysis

3. Polyurethane Pad FE Model

To improve the accuracy of pelvic combined force prediction by FE analysis, the polyurethane pad FE model was improved so that it could directly transmit impact loads to the test dummy's pelvis on impact.

3.1 Estimating the Major Causes of Pelvic Combined Force Prediction Error

A cross sectional view of the test dummy's hip point height of the model used for FE analysis of the oblique side pole impact is shown in Fig. 3. This figure shows that the polyurethane pad struck the dummy's pelvis at an angle of approximately 30 degrees from the "material axis." Here, the material axis is defined as the direction normal to the polyurethane pad plane facing the dummy's pelvis. In the crash test for comparison with this FE analysis, the test's polyurethane pad cracked as shown in Fig. 4. To understand the differences between the test and the simulation, we investigated the effects of compression direction and cracking to the compression characteristics of polyurethane pads, which had not been taken into consideration in the previous model.

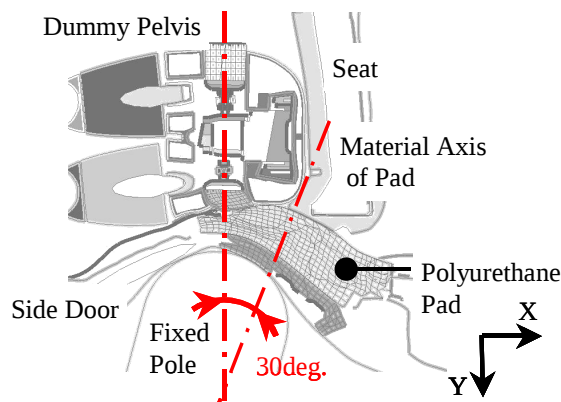


Fig. 3 Cross Section of H-Point Height

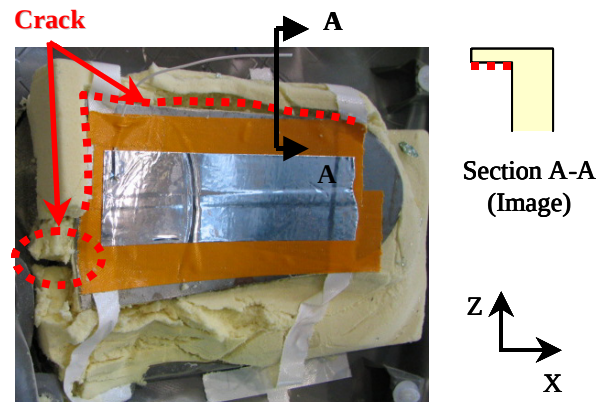


Fig. 4 Deformation and Crack of Polyurethane Pad

3.1.1 Effect of the Polyurethane Pad Compression Direction

Tests were carried out in which the polyurethane pad specimens were statically compressed in three directions at angles of 0, 45, and 90 degrees from the material axis. The test results are shown in Fig. 5. In this figure, the deformation force ratio represents the ratio of the force produced when the polyurethane pad was compressed along the material axis to the deformation force corresponding to a compression ratio of 50%. It was found as shown in Fig. 5 that the polyurethane pad demonstrated an anisotropic property; the deformation force decreased as the compression angle from the material axis increased, with the force being greater in the direction of the material axis.

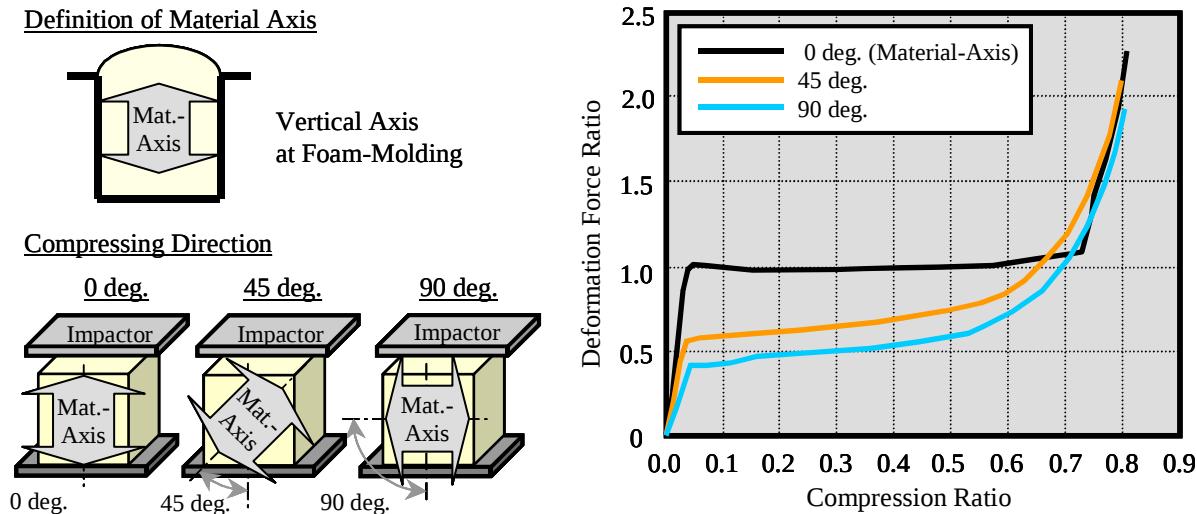


Fig. 5 Comparison of Compression Characteristics in 3 Different Compression Directions

3.1.2 Effect of the Polyurethane Pad Cracking

With the assumption that the polyurethane pad was cracked when it was partially compressed by the side door inner panel, side door beam, and other components on impact, a confirmation test was carried out by pressing only 50% of the test polyurethane pad area as shown in Fig. 6. The test results were compared with the corresponding FE analysis result.

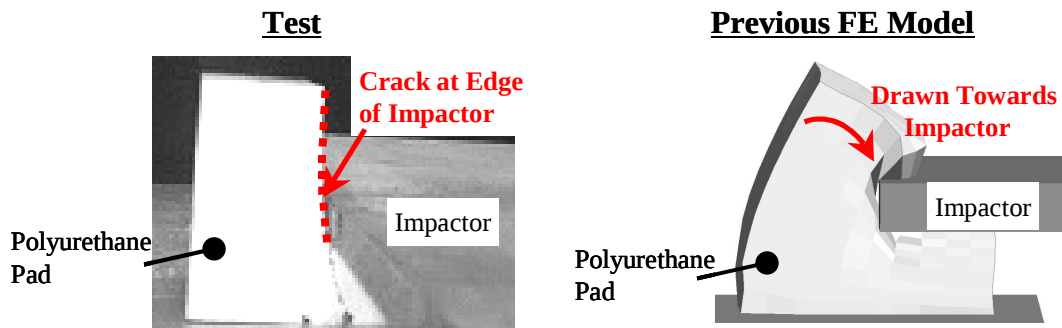


Fig. 6 Comparison of Deformation Behavior of Polyurethane Pad with 50% Pad Compression

In the test, the polyurethane pad demonstrated a deformation pattern different from that obtained by the FE analysis, as shown in Fig. 6. In the test, the polyurethane pad was cracked at the point of contact with the edge of the impactor, while the FE analysis results showed that the polyurethane pad would be deformed while involving the portion free from contact with the impactor. Based on the above comparative study, we concluded that the FE analysis included the force necessary to deform the portion of the pad that was not actually deformed, resulting in a deformation force approximately 15% higher than the test result, as shown in Fig. 7.

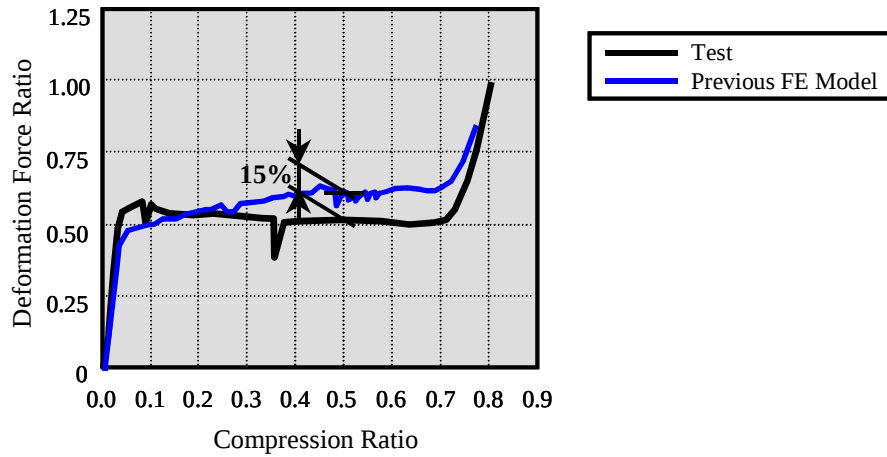


Fig. 7 Comparison of Compression Characteristics with 50% Pad Compression

3.2 Improving the Polyurethane Pad FE Model

The previous polyurethane pad FE model was improved so that it could simulate the anisotropic property and cracking behavior of the polyurethane pad.

3.2.1 Reproducing the Anisotropy of the Polyurethane Pad

To reproduce the anisotropy of the polyurethane pad, we selected *MAT_TRANSVERSELY_ANISOTROPIC_CRUSHABLE_FOAM among the material models implemented in the LS-DYNA. The selected model made it possible to change the deformation resistance depending on the direction of compression.

This material model required a shear stress characteristic (σ_{xy}) as an input. Since it was difficult to obtain this characteristic from a test, we derived the following equation (1) from the paper^[3] presented by Andreas Hirth, Paul Du Bois, Dr. Klaus Weimar, and others. The shear stress characteristic (σ_{xy}) could thus be determined from three-directional compressive stress characteristics (σ_{xx} , σ_{yy} , σ_{45}).

$$\sigma_{xy} = \sqrt{\frac{\sigma_{45}^2 * \sigma_{xx}^2 * \sigma_{yy}^2}{4 * \sigma_{xx}^2 * \sigma_{yy}^2 - \sigma_{45}^2 (\sigma_{xx}^2 + \sigma_{yy}^2 - \sigma_{xx} * \sigma_{yy})}} \dots\dots\dots (1)$$

where,

σ_{xx} : compressive stress along the material axis

σ_{yy} : compressive stress in the direction at right angles to the material axis

σ_{45} : compressive stress in direction at 45 degrees from the material axis

Comparison of the shear stress characteristic determined from the above equation with the test results is shown in Fig. 8. This figure plots the deformation force FE analysis results for a compression ratio of 50% at the compression angle in increments of 10 degrees from the material axis, together with the deformation force test results at compression angles of 0, 45, and 90 degrees from the material axis. As understood from Fig. 8, the improved FE model predicted that the deformation force would decrease as the angle between the polyurethane pad

compressing direction and material axis increased. The analysis results agreed with the test results, verifying that the above described shear stress characteristic (σ_{xy}) determination method was reasonable.

The relations between deformation force ratio and compression ratio obtained by using the improved and previous FE models are compared with the test result in Fig. 9 for a compression angle of 45 degrees from the material axis. As can be seen from this figure, the improved FE model yielded conformity between the test result in the deformation force ratio versus compression ratio curve.

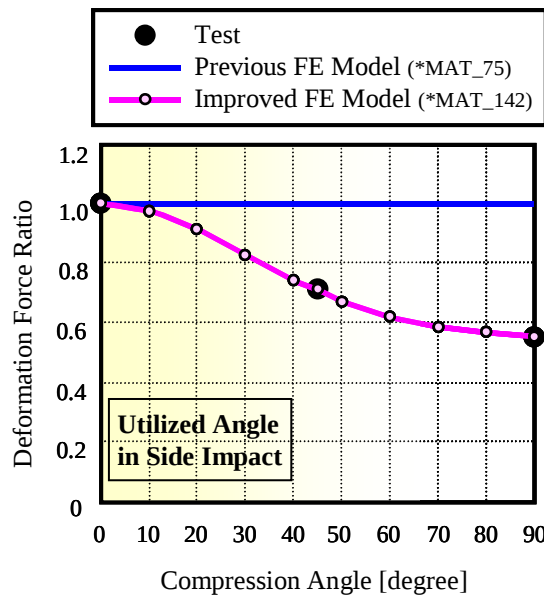


Fig. 8 Comparison of Deformation Force at 50% Compression Ratio

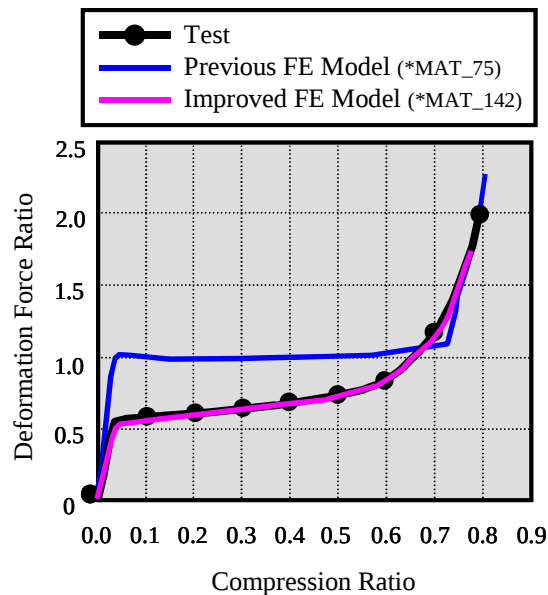


Fig. 9 Comparison of Compression Characteristics in 45 Degrees Compression

3.2.2 Simulating the Polyurethane Pad Cracking Behavior

To simulate the polyurethane pad cracking behavior using the same material model as that used for reproducing the pad anisotropy in the preceding section, we added *MAT_ADD_EROSION implemented in the LS-DYNA. The *MAT_ADD_EROSION made it possible to simulate the cracking behavior by erasing the element when the maximum principal strain reaches the critical value. We determined the critical breaking strain so that the polyurethane pad would break at the same strain as that obtained by the test.

Fig. 10 compares the deformation force ratio versus compression ratio curves predicted by the previous and improved FE models with the test data results. In contrast to the previous model that did not reproduce the cracking behavior of polyurethane pad, the improved FE model enhanced the accuracy to a level of almost exactly reproducing the test result. The improved FE model also reproduced the cracking that occurred at the area in contact with the impactor edge, verifying that this model enhanced the accuracy of the polyurethane pad deformation, as shown in Fig. 11.

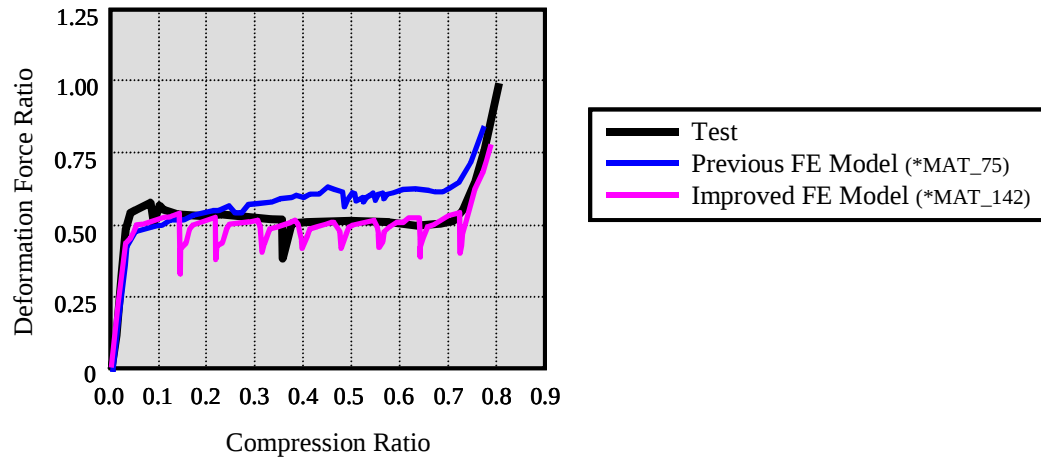


Fig. 10 Comparison of Compression Characteristics with 50% Pad Compression

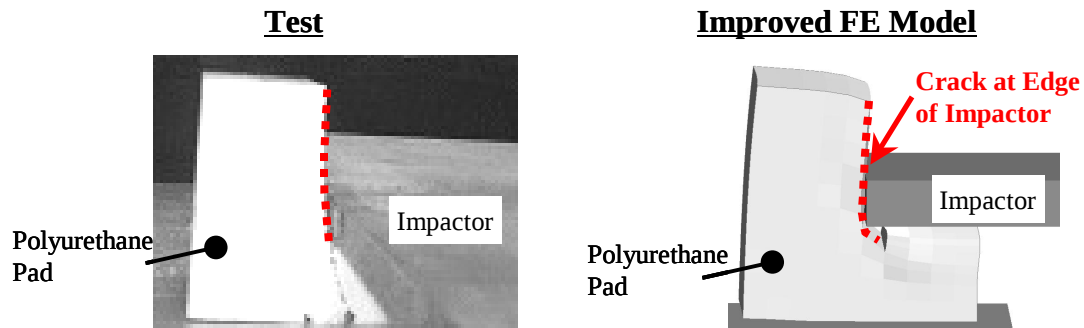


Fig. 11 Comparison of Deformation Behavior of Polyurethane Pad with 50% Pad Compression

4. Torso Airbag FE Model

To enhance the accuracy of thoracic rib deflection prediction by FE analysis, the previous torso airbag FE model was improved so that it would directly apply the impact onto the test dummy's thorax.

4.1 Estimating the Main Cause of Thoracic Rib Deflection Prediction Error

In an actual vehicle, a torso airbag is installed inside the seatback and deploys from inside the seatback. Notwithstanding this, the previous torso airbag FE model had been constructed to simulate the deployment of a flat airbag in place of a folded airbag as already described. The torso airbag deployment behavior in the previous FE analysis of oblique pole side impact is shown in Fig. 12.

The previous torso airbag deploys only outside the seatback, and restrain the dummy's thorax. In an actual vehicle, however, a torso airbag will deploy inside the seatback and restrain the dummy's thorax through the seatback. Therefore, we considered that the previous torso airbag model did not completely and accurately reproduce the thorax restraining force. In other words,

the previous FE model simulated only the deployment of a flat airbag and did not involve the seat foam behavior during airbag deployment.

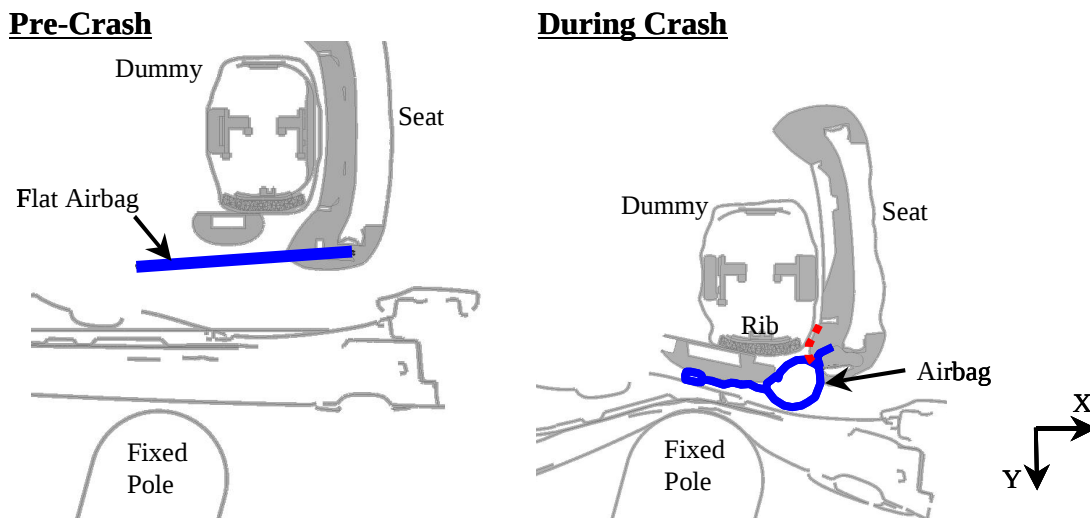


Fig. 12 Torso Airbag Deployment Behavior

4.2 Improving the Torso Airbag FE Model

To simulate torso airbag deployment from inside the seatback, we improved the previous FE model.

It was essential to define the gas flow in a torso airbag to enhance airbag deployment analysis accuracy. In this research study, we divided the torso airbag into multiple chambers and introduced the CV method to improve the previous FE model so that it would reproduce torso airbag inflation in response to gas flow.

4.2.1 Dividing the Torso Airbag into Multiple Chambers for CV Method

Prior to dividing the torso airbag into multiple chambers, we carefully observed a videotape of the deployment behavior of a flat torso airbag to fully understand the gas flow pattern. During the initial stage of torso airbag deployment shown in Fig. 13, most of the gas emitted from the inflator ran forward through the upper and lower portions in the airbag. Based on this observation, we divided the airbag longitudinally and transversely. After taking the bag folding positions into account, the airbag was divided into 15 chambers as shown in Fig. 14.

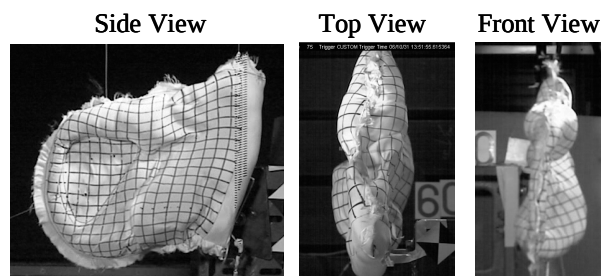


Fig. 13 Initial Gas Flow Pattern

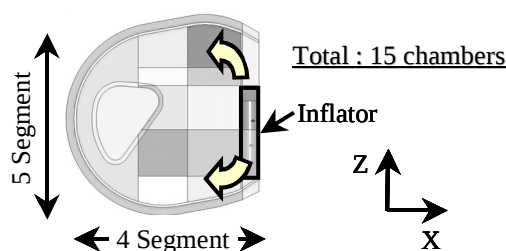


Fig. 14 Multiple Chambers Airbag Model

4.2.2 Observing the Deployment of the Torso Airbag in a Free Space

Fig. 15 compares the FE analysis of the deployment behavior of a folded torso airbag with the test result. Fig. 15 illustrates that the improved FE model approximately simulated the deployment shape and sequence of a folded torso airbag.

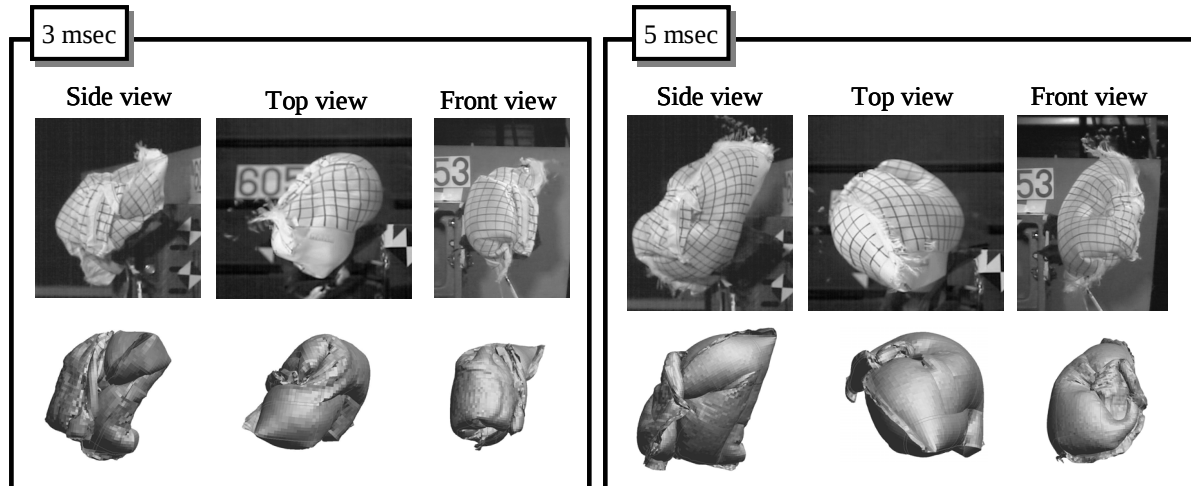


Fig. 15 Comparison of Deployment Behavior of Folded Torso Airbag

4.3 Improving the Seat FE model

The previous seat FE model was improved by simulating the interaction between the deploying torso airbag and the seat foam and seat fabric.

Since the seat foam and seat fabric usually separates at a specific location because of the structural design, a rupture element at this specific location was defined. The rupture criteria was determined from the tensile test data of the seat foam and sewing thread. The model construction is shown in Fig. 16.

Comparison between the FE analysis and test results for the torso airbag deployment from inside the seat is shown in Fig. 17. The improved seat FE model approximately reproduced the deployment of a folded torso airbag from inside the seat back as well as the condition where the seat foam was expanded and deformed when the torso airbag was deployed.

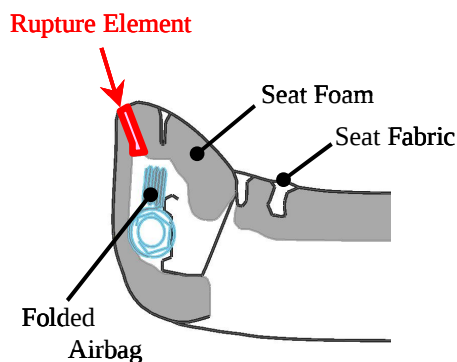


Fig. 16 Seat and Airbag Model

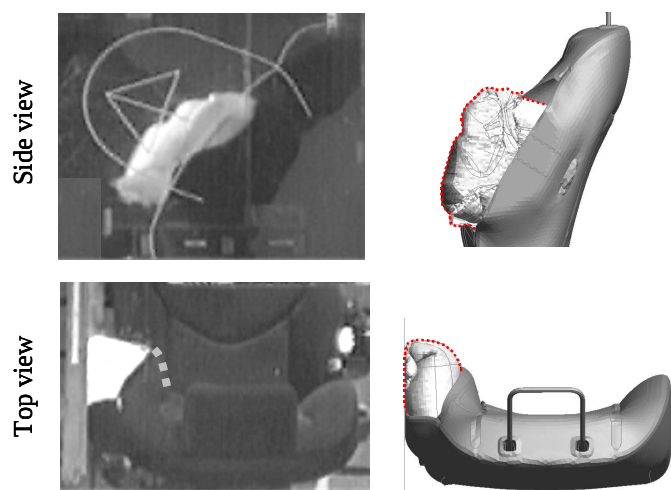


Fig. 17 Comparison of Torso Airbag Deployment Behavior and Seat Foam Deformation

5. Injury Index Prediction by Means of the Improved FE Model

5.1 Predicting Injury Index in Oblique Pole Side Impact

An oblique side impact was analyzed using the improved polyurethane pad and torso airbag FE models. Fig. 18 compares the principal injury indices predicted by using both previous and improved FE models. In this figure, the vertical axis represents the analytically determined maximum injury index divided by the maximum test value. As seen from Fig. 18, the three thoracic rib deflections and pelvic combined force for the improved FE models more closely resembled the test results.

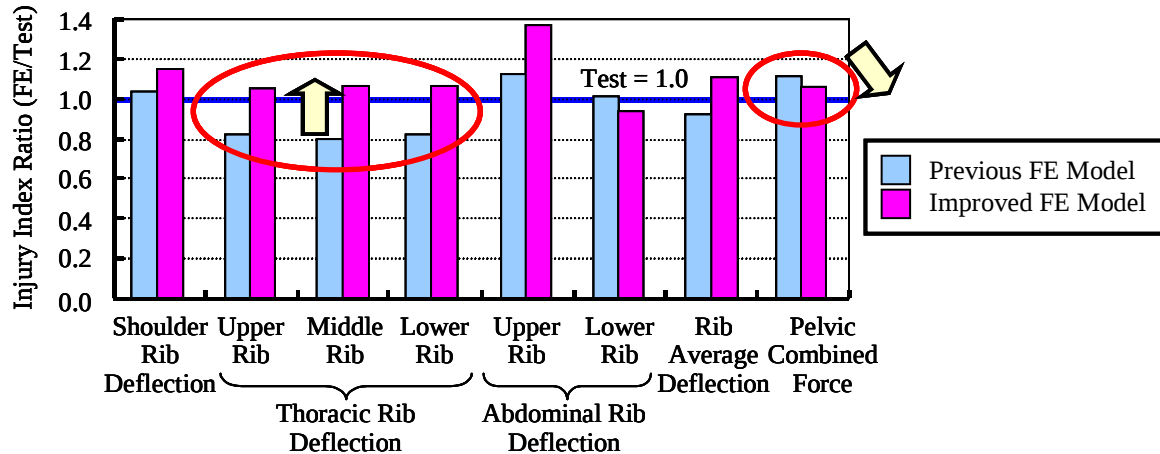


Fig. 18 Comparison of Predicting Injury Indices in Oblique Pole Side Impact

The FE analysis result for the deformation behavior of polyurethane pad using the improved pad model is shown in Fig. 19. This figure shows that the deformation analysis result agreed with the test result and that the cracking occurred during the test could be reproduced.

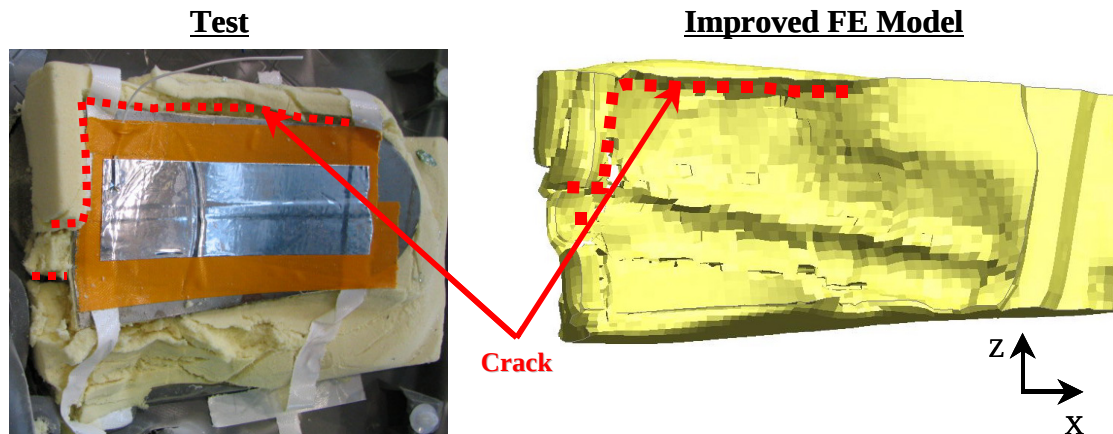


Fig. 19 Comparison of Deformation Shape of Polyurethane Pad

The cross sectional views of the dummy in the seat at the dummy's upper thoracic rib height are shown in Fig. 20 for both the previous and improved FE models. For the improved torso airbag model, the airbag inflated inside the seat and expanded the seat foam. As a result, the rear parts of the dummy's thoracic ribs were loaded. Since the improved torso airbag model had enhanced thoracic rib deflection prediction accuracy as shown in Fig. 18, it was concluded that

the major reason for the difference in thoracic rib deflection between the previous and improved models was that the previous model did not include the seat foam in the torso airbag deployment analysis.

The improved torso airbag FE model did reduce the upper abdominal rib deflection prediction accuracy, probably because the deformation force of the armrest on the door trim located at the dummy's upper abdominal rib height differed between the test and FE analysis result.

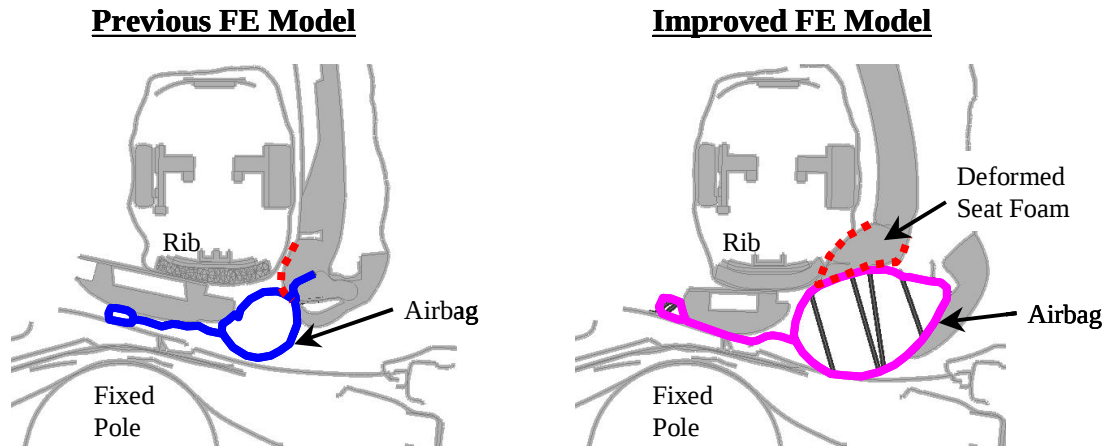


Fig. 20 Comparison of Torso Airbag Deployment Behavior and Seat Foam Deformation

5.2 Simulation Results of the Improved Models for the IIHS SUV Side Impact Test

An IIHS SUV side impact test was simulated using the improved polyurethane pad and torso airbag FE models. The FE analysis results obtained from the previous and improved models are compared in Fig. 21, the vertical axis of which represents the maximum values of principal injury indices divided by the maximum test values, as well as the standard deviations of errors. The improved models reduced the standard deviation of error to 0.13 from the previous 0.16, demonstrating that the improved models also provided enhanced accuracy for the IIHS side impact test.

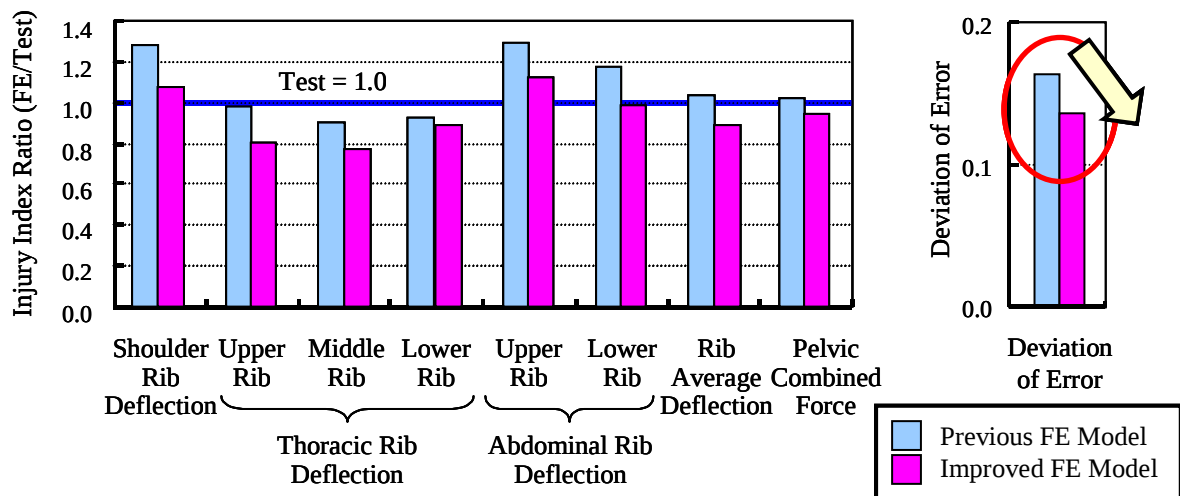


Fig. 21 Comparison of Predicting Injury Indices in IIHS Side Impact

6. Discussion

6.1 Checking Injury Index Variation Range

When the improved FE models were used for IIHS SUV side impact analysis, both the thoracic upper and middle rib deflections differed by approximately 20% from the test values. The injury index variation range was analytically determined by combining the upper and lower limits of $\pm 3\sigma$ variation of six restraint system design variables and four test parameters. The six design variables included the inflator output and vent-hole size of the torso airbag and polyurethane pad hardness, while the four test parameters included MDB collision speed, collision point, and dummy seating position. The results showed that the thoracic upper rib deflection varied widely in the range of approximately $\pm 30\%$ as shown in Fig. 22. This range was wider than that between the FE analysis result with the improved models and the test result. This result suggests that it is not possible to identify FE analysis accuracy or variation in test values as being the major cause of the difference between the improved model FE analysis result and test result.

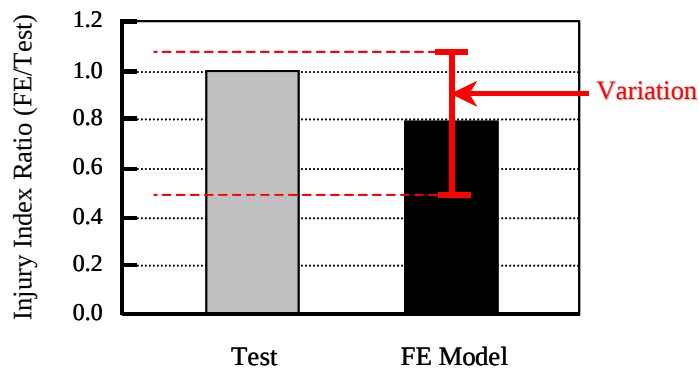


Fig. 22 Variation of Thoracic Upper Rib Deflection

6.2 Application of Injury Index FE Analysis for Vehicle Development

Since injury indices can vary widely as discussed above, before this prediction method can be utilized for vehicle development, additional research is needed to establish an analysis method that can also deal with such variations.

7. Conclusions

- (1) An FE model that can reproduce the anisotropic property and cracking behavior of a polyurethane pad has been developed.
- (2) An FE model that can approximately reproduce the deployment of torso airbags from inside the seats has been developed.
- (3) Dummy injury indices were predicted by incorporating the newly developed polyurethane pad and torso airbag models into a vehicle side impact FE model.
- (4) To further enhance the injury index prediction accuracy, the door trim model could be improved.

8. Acknowledgment

We gratefully acknowledge the cooperation of Bridgestone Corp. in testing the compression characteristics of polyurethane pads.

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