An enhanced Design exploration using Modal decomposition of Key events in Frontal crash simulation

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Introduction

In recent years, CAE has been used extensively in vehicle development, and parameter study of sheet metal thickness for design exploration and optimization is one of the major applications.
Response surface method is commonly used for this application among various analysis tools. The concept is to connect input variables such as sheet metal thickness and output variables such as firewall intrusion with non-linear functions such as radial base, kriging, and neural network.

1 Issue of conventional approaches

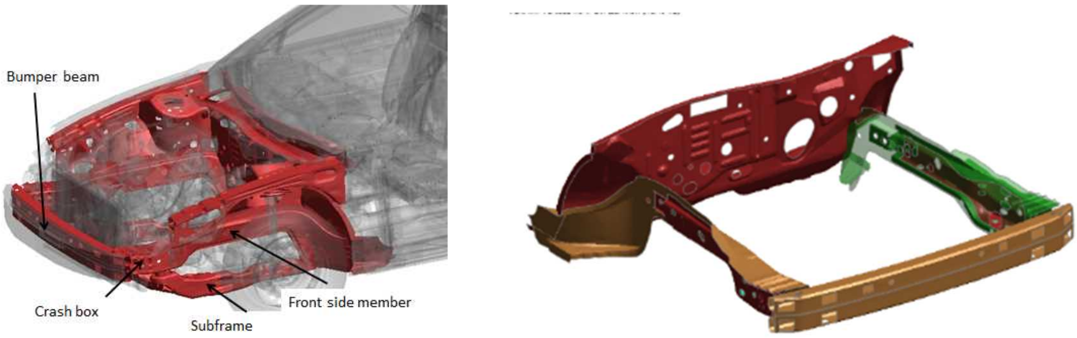
This approach works fine with problems in case the degree of non-linearity is low. However, problems such as frontal crashes are highly non-linear so that this approach tends not to work well. The fundamental problem is a lack of understanding of the mechanisms and physics behind the phenomenon. Directly connecting scalar values from input and output does not fully explain “why” and “how” the changes in input affect the output, since complex causal chains of events behind the relationship between input and output variables are in a black box. Another point is missing information from deformation. Deformation of parts and assemblies are key aspects to fully understand the mechanisms. However, for the response surface method, variables need to be scalar values so that engineers need to choose a single value that represents the event most either by summarizing or extracting. This approach works well with simple problems, but this process requires lots of time for preparation and know-how for complex phenomena such as frontal crashes.

2 Proposed approach using DIFFCRASH

The proposed approach takes into account the time and spatial chain during crash events as well as the deformation mode of important assemblies at key events. The deformations of important parts are captured for each major event such as the collapse of the crash box and maximum firewall intrusion. Deformed shapes from Monte-Carlo simulation runs are transformed into modal spaces with principal component analysis so that the coordinates in the modal space represent how the assembly behaves during the crash at the point of time. Regression analyses among the input parameters, the coordinates in modal space, and output values for each event give engineers clues to causal chains of phenomena during crash events.

2.1 An example frontal crash problem

In order to showcase the proposed approach, a parameter study of the US NCAP full-frontal crash model has been used. NCAC Ford Taurus model[1] has been selected for this application as shown in Fig.1. Front side members absorb energy and the firewall protects passengers so that minimum intrusion of firewall is one of the important requirements for occupant safety design.
In this study, the thicknesses of 8 parts from the front side members have been varied as design variables. The ranges of parameters are shown in Table 1. Floor intrusion and maximum acceleration level have been chosen as response variables to be predicted.



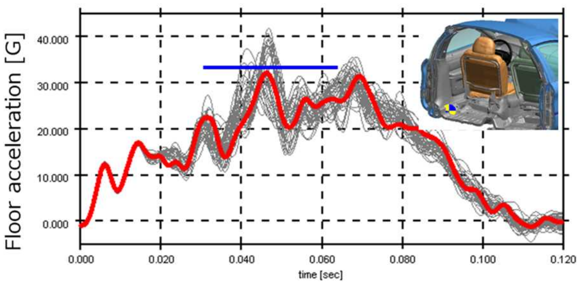
(a) The engine room of NCAC Ford Taurus model (b) Selected parts for the parameter study

Fig.1: Design parameters of the frontal crash model

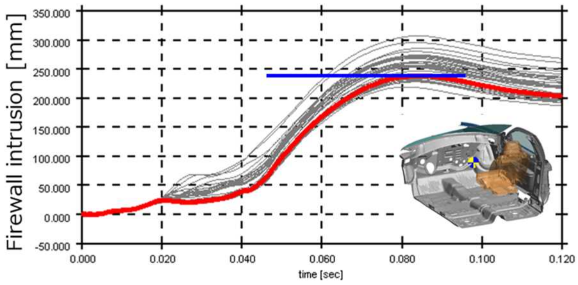
name	Description	Range [mm]
THK25	Thickness – Bumper	1.0 – 2.0
THK12	Thickness - Inner L	1.4 – 2.4
THK08	Thickness - Outer L	1.4 – 2.4
THK14	Thickness - Reinforcement L	1.9 – 2.9
THK21	Thickness - Inner R	1.4 – 2.4
THK18	Thickness - Outer R	1.4 – 2.4
THK23	Thickness - Reinforcement R	1.9 – 2.9
THK37	Thickness – Firewall	0.4 – 1.4

Table 1: Thickness variation of the crash relevant parts

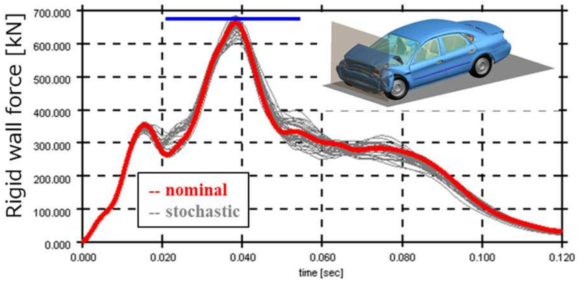
A quasi-Monde Carlo simulation with 160 runs by Latin-Hyper Cube sampling has been conducted with LS-OPT. Fig.2 shows the response values used for this study. The maximum acceleration is calculated from the driver-side B-pillar acceleration signal filtered with CFC60. The maximum firewall intrusion is measured on the passenger side. The maximum wall force is the contact force between the rigid wall part and the vehicle filtered with CFC60.



(a) Maximum acceleration



(b) Maximum firewall intrusion



(c) the maximum wall force

Fig.2: Definition of response values.

2.2 Analysis process

By using DIFFCRASH[2] from SIDACT GmbH, the influence of parameters is visualized as a contour plot in animations. Using this information together with the time history curves will enable engineers to easily find out major events in the crash and relevant areas. Once parts that play a key role in each important event and its timing are determined, 2-3 dimensional vectors which represent the event can be derived from modal decompositions of deformation with PCA (Principal Component Analysis) for each event. The vectors from input, PCA, and output are processed with regression analysis.

2.2.1 Detection of major events and important areas

DIFFCRASH BASIC METHOD was used for scatter contour plots of the behavior of the energy absorption area. Fig.3 shows the animation of important parts filtered by DIFFCRASH visualization. The major events are the following. The bumper crushes at around 20ms. The left and right crash boxes collapse at around 30ms. The maximum intrusion of the firewall is at around 80ms. With this process, important parts and the timing of major events have been determined.

20ms: bumper crush *30ms: crash box collapse* *80ms: maximum firewall intrusion*

Fig.3: Scatter of important parts for the frontal crash.

2.2.2 Extraction of modal contribution factors

Deformations of key parts are decomposed by DIFFCRASH PCA METHOD for each key event. Fig.4 (a) shows the ranking of eigenvalues derived from PCA analysis of the bumper at 20ms. The first 2 values are outstanding, and this means complex shapes and deformation can be transformed into 2-dimensional vectors (modal contribution factors). Fig.4 (b) shows the modal space plot. It clearly shows a non-linear correlation between mode 1 contribution factor and that of mode 2.

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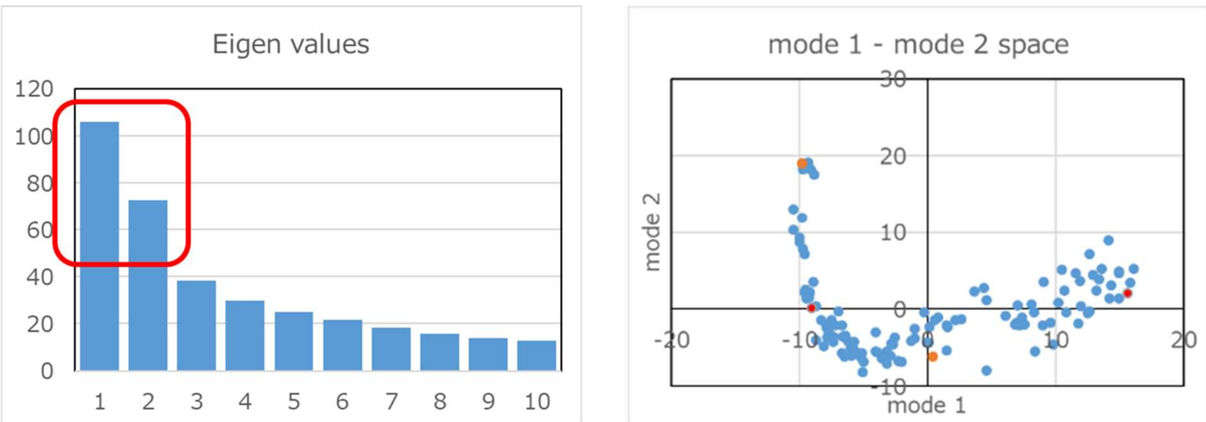


(a) Eigenvalue ranking *(b) mode1-mode2 space plot*

Fig.4: Result summary of PCA analysis of the bumper at 20ms

Fig.5 shows the modal space plot with snapshots from the animation of the bumper. The first mode is the level of compression of the bumper. The negative side is more compressed than the positive side. The characteristics of the second mode are not as clear as the first one, but the bumper appears to collapse upward on the negative side, and downward on the positive side.

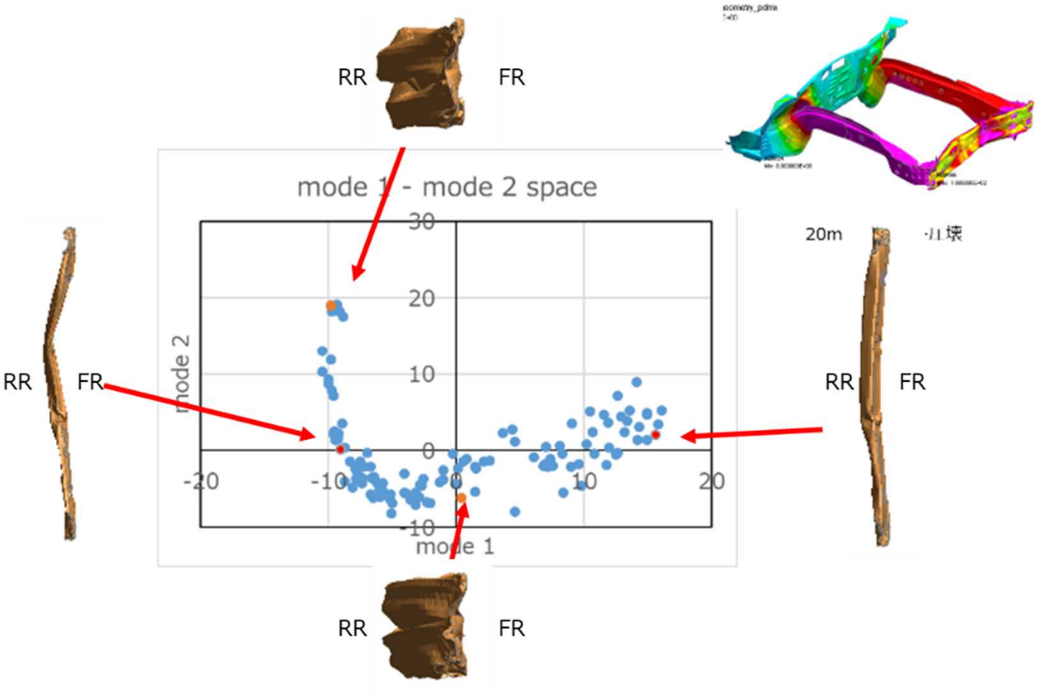
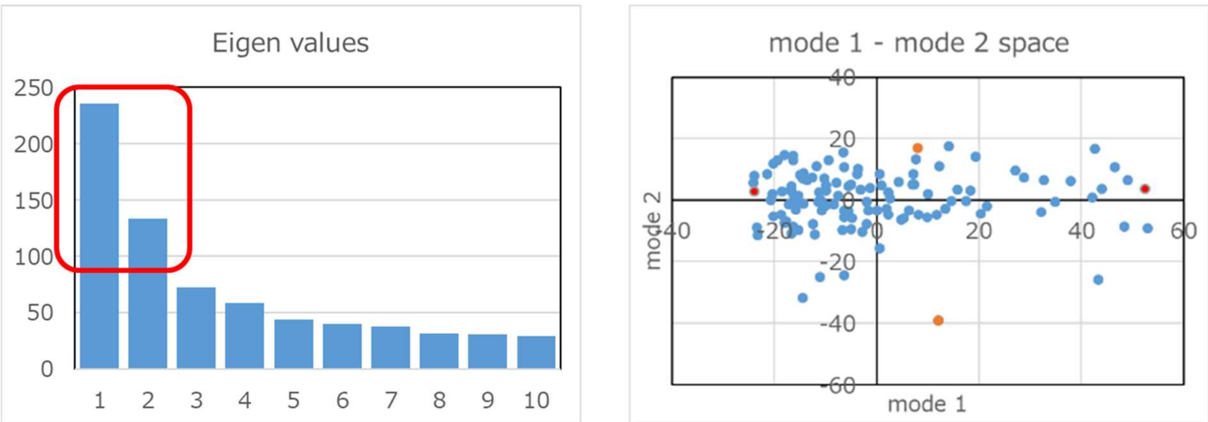


Fig.5: Modal plot with deformation mode of the bumper from the animation at 20ms

Fig.6 (a) shows the eigenvalue ranking of the front side members at 30ms. The first 2 values are outstanding similar to the bumper mode. As shown in Fig.7, the first mode is related to the right front side member. The crash box collapses on the negative side, but it does not clearly happen on the positive side so that the firewall intrusion is more severe. The second mode is about the left front side member. The behavior is quite similar to the right-hand side.



(a) Eigenvalue ranking *(b) mode1-mode2 space plot*

Fig.6: Result summary of PCA analysis of the front side members at 30ms

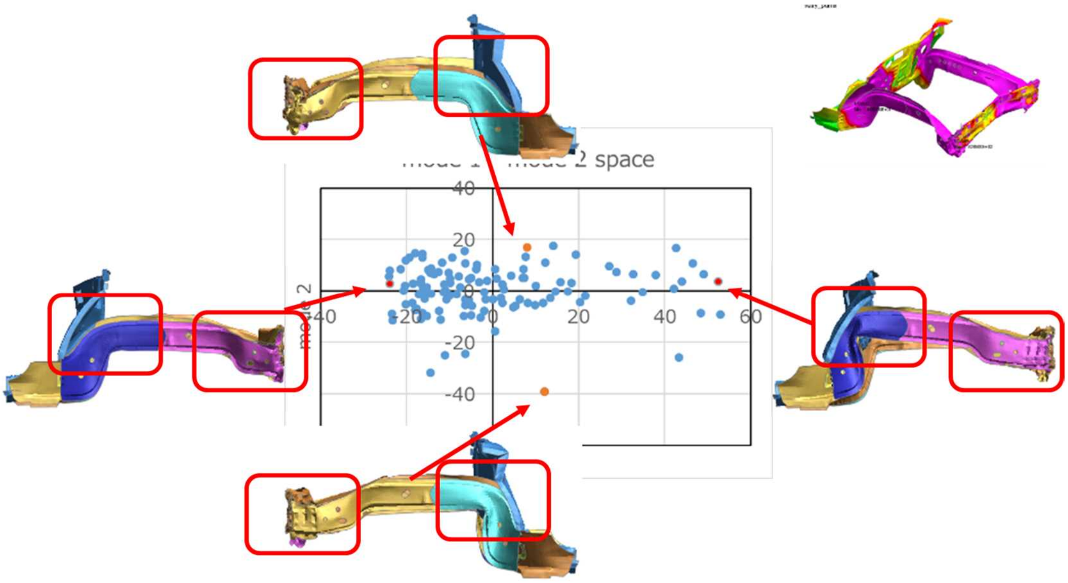
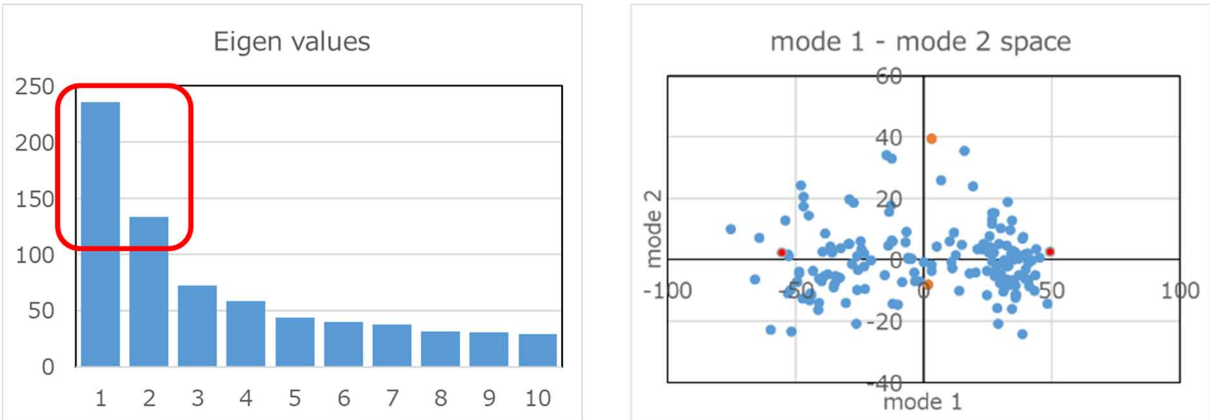


Fig.7: Modal plot with deformation mode of the front side members from the animation at 30ms

Fig.8 (a) shows the eigenvalue ranking of the firewall at 80ms. The first 2 values are outstanding again. As shown in Fig.9, the first mode is the flip mode. The bottom of the firewall intrudes more on the negative side, but the top of the firewall intrudes more on the positive side. The second mode is the translational mode. The entire part intrudes more on the positive compared to the negative side.



(a) Eigenvalue ranking *(b) mode1-mode2 space plot*

Fig.8: Result summary of PCA analysis of the firewall at 80ms

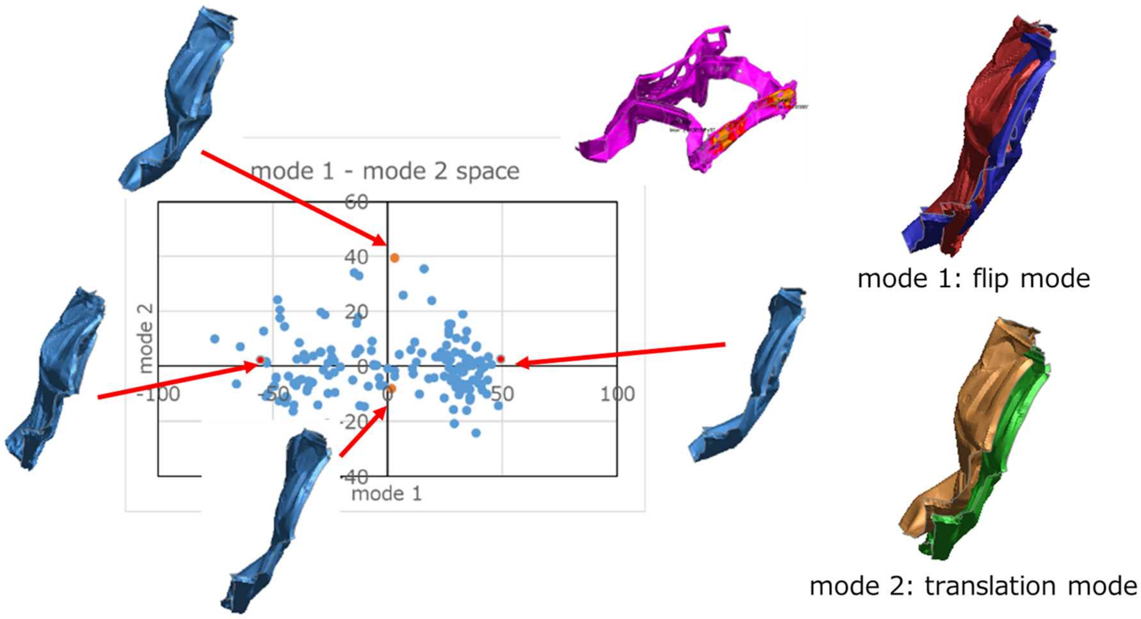


Fig.9: Modal plot with deformation mode of the firewall from the animation at 80ms

2.2.3 Correlation between input parameters and the modal contribution factors of the bumper at 20ms

Part thicknesses, which are the input parameters in this case, give influence to the behavior of relevant parts. The influence appears in the modal plot so that regression analyses of the input parameters and modal contribution factors will reveal which input parameters are dominant.
As the first step, thickness variation and modal contribution factors of each part in each event are studied by regression analysis. Fig. 10 is the summary of regression analyses between thickness parameters and the first modal contribution factor at 20ms. The figure clearly shows that the bumper thickness (THK25) is the dominant parameter for the behavior of the bumper.

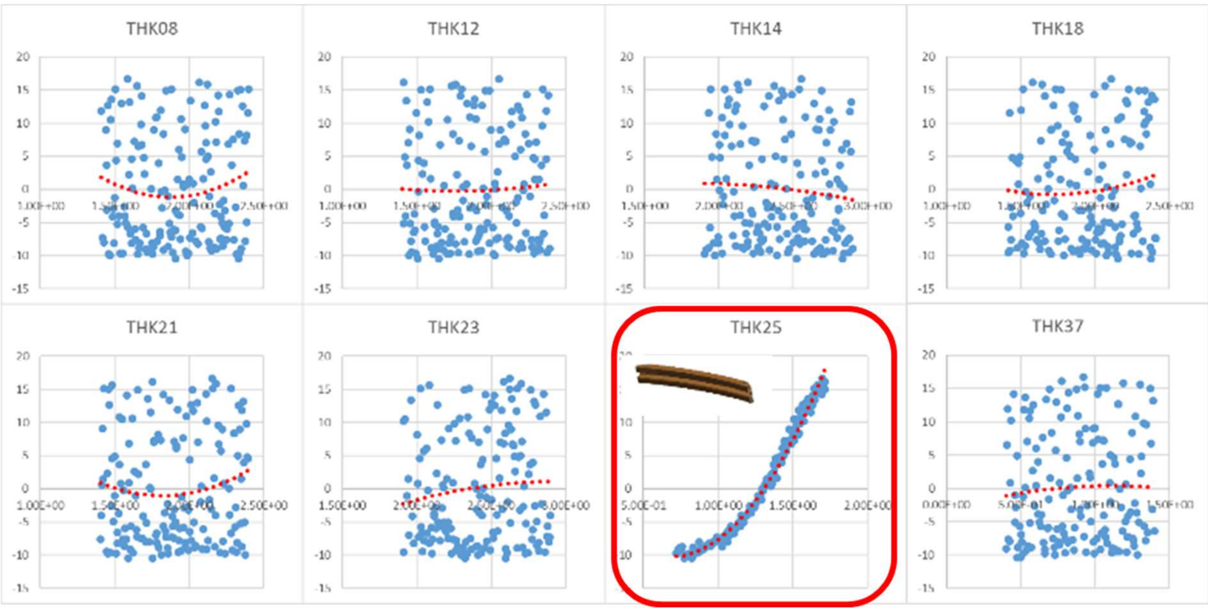


Fig.10: Correlation plots between the parameters and the first modal contribution factor at 20ms

Fig. 11 is the summary of regression analyses between thickness parameters and the first modal contribution factor at 30ms. The thickness of the front side member on the right-hand side (THK25) shows a high correlation to the major behavior of the front side member.

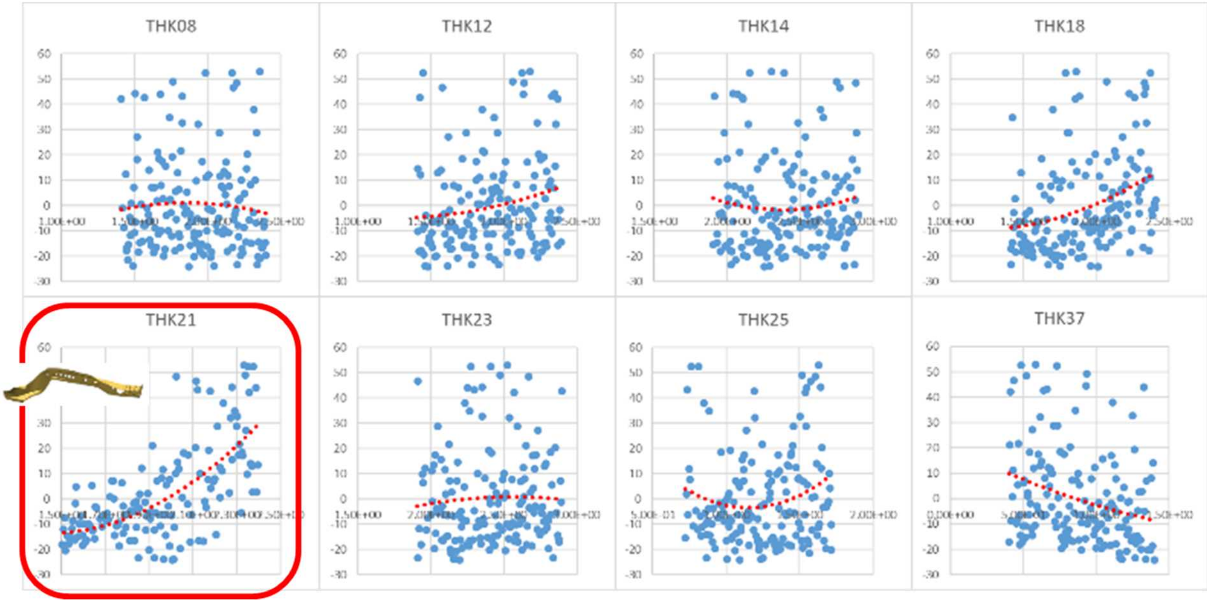


Fig.11: Correlation plot between the parameters and the first modal contribution factor at 30ms

Similarly, the second modal contribution factor at 30ms shows a strong correlation with the thickness of the front side frame on the left-hand side in Fig. 12. It also shows a relatively high correlation with the bumper thickness.

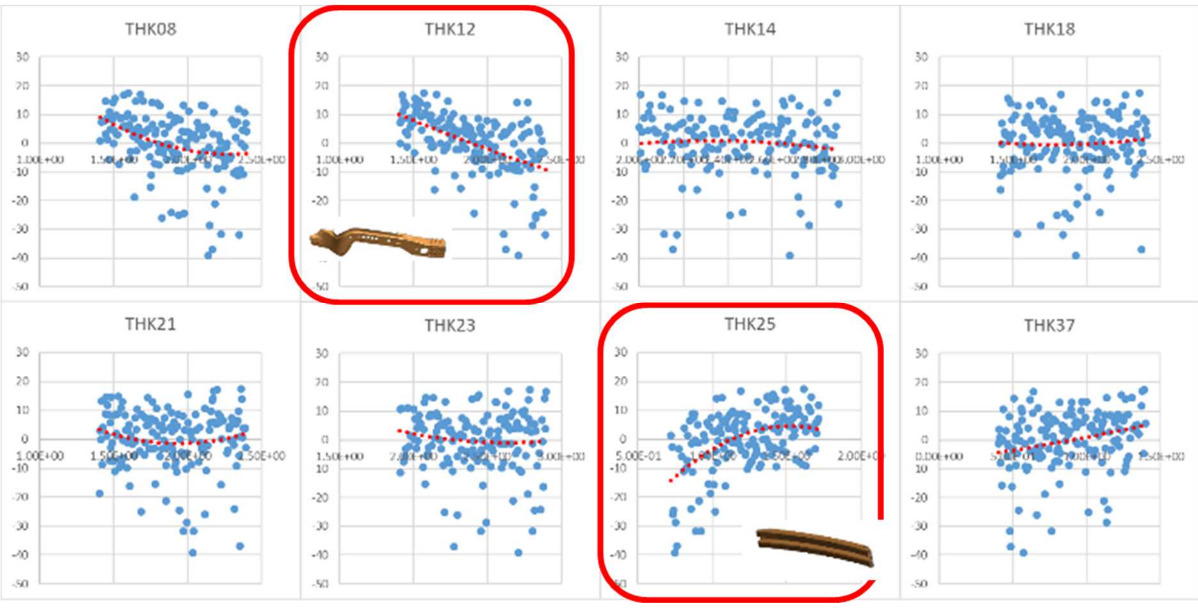


Fig.12: Correlation plot between the parameters and the second modal contribution factor at 30ms

Fig. 13 shows the correlation between the part thickness parameters and the first modal contribution factor at 80ms. It shows a strong correlation with the firewall thickness.

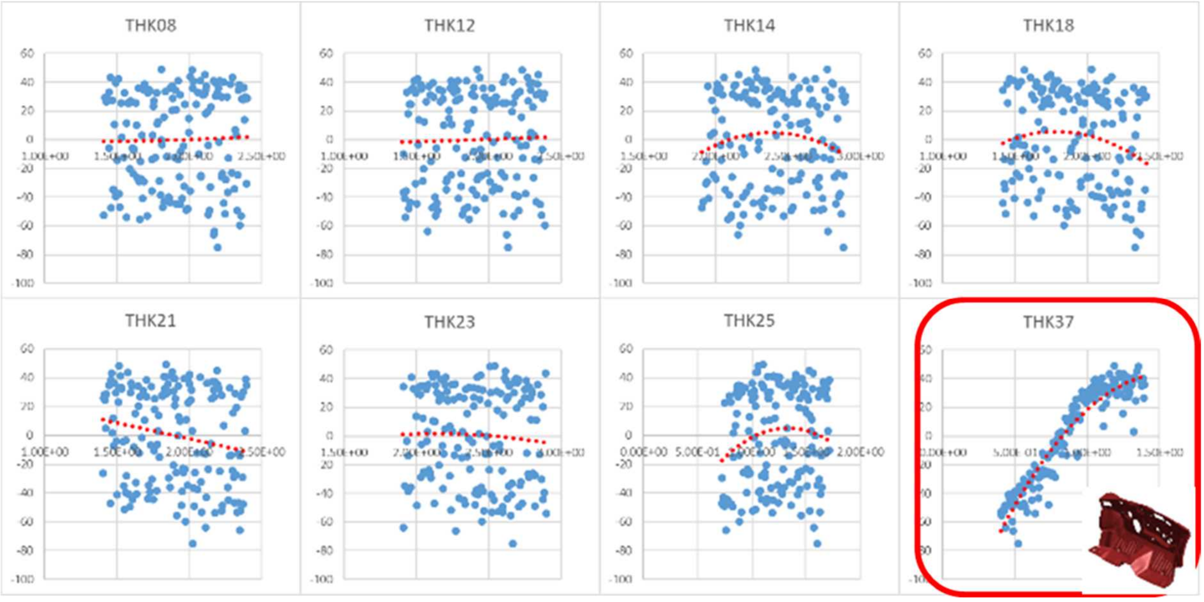


Fig.13: Correlation plot between the parameters and the first modal contribution factor at 80ms

2.2.4 Correlation between modal contribution factors at different points of time

The behavior of a part will give influence to connected parts during the crash as a causal chain. In this case, the behavior of the bumper beam gives influence to the crash box and side members, and they affect the behavior of the firewall. Regression analyses of the modal contribution factors will visualize the causal chain.

Fig. 14 shows a correlation between modal contribution factors at 20ms and 30ms. In the figures, the first modal contribution factor at 20ms shows a correlation with the second modal contribution factor at 30ms. Similarly, Fig. 15 shows the correlation between modal contribution factors at 30ms and 80ms. The first modal contribution factor at 30ms shows a strong correlation with the second modal contribution factor at 80ms.

Fig.14: Correlation between modal contribution factors at 20ms and 30ms

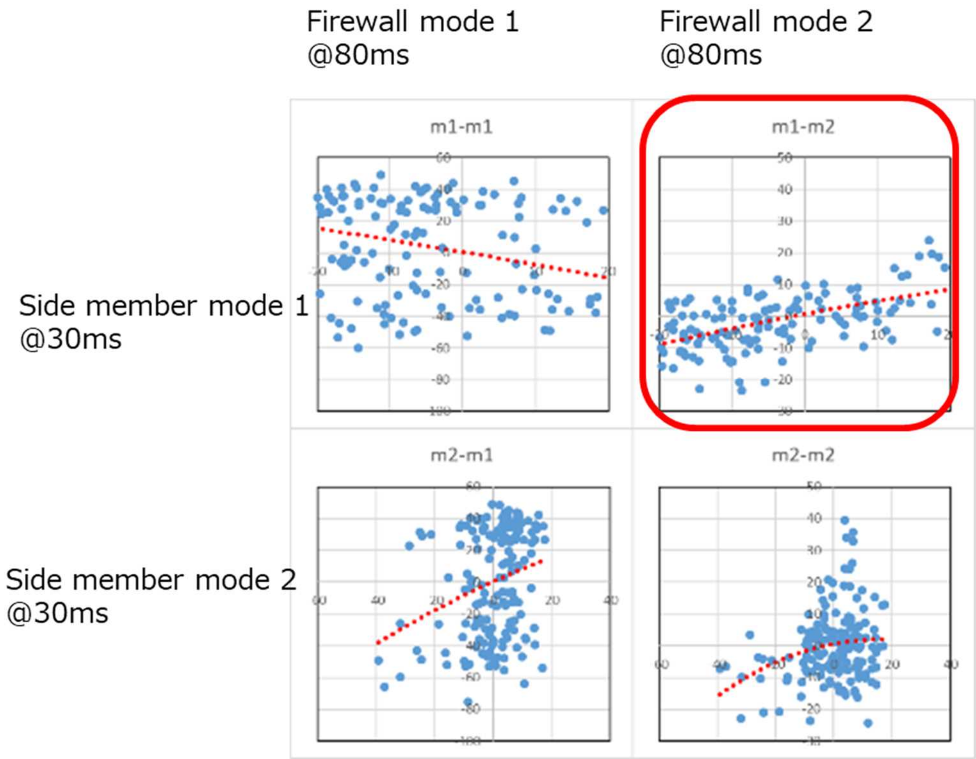


Fig.15: Correlation between modal contribution factors at 30ms and 80ms

The correlation between the modal contribution factors at 80ms and output values has also been checked in Fig. 16. The first modal contribution factor shows a strong correlation with maximum acceleration and maximum firewall intrusion, and the second modal contribution factor shows a strong correlation with the rigid wall force level.

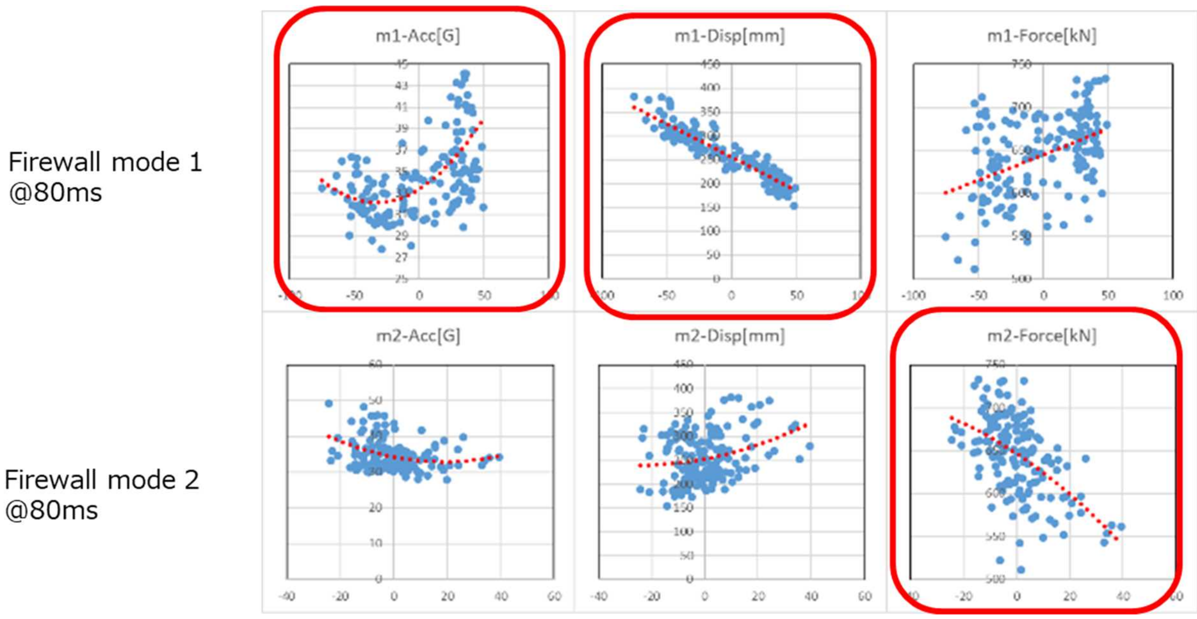


Fig.16: Correlation between the modal contribution factors at 80ms and the output values

2.2.5 Summary of the analysis results

The analysis results through the process are summarized in Fig. 17. It shows the main path for the maximum wall force is from THK25 through mode1 at 20ms (also influenced by THK12), mode2 at 30ms, and mode2 at 80ms. On the other hand, The maximum acceleration and the maximum firewall intrusion are influenced mainly by THK37.
A similar result can be obtained by the response surface method. However, this approach gives engineers a clear view of the causal chain in the time & spatial domain, and helps engineers understand the mechanism for better and efficient structural design.

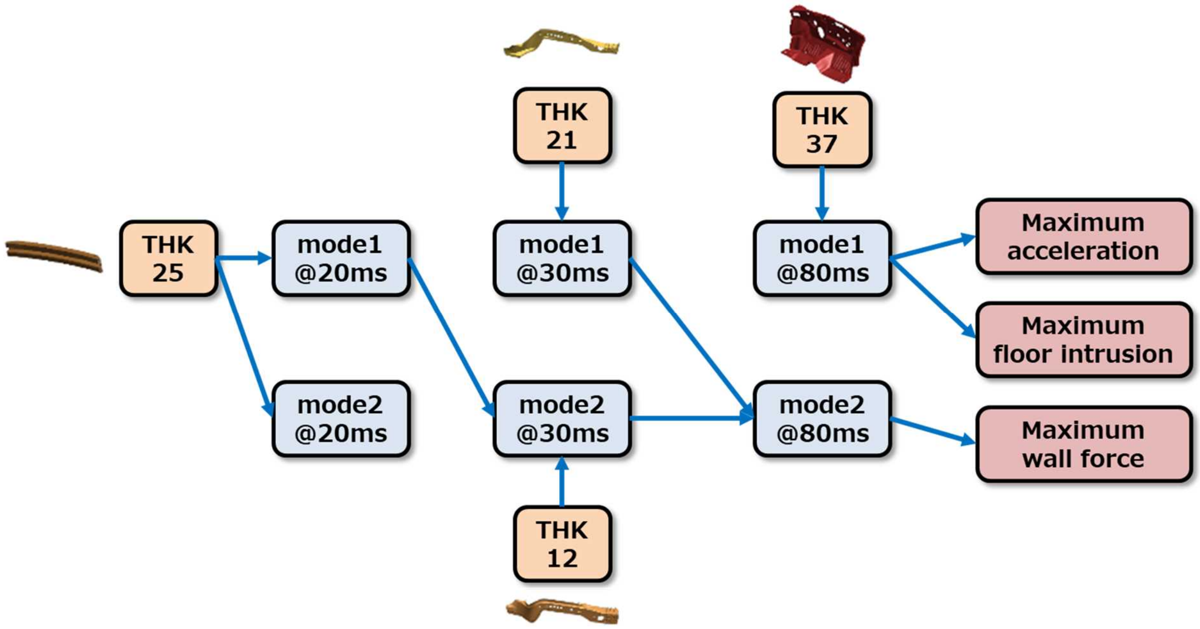


Fig.17: The influence path of the crash event in this study

3 Summary

The US NCAP full-frontal case was used for showcasing the proposed approach of enhanced parameter study using modal decomposition by DIFFCRASH. Taking into account the time & spatial chain of events, and introduction of modal decomposition by PCA will give engineers clues to better understand the phenomena and mechanism. This approach will address the shortcoming of the response surface method, which tends to become a black box for complex phenomena such as the frontal crash of an automobile.

4 Acknowledgment

The author would like to acknowledge technical support and use of the DIFFCRASH license for this study to Mr. Dominik Borsotto and Mr. Clemens-August Thole of SIDACT GmbH.

5 Literature

[1] National Crash Analysis Center: Finite Element Model Archive,
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[2] Borsotto D. et. al.: “Improving robustness of Chevrolet Silverado with exemplary design adaptations based on identified scatter sources”, 10th European LS-DYNA Conference, 2015