Mode controlling approach on multi mode optimization for crash safety design of vehicle

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Abstract

It is important to improve the deceleration characteristic and the cabin deformation for a collision safety design of vehicle. At the same time it is required to reduce the vehicle weight to satisfy the driving performance and environmental restriction. Therefore there is a resistant demand to develop an optimization approach to design a safer and lighter vehicle. The authors have proposed a Statistical Design Support System (SDSS), and brought forward that the SDSS is one of the available optimal approaches for the nonlinear and dynamic phenomena. In this study, they proposed a new concept called as mode controlling approach to keep the side members in ideal buckling mode. As a result, it was shown that high deceleration performance and light body can be realized by using this approach and SDSS.

1 Introduction

Recently, CAE technology has been widely applied for the crash safety of vehicles, and made it possible for complicated non-linear problems such as a collision phenomenon to be simulated at high precision. Development of CAE analysis had a tendency to focus on the simulation of the mechanical behavior
for the crash analysis, though the designers need not only to get the evaluation characteristics value by CAE analysis, but also to improve it in a strict restriction of the development period. Therefore, the efficient design support systems or optimum design systems become indispensable to clear such critical requirements. The authors have proposed a Statistical Design Support System (SDSS), which is one of the available optimal approaches for the non-linear and dynamic problem such as the vehicles crashing. For a collision safety design it is important to improve the deceleration characteristics to reduce the injury of the crew. It is well known that the side members are the main objects absorbing the impact energy of a crashing car. The authors have applied the SDSS for the optimization of the thickness design for the reinforced members of vehicle body with a full car model. The results showed that the thickness optimal design could decrease the weight by 20-30% of the initial weight of all discussed members. However the results also showed that the buckling mode of the main side members could not be improved any more. This means that if the buckling mode of the main side members can be kept in the ideal mode, it is possible not only to get a more steady deceleration characteristic, but also to reduce the weight more. In this study, based upon the results of the full car model the authors proposed a new mode controlling approach to control the buckling mode of the side member. It is considered that by handling the collision safety design as a multi-mode problem like this, high deceleration performance and light body can be realized.

2 Statistical design support system

As shown in Figure 1, the basic concept of Statistical Design Support System (SDSS) is the effectivity analysis, where the effects of the design factors on the objective functions are evaluated quantitatively by combining the structural analyses and the design of experiments (orthogonal array designs). Based upon the analysis of variance for the results of the structural analysis the correlation between the objective functions and design variables can be given in some simple estimation expressions. By using the estimation expressions, this system can deal with almost all kind of design processes.
As shown in Figure 2, the SDSS is composed of seven functions: the effectivity analysis, reanalysis, evaluation of dispersion, robustness analysis, optimization analysis, and reliability evaluation. All of the subsequent treatments such as optimization are performed based on the estimation expressions. Because the structural analyses are separated from the other functions in this system, the optimization of the nonlinear phenomenon can be carried out within any commercial CAE environment. (Please refer to [1] and [2] for further details.)

3 Multi-mode problem and mode controlling approach

It is well known that impacting energy of car crashing is greatly absorbed by the plastic buckling deformation of the side members. Therefore, the energy absorbability of the members depends on the rate of plastically deformed weight to the total weight. As shown in Figure 3, there is a high probability for a side member to buckle in several different modes, as the design variables are changed over a large design space. It can be supposed that the basic behavior of energy absorbability will be much different from the side member, whose deformed mode is different from each other. Therefore, the relation between the energy absorbability and design variables may appear as a multi-maximum (or minimum) problem, because of the multi-mode deformation, as shown in Figure 3.

![Multi mode problem](fig3.png)

Real behavior

Design space

Fig.3 Multi mode problem
Generally, a great amount of study points should be selected to map an accurate response surface for this kind of objective function. On the other hand, if study points are limited to few numbers because of the restriction of analytical time or some other reasons, available response surface can rarely be mapped, as shown in Figure 4. Furthermore, even if multi-points studies are carried out, it also may be very difficult to get good response surface solutions for this kind of problems. Fortunately, it is not necessary to know every thing about this complicated behavior before an optimization design, since only one mode, the optimum mode is concerned with the optimum design point, and the others are the valueless modes or the modes to have to be avoided. The optimum mode for a side member is shown in Figure 5, because it can give high rate of plastic deformation weight.

In this study, the authors proposed a mode controlling approach to define the boundary conditions for the ideal mode, instead of mapping the response surface of whole design space. Using this approach, accurate response surface can be given for the controlled mode by very few study points. The basic concept of this approach is given as followings:

\[
\begin{align*}
\text{Objective functions} & \quad \text{minimum} & \quad \text{Normal optimization} \\
\text{With} & \quad \text{Side constraints} & \quad \text{Mode controlled approach} \\
\text{Behavior constraints} & \quad + \\
\text{Mode controlling constraints} & \quad + 
\end{align*}
\]

General optimization analysis is usually carried out with side constrains and behavior constrains. Side constrain means a definition of range of each design variable, and behavior constrains give some known boundary conditions for the necessary design characteristics. In the proposed approach, in addition to above two kinds of constraint conditions, mode controlling constrants are newly
instituted. Differing from the behavior constrain conditions, not only the characteristic behavior but also its boundary conditions for the mode controlling constrain are unknown functions before optimization study. In this study, the mode controlling constrains are expressed as:

\[ M_i(X_j) < L_i(X_j) \]

\( M_i \) mean the critical functions for mode arising, and \( L_i \) mean the loads which cause the mode. The equations mean when the loads increase over the critical functions, the mode dominates the behavior. In this study, the critical functions as well as the load functions are mapped using SDSS.

4 Mode controlling and optimization for side member

Buckling Mode Analysis Figure 6 shows the buckling mode of side member in the full-lap collision model. It is shown that at the beginning of crash, a local buckling deformation occurred in the front part, and then the side member bended at the center part in a global buckling mode. Here, the buckling mode can be discriminated about two modes. One is the local buckling mode. The other is global bending-buckling mode. Figure 6 shows that the global bending-buckling mode is the main mode in this design. It means that the crashing energy was absorbed only by a small part (deformed part), and the non-deformed part did not contribute to absorbing the crashing energy. It can be considered that repeated local buckling is the ideal mode, because almost all part of the member deforms, transforms the crashing energy into the plastic deformation energy.

Furthermore the crashing energy is absorbed steadily over full buckling stroke. Therefore, it can be said that if the buckling mode of side member can be kept in the ideal mode, its energy-absorbing characteristic can be improved to the optimal level.

4.1 Analysis model

In order to study the buckling modes of a side member and the mode controlling method, a side member shown in Figure 7 was used. Used material properties
are; Young's modulus: 199.4 GPa, Poison rate: 0.3, yield stress: 336.6 MPa. The simulating conditions are; the initial velocity of side member is 56km/h before it crushes on the rigid wall, total simulation time is 30ms. The dynamic simulation software PAM-CRASH on the market was used for the structural analyses.

Fig.7 Analysis Mode

4.2 Buckling mode

The buckling deformation of the ideal member can be classified into the following modes; as shown in Figure 8.

(1) Local buckling in the part II
(2) Local buckling in the part I
(3) Global buckling due to bending deformation in the part III
(4) Global buckling in the part II

Local-buckling at the part II

In order to get the estimation expression for the average crushing load $F_{local}[N]$ in this local-buckling mode, the effectivity analysis for $F_{local}$ to the thickness $t$ and width $H$ was studied. Table 1 shows the level values. From results of variance analysis, the estimation expression of $F_{local}$ was given as:

$$F_{local} = 11000 + 3300t + 13800t^2 [N]$$  \hspace{1cm} (1)
Local-buckling at the part I

The local-buckling at front part is due to the crushing load from part II, $F_{\text{local}}$ and the bending moment caused by the crashing contact between the side member and rigid wall. Here, to prevent this local buckling, a reinforced plate was attached at the part A, and its thickness is $t'$.

It was assumed that the moment, $M$, is a function of the design variables $t$, $t'$, and $H$, and the estimation expression of $M$ was studied using effectivity analysis. As a result $M$ was expressed by the equation (2):

$$M = 1268.4 - 44.0H + 0.2H^2 + 1878.4t' - 1414.9t'^2 + 2471t - 748.9t^2 \ [\text{Nm}] \ (2)$$

Global buckling due to bending deformation at part III

Because the evaluation method for this global buckling is mostly similar to the approach for the local buckling mode at I, the details will be discussed in another study. In this study, this buckling was not included in the following results.

Global buckling at the part II due to $H$ narrowing

This global buckling mode arises by the width $H$ narrowing, and in this case the side member becomes very unstable to the impact loading. The behavior of the mode was investigated by parametric study, and it was made clear that how the parameters $H$ and $t$ affected the instability. The results are shown in Figure 10.
These results show that the boundary between the stable local buckling and unstable global buckling is located near to $H=95\text{mm}$. Of course, the accurate boundary may be affected by the parameter $t$, but it can be said that the difference is not so great. Here, the boundary was set approximately at $H=95\text{mm}$.

### Table 1: Level of variable

<table>
<thead>
<tr>
<th>Variable</th>
<th>Level1</th>
<th>Level2</th>
<th>Level3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>0.5</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>5</td>
<td>17.5</td>
<td>30</td>
</tr>
<tr>
<td>Width</td>
<td>70</td>
<td>95</td>
<td>120</td>
</tr>
</tbody>
</table>

5 Mode controlling and optimization design

Based upon the results of mode analyses of the foregoing, the ideal buckling mode of the side member can be considered to be the mode arising in order of the next steps; (1) at first, just the local buckling of part II without the occurrence of the other buckling modes, (2) and then the local buckling of part I, (3) finally, the global buckling of part III. However, the global buckling of part II is not allowed to occur at any step.

The ideal buckling mode can be controlled by the results of the mode analyses, and the new mode controlling approach was proposed with the following conditions as:

$$F_{\text{local}}(t + t')/2 \geq F_{\text{local}}(t)/2 + M(H,t,t')/h$$

$$H \geq 95\text{[mm]}$$

Under the constraint of the mode controlling conditions, the side member can be optimized without losing the ideal buckling mode.

In this study the weight of the side member was chosen as the objective function, and its estimation expression was given as:

$$W_{\text{weight}} = -0.56 + 7.11E^{-3}H + 6.04E^{-6}H^2 + 5.33t + 0.35t' - 0.33t'^2\text{[kg]}$$

The optimization analysis was carried out with the following problem description as:

Objective function: $W_{\text{weight}} \rightarrow \text{Minimum}$

Constraint: $F_{\text{local}}(t + t')/2 \geq F_{\text{local}}(t)/2 + M(b,t,t')/h\text{[N]}$

$H \geq 95\text{[mm]}$

$F_{\text{local}} \geq 25000\text{[N]}$
The optimized results are shown in Tables 2 and 3. The reanalysis was carried out to confirm the optimization analysis is true. The reanalysis results are shown in Table 3 and Figure 11. It is shown that in comparison with the results under the initial condition, the optimized structure realizes 35% weight down, while the equal absorbed crashing energy was maintained. Furthermore, the energy was absorbed during whole stroke very stably.

**Table 2 Optimal solution**

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Crush Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum</td>
<td>4.95kg</td>
<td>23300N</td>
</tr>
</tbody>
</table>

**Table 3 Results of optimization**

<table>
<thead>
<tr>
<th>Absorbed Energy(E)</th>
<th>Weight</th>
<th>dE/dt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>9840J</td>
<td>79.1-604J/ms</td>
</tr>
<tr>
<td>Optimum</td>
<td>9320J</td>
<td>169.3-316J/ms</td>
</tr>
</tbody>
</table>

**Fig. 11 Comparison of Buckling mode**

**Fig. 12 Comparison of Crush Load**
6 Conclusion

The mode controlling optimization approach in the Statistical Design Support System (SDSS) was proposed for the multi-mode optimum design of car safety. In the full car model, the optimization analysis of the thickness of reinforced frame members was carried by using the multi-objective optimization approach, and the results showed that this approach could reduce the weight of the members without losing the safety of the design. Furthermore, in the side member level, a new mode controlling approach was proposed to design the main reinforced member to absorb the crashing energy with the ideal buckling modes. The results of the optimized design given by the new approach showed that not only can this new design method reduce the weight of the side member at the geometric design step, but also it can improve the basic characteristic of the energy absorbing behavior of side member.

7 Contact

If you require further detailed information or would like to know about anything else related to this subject, please send an e-mail to <qiang@swan.me.ynu.ac.jp>.

8 Reference