Robustness Analysis of a Vehicle Front Structure Using Statistical Approach

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1 Abstract

In this study, a process for assessing the robustness of designs has been presented, and the results are discussed using front structures of a vehicle FE model as an example. Statistical approaches have been introduced in order to assess the robustness of the structural design. Dozens of numerical simulations have been conducted taking into account uncertainties in input parameters such as spotweld failure criteria. The scatters in input parameters and the resultant deformations are statistically analyzed using a tool DIFFCRASH in order to capture the timing and location of bifurcations, and to understand the mechanisms inducing scatters in results. Spotweld strength of detected bifurcation triggers have been modified as countermeasure, and reduction of scatters by suppressing bifurcations has been confirmed.

2 Introduction

In recent years, it has become more and more important to take account of scatter in automotive industry. Liability and performance has been guaranteed by adding safety margin to its target in the past. However, needs in cost reduction and trade-off of conflicting requirements do not allow manufacturers enough amount of safety margin anymore [1].
One way to reduce scatter in product performance is to control production quality. However, too much control increases managing cost, and scatter cannot be reduced more than tolerance allowed by standards. There are some studies showing major scatters in response are sensitive to boundary conditions such as dummy position and offset or angle of barriers [1, 2]. However, these are set up by third parties in hardware tests so that the parameters are beyond control [3].
For the reasons above, realistic approach for the problem is to enhance product design which absorbs scatter in production process and boundary conditions, and several methods have been introduced [4]. However, conventional methods based on design space scanning only visualize non-linear transformation of input/output variables, which illustrate direct relationship of scatters, and the physical mechanisms and how scatters propagate is a black box.
In this paper, scatter propagation mechanism is visualized based on statistical calculation and structural design is enhanced after understanding the scatter initiation and propagation in order to reduce scatter. This time, the front side structure of an automobile is used as an example.

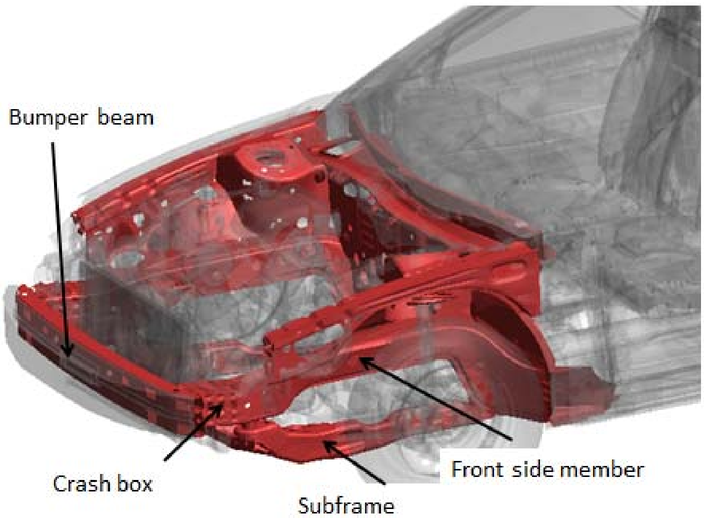

Fig.1: energy absorption area of an automobile

3 Main structural frame during frontal crash

Fig.1 shows the structure around engine room of as automobile. Among the structural frames, front side member plays an important role during frontal crash. It catches the obstacles in front of the vehicle and absorbs energy by its own deformation in order to decelerate the cabin. In recent years, some load cases which the barrier come into contact outside of the frame[5], but several automobile try to catch the barrier with front side frame even in that case so that the frame will remain important.
Input from barrier to front side frames is an axial load. However, front side frame is represented by S shaped rail due to layout around engine room and cabin [6-8]. This generate mixed mode of axial load and bending load to the frame, and influence of production scatter and contact condition to barrier initiates bifurcation, which leads to large scatter in final deformation mode and reaction force time history.
Large amount of scatter caused by bifurcation tend to occur more in frontal crash compared with side crash and rear crash, so that how to control bifurcation by design is the key to control scatter in response.

4 Scatter and bifurcation

When scatter is categorized by Gaussian distribution which shows continuous transition, and bifurcation which shows discontinuous transition, Gauss distribution shows less non-linearity so that response surface method can approximate phenomena in reasonable level. On the other hand, scatter caused by bifurcation tend to show greater error on response surface in the vicinity of the discontinuity. For the reasons, it is preferred to remove scatter caused by bifurcation before scanning the design space.

5 FE simulation of a frontal crash

For this study, A finite element model developed by NCAC[9] has been used in order to evaluate scatter in deformation of front side member and floor intrusion level.
A full width frontal crash case has been chosen for an example case. In order to simplify the problem, rear structure of the cabin, seats, IP beam structure, door, and engine components have been removed from the model as shown in Fig.2. Characteristics of spotwelds have referred to literatures [10].

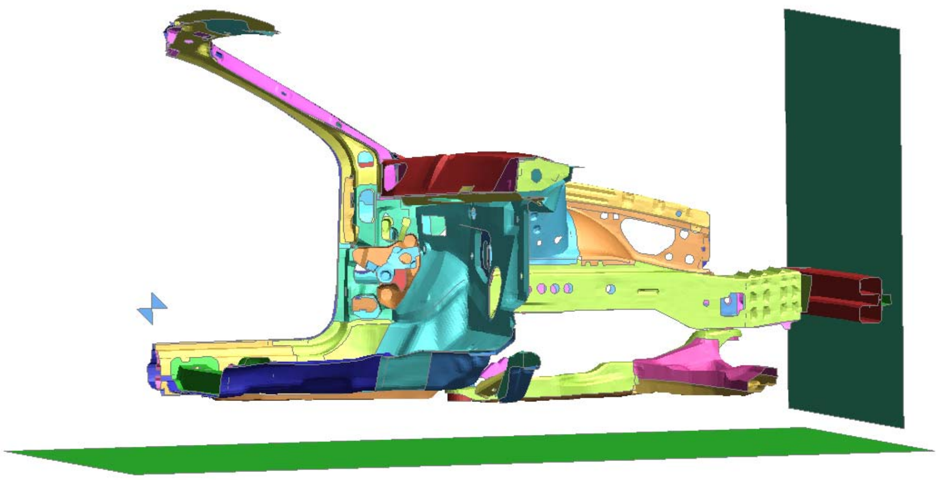

Fig.2: Study model

Before making a study on scatter, the cut-out model has been run with a nominal value of the spotweld strength. Barrier reaction force and floor intrusion has been evaluated. The peak value of the barrier reaction force is 130[kN], cross section force of the front side member is 70[kN]. These values are reasonable level compared with literatures [11]. During crash around 10ms, bumper beam crush and bottoms out. Local buckling of crash box starts round 10-15ms. In parallel to that, bending moment applies to front side member and starts to bend. The deformation mode at 25ms shows reasonable correlation to literatures [11] so that the validity of the base model has been confirmed.

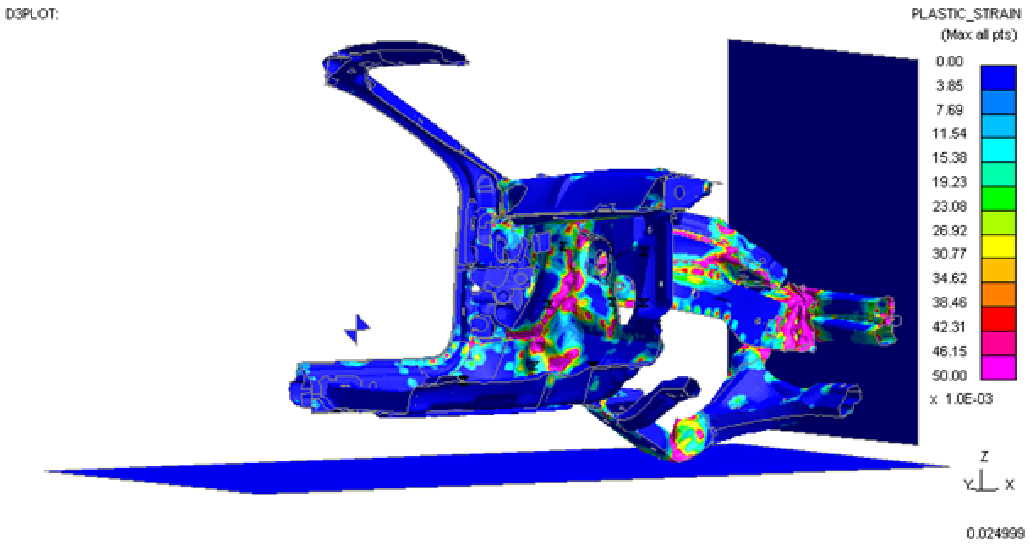

Fig.3: Deformation mode at 25ms (plastic strain contour)

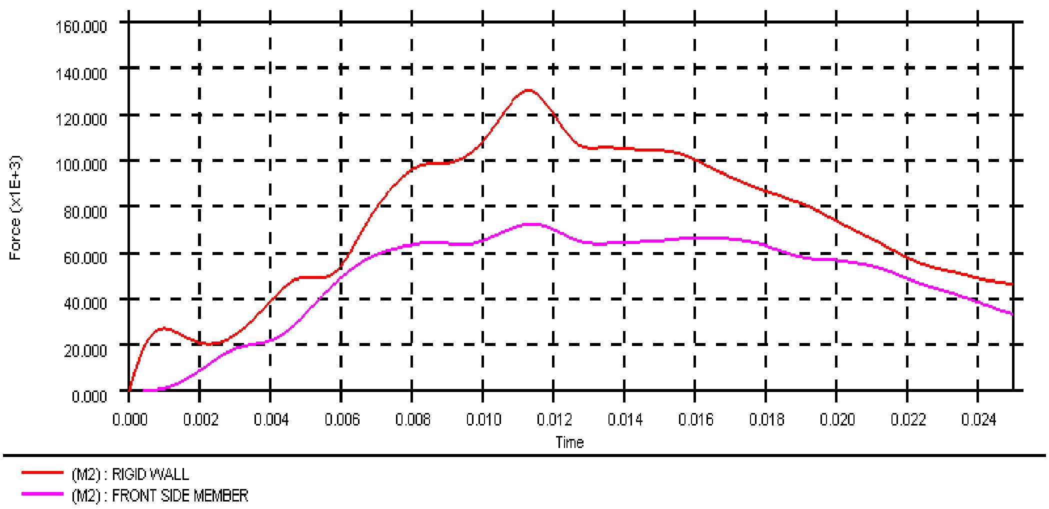

Fig.4: Barrier reaction force and cross section force of the front side member

6 Simulation with scatter in spotweld strength

In order to take account of production scatter, spotweld strength has been varied. Around 15% of scatter is observed in literatures, but around 20% variation has been randomly applied in this study in order to emphasize the influence by making the base model relatively unstable. Fig. 5 shows the barrier reaction force. The red line shows the base line model, and magenta lines show 30 additional runs with variation in spotweld strength. Magenta curves show a clear bifurcation at around 8ms and the scatter in reaction force remains wide. Floor intrusion level is evaluated at the point highlighted on Fig. 6. Fig. 7 shows that the intrusion level of the base model is 35mm and average of the stochastic simulation is 29.9mm, standard deviation of 5.98.

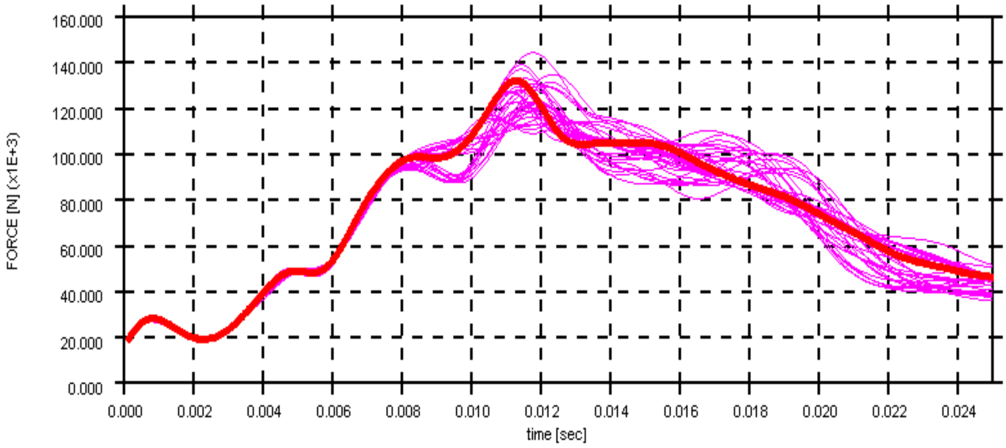

Fig.5: barrier reaction force (red: baseline model)

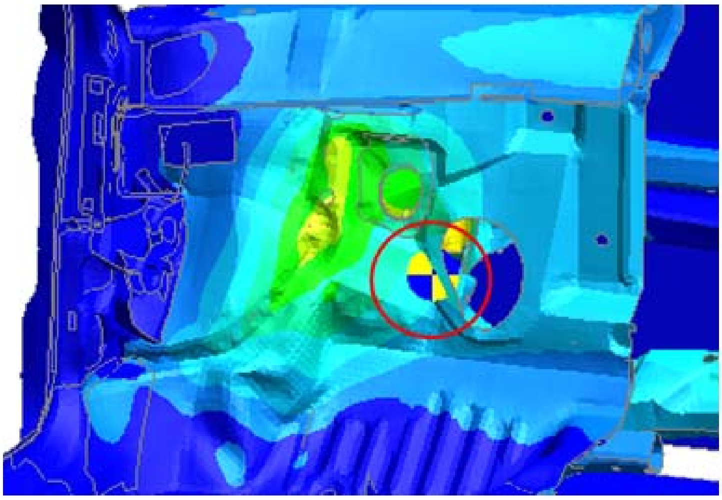

Fig.6: floor intrusion evaluation point

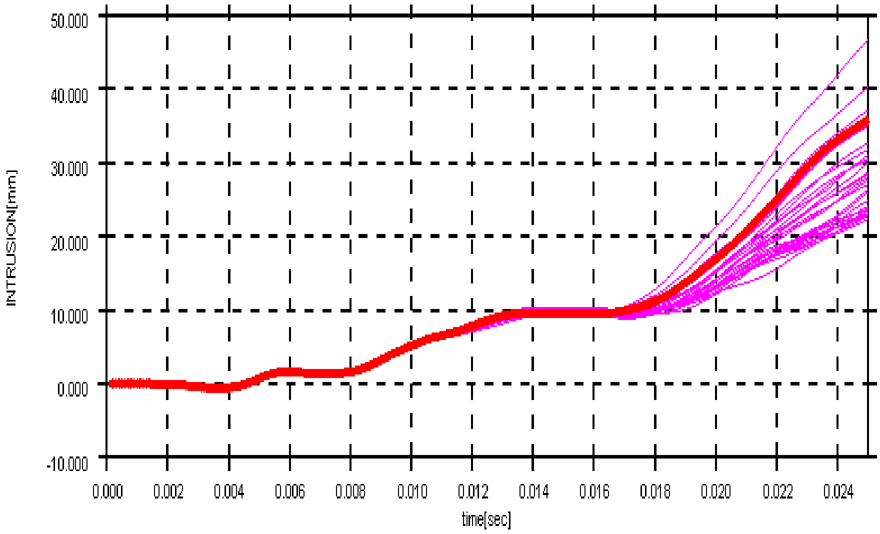

Fig.7: Floor intrusion (red: baseline model)

7 DIFFCRASH

DIFFCRASH is a visualization tool for scatter in simulation which is developed by SIDACT GmbH. It enables engineers to visualize propagation of scatter of nodal coordinates by conducting statistical analysis of FE simulation results.

BASIC method of DIFFCRASH visualizes scatter of nodal coordinate from several simulation runs and visualizes the results with contour plot throughout the simulation run. Fig. 8 on the left shows an overlay of several simulation results with a post processer and on the right shows the result of DIFFCRASH analysis. Global scatter on the front side member and local scatter around the opening near the bumper is highlighted in the DIFFCRASH result.

Fig. 9 shows an animation of the baseline simulation with contour plot of scatter of nodal coordinate from 30 runs. This shows that scatter appears at around 5 ms around bumper and crash box, it spread throughout front side member from 15 ms, and finally at 25 ms, scatter is observed around bending point of the front side frame and the front end of the center floor.

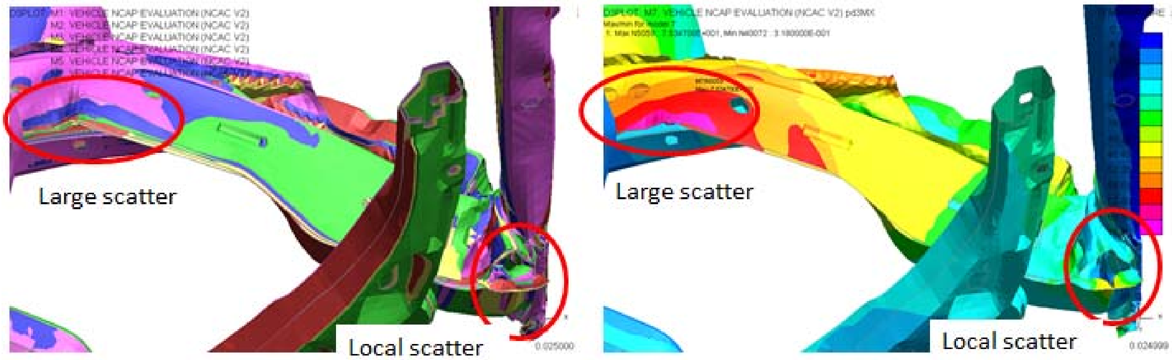

Fig.8: Visualization of scatter by DIFFCRASH BASIC method

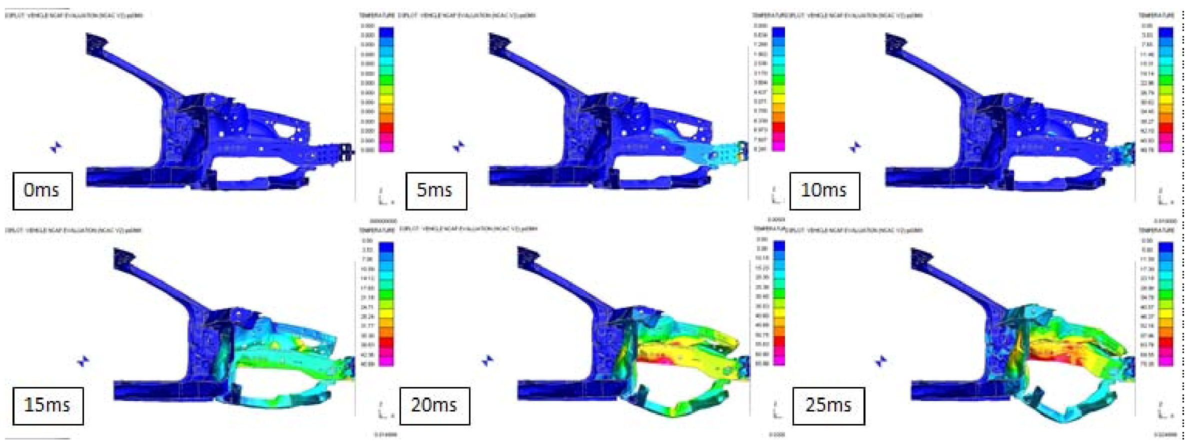

Fig.9: Scatter contour plot

In this study, scatter is applied only to spotweld strength so that the scatter in frame deformation and floor intrusion is assumed to be caused by difference in number and order of spotweld failures. DIFFCRASH detects spotweld failure as scatter in nodal coordinate and shows high value in the contour plot. Fig. 10 shows the location and order of the major spotweld failure up to 20ms. It is observed that lower connection between bumper beam and crash box at 1ms and 5ms, later left end of the bumper beam and the bottom of the crash box around 10ms and 15ms. From this result the spotweld failure shown in Fig. 10 are candidates of the triggers of scatter and bifurcation.

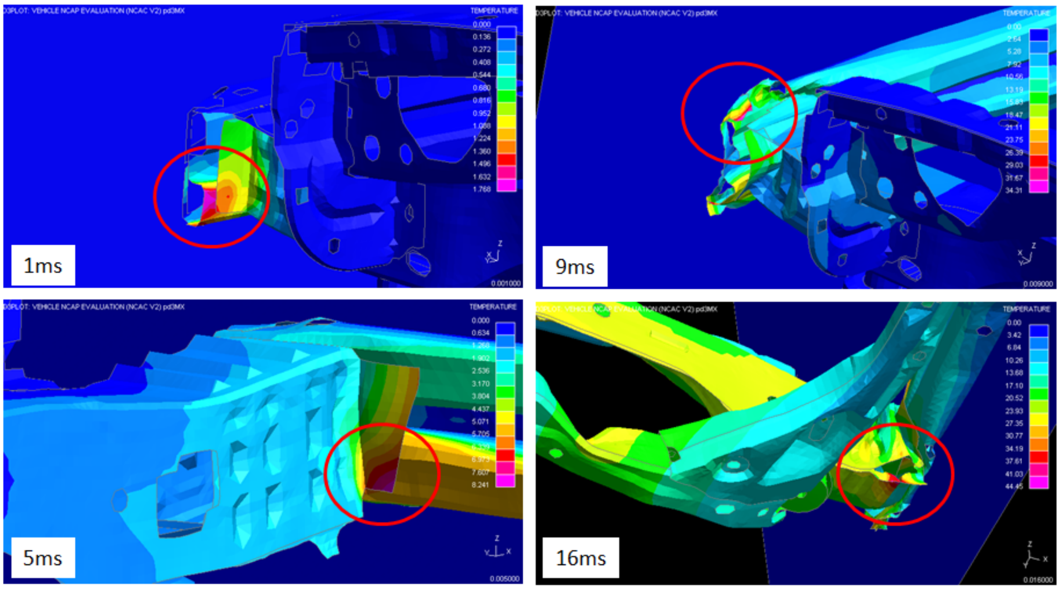

Fig.10: Local scatter near spotweld around bumper beam and crash box

8 Modal decomposition and selection of preferable deformation mode

As the next step, PCA method of DIFFCRASH is applied in order to characterize the deformation pattern and scatter of the 30 runs and extract major deformation mode.

PCA method of DIFFCRASH is based on principle component analysis. It calculates the tendency of deformation from series of simulation runs by statistical calculations. By using this analysis, major deformation mode can be derived.

Fig.12: shows the major deformation mode at 25ms, and define these modes as MODE 1, MODE 2 respectively. By comparison, MODE 2 shows less floor intrusion due to bend in the middle of the front side frame, while MODE 1 shows that front side frame pushes floor harder. For the reason, MODE 2 is defined as the preferable mode in this study.

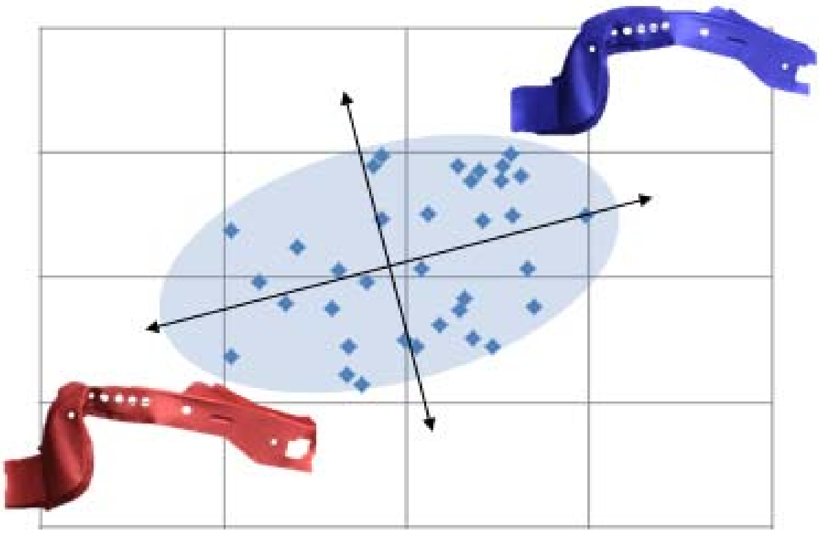

Fig.11: Schematics of the result of PCA method

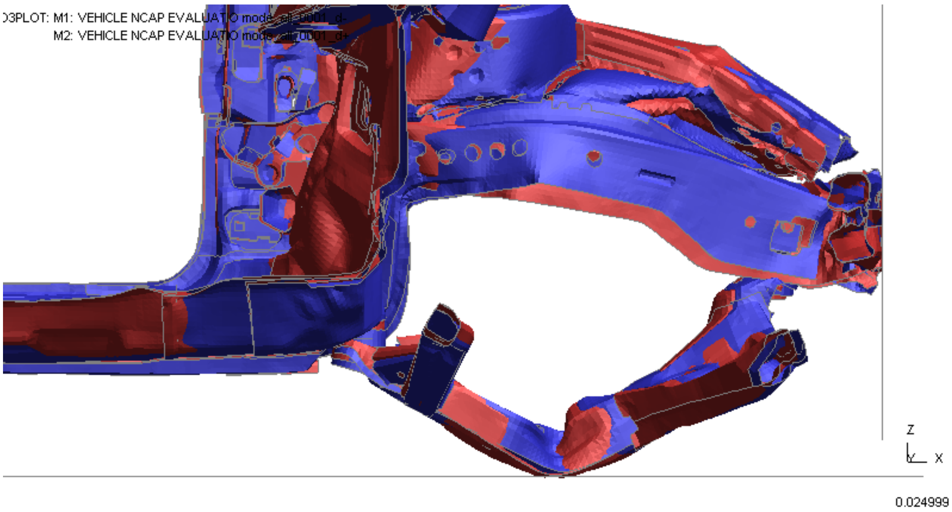

Fig.12: Scatter mode (Red: MODE 1, Blue: MODE2)

9 Scatter trigger analysis

Animation plots derived by PCA method have been overlaid and behavior of the spotwelds on Fig. 10 have been studied.
As a result, all spotwelds showed difference in behavior as shown in Fig. 13, and spotwelds of MODE 2 in animation showed earlier failure. This indicates the spotwelds are the trigger of the bifurcation and controlling the failure of the spotwelds and make the behavior closer to MODE 2 may guide simulation which currently result in MODE 1 to MODE 2.

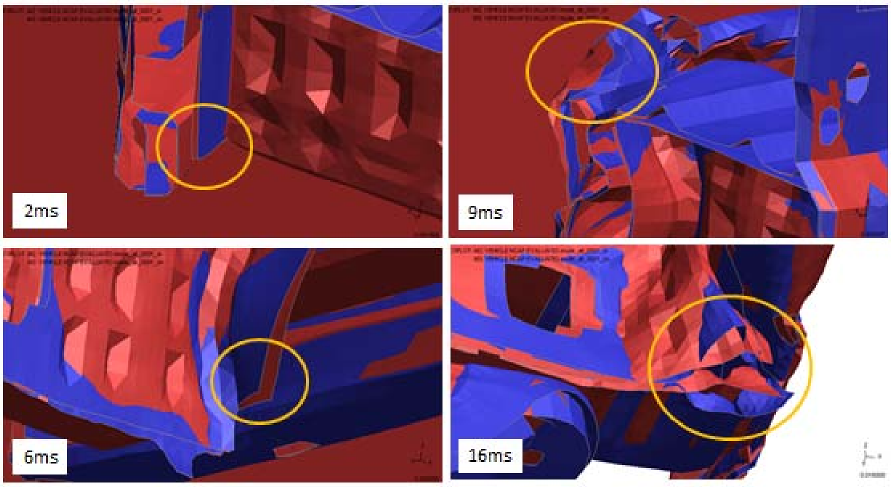

Fig.13: Spotweld behavior at trigger candidates(Red: MODE 1, Blue: MODE 2)

10 Design enhancement for robustness

A trial has been made to reduce scatters of barrier reaction force and floor intrusion by making design change based on the results from BASIC/PCA method of DIFFCRASH without changing scatter in spotweld strength.
From the result of BASIC/PCA analysis, 4 spotwelds shown in Fig. 14 are the candidates of the triggers of bifurcations so that the characteristics are modified to make them closer to MODE 2.
In this case, all spotweld other than point A failed earlier in MODE 2 so that it is assumed that weakening spotweld will make MODE 2 more likely to happen. The weld at Point A did not fail in both MODEs, but the weld was deleted in order to make the behavior constant. Since weld B and C are the connection between the bumper beam and the crash box so that removing the spotweld is not realistic. In this study, the strength of these spotwelds was reduced down to 1/4 of the original model with +-20% of scatter. Point D was deleted in order to make the behavior constant, since there are other spotwelds near them.

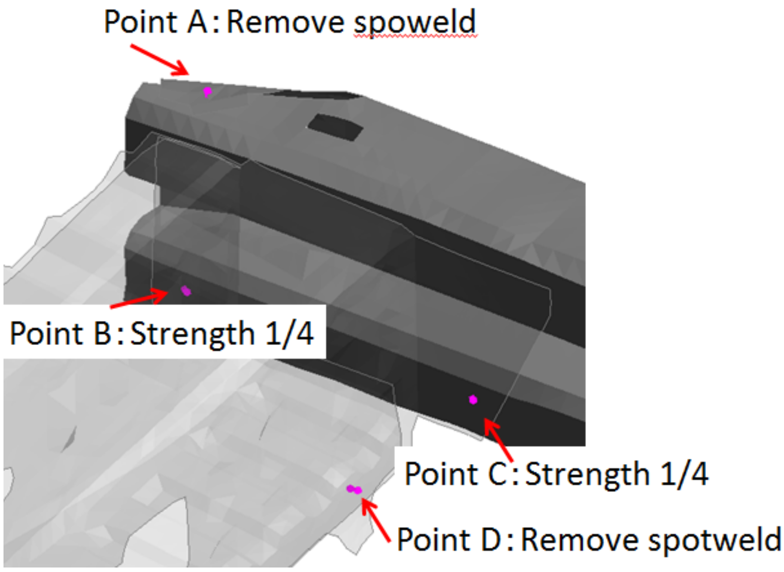

Fig.14: Modification to spotwelds at bifurcation trigger candidates

In order to evaluate only the influence of spotwelds at the trigger candidates, these changes above have been applied to the original models and run again.
Fig. 15 shows the scatter contour plot of the original and modified model.
The standard deviation of the nodal coordinate at 10 ms of the modified model is reduced from 49.8 to 13.8 about -75%, and 66.0 to 58.4 about 13% also at 20 ms. Much scatter is observed around the bending point of the front side member at 25 ms in modified model. However, the focus in this study is on the floor and the scatter is reduced from 55.7 to 40.5 about 27% as shown in Fig. 16 so that this is acceptable.
Deformation of the bumper and front side frame is guided to MODE 2 by the modification so that it is clear in Fig. 17 the bifurcation of the barrier reaction force is suppressed.

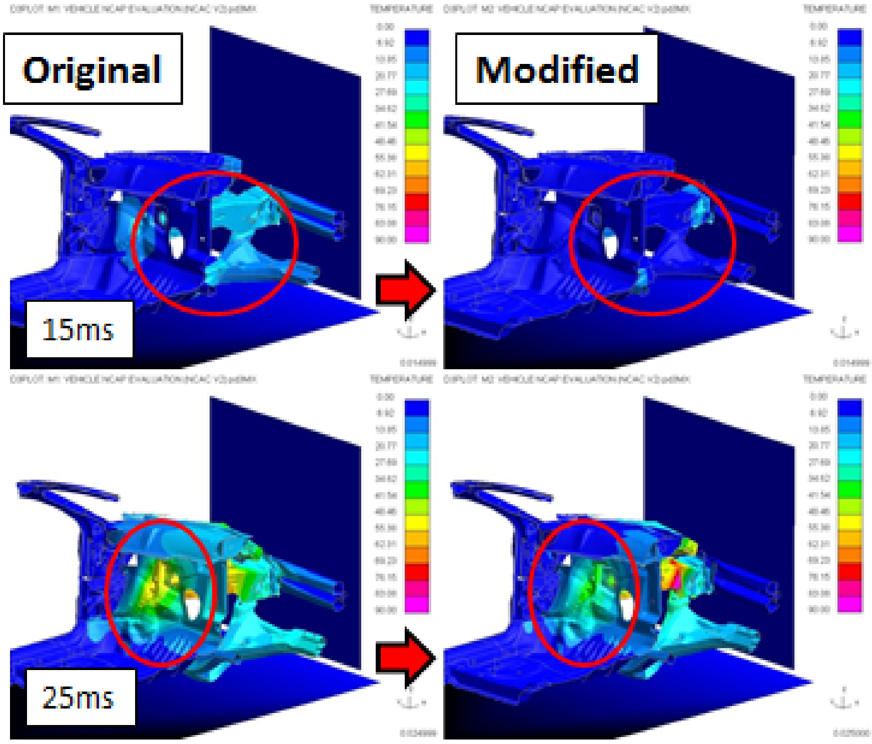

Fig.15: Scatter distribution before and after modification

Regarding the floor intrusion, the intrusion of the base model is reduced from 35 mm to 22 mm at 25 ms.
Not only is the standard deviation reduced from 5.98 to 4.22, but also the average level is reduced from 29.9 mm to 25.4mm as shown in Fig. 18.

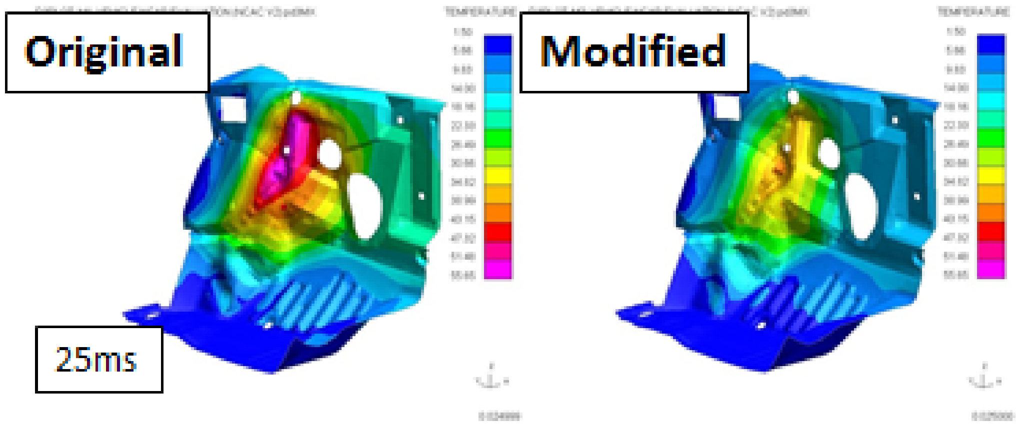

Fig.16: Scatter of floor intrusion

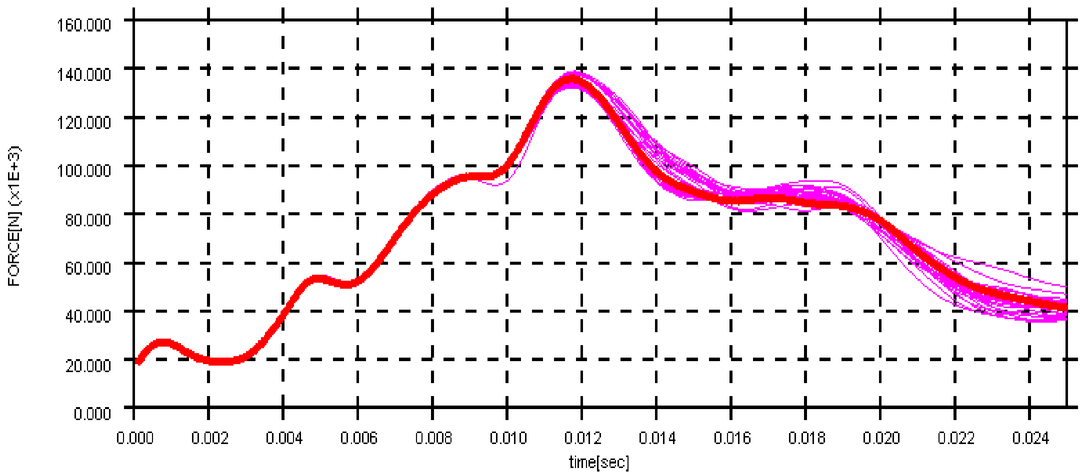

Fig.17: Barrier reaction force after modification

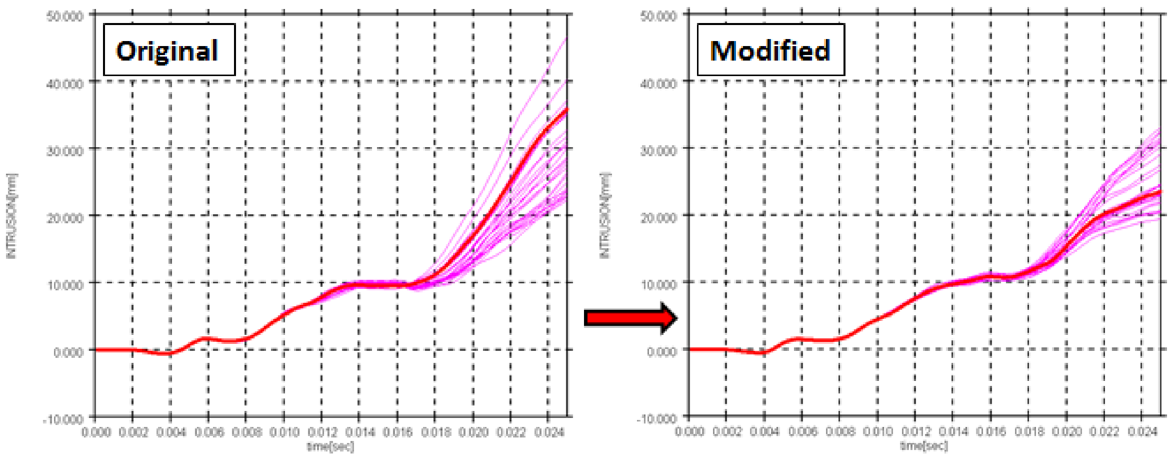

Fig.18: Floor intrusion (Red: baseline model)

11 Conclusion

Conventional robust design improvement based on response surface method focus on direct relationship between input variant and output variable so that the analytical results gives only acceptable variable range, but do not give much insight to the mechanisms of scatter. On the other hand, the proposed method adds timing and special information of the scatter initiation and propagation so that it gives more hints for design improvement for suppressing bifurcation and reduce scatter.

12 Literature

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