RESEARCH ON STIFFNESS MATCHING BETWEEN VEHICLES FOR FRONTAL IMPACT COMPATIBILITY

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ABSTRACT

To achieve good frontal impact compatibility, it is necessary to help match stiffness between vehicles in addition to the enhancement of structural interaction. In this paper, the issues of helping stiffness matching in frontal SUV-to-car impacts were studied using MADYMO vehicle simulation and MADYMO occupant dummy simulation.

1. INTRODUCTION

The introduction of various vehicle impact safety regulations and new car assessment programs in addition to automobile manufacturers' continuing efforts to improve vehicle safety performance have led to the significant improvement of vehicle safety performance over the past years. Especially the protection performance that a vehicle helps provide for its own occupants, which is referred to as self-protection, has been improved. Additionally, in recent years, the further improvement of the protection performance that a vehicle helps provide for the 'opponent' vehicle's occupants, which is referred to as partner-protection, and the optimization of both self-protection and partner-protection is recognized as an approach to further help enhance vehicle safety performance. This approach is generally called compatibility.

Generally, it is thought that enhancing structural interaction between the front-end structures of vehicles is a first step to achieve compatibility and helping match stiffness between vehicles is a next step [1]. Approaches to enhance structural interaction have been proposed and discussed [2]-[8]. On the other hand, researches on helping match stiffness seem few.

In this paper, the following issues in the case where SUV impacted on car under the condition shown in Table 1 were quantitatively studied.

i) Required the increase of the car body stiffness to lower the deformation of car body.

ii) Influence of the increase of car body stiffness on occupant injury indexes in fixed-barrier impact tests.

For the purpose of focusing on stiffness-matching, an assumption was set in following study that structural interaction is satisfactory. The study was done using MADYMO vehicle model (Figure 1), in which vehicle components were modeled as multi-DOF masses and nonlinear-springs, and MADYMO occupant dummy model (Figure 2). Each MADYMO vehicle model had been correlated with the corresponding fixed-barrier physical impact tests.

Table 1. Selected vehicles and impact condition

Vehicle type	SUV	Car (Middle-sized sedan)
Kerb mass	2,500 kg	1,400 kg
Impact speed	56km/h each vehicle (closing speed=112km/h)	
Overlap ratio	50% of car's width	

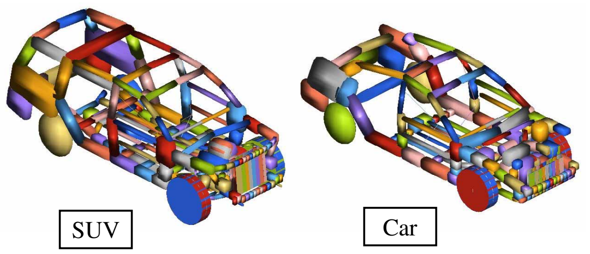

Figure 1. MADYMO vehicle model.

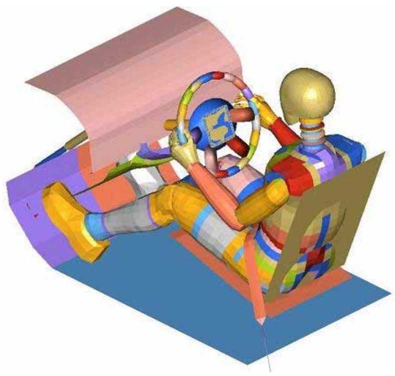

Figure 2. MADYMO occupant dummy model.

2. BASIC STUDY OF STIFFNESS MATCHING

As a first step, basic study of stiffness matching by means of simplified method was made.

When SUV with mass of m_1 and pre-impact velocity of v_1 impacts on car with mass of m_2 and pre-impact velocity of v_2, the impact phenomenon can be modeled simply as shown in Figure 3.

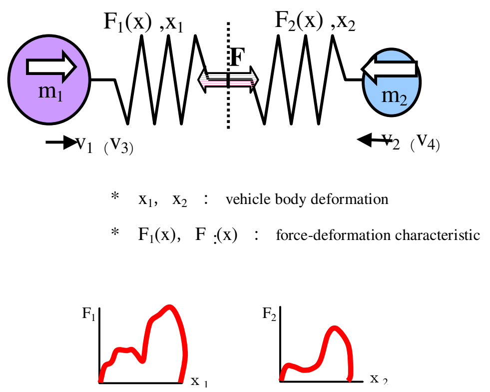

Figure 3. Simplified SUV-to-car impact model.

In this case, from the law of conservation of momentum (1) and the definition of coefficient of restitution (2), post-impact velocity of each vehicle can be described as (3) and (4).

$$m_1 v_1 + m_2 v_2 = m_1 v_3 + m_2 v_4 \qquad \cdots\cdots(1).$$

$$v_3 + v_4 = e \cdot (v_1 + v_2) \qquad \cdots\cdots(2).$$

$\therefore$

$$v_3 = v_1 - \frac{m_2}{(m_1 + m_2)}(1+e)\cdot(v_1 + v_2) \qquad \cdots\cdots(3).$$

$$v_4 = v_2 - \frac{m_1}{(m_1 + m_2)}(1+e)\cdot(v_1 + v_2) \qquad \cdots\cdots(4).$$

where,

m_1, m_2 : mass of vehicle

v_1, v_2 : pre-impact velocity

v_3, v_4 : post-impact velocity

e : coefficient of restitution

The energy which is spent to deform both vehicles, the deformation energy E, is given by equation (5).

$$E = \frac{1}{2}(m_1 {v_1}^2 + m_2 {v_2}^2) - \frac{1}{2}(m_1 {v_3}^2 + m_2 {v_4}^2)$$
$$= \frac{1}{2}\frac{m_1 \cdot m_2}{m_1 + m_2}(1-e^2)(v_1 + v_2)^2 \qquad \cdots\cdots(5).$$

Impact forces F acting on front of each vehicle are equal by law of action and reaction. Therefore, deformation of each vehicle x_1, x_2 in the impact are calculated under condition satisfying equation (6) on force-deformation characteristic curves F_1, F_2, as figure below.

$$\int_0^{x_1} F_1(x)dx + \int_0^{x_2} F_2(x)dx = E_1 + E_2 = E \cdots\cdots(6).$$

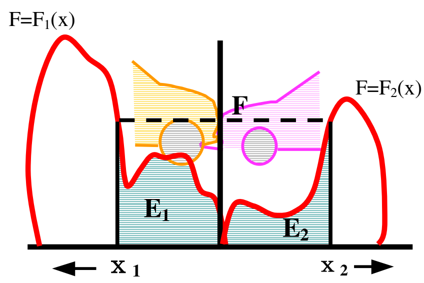

Figure 4. Calculation method of vehicle deformation.

According to the above-mentioned method, the deformation of each vehicle body in frontal SUV-to-car impact under the condition shown in Table 1 was predicted using each vehicle's force-deformation curve obtained in MADYMO 64km/h ODB impact simulation (Figure 5). From Figure 5 it is known that there is a great difference in stiffness between two vehicles. Figure 6 shows the result of predicted deformation. Here, coefficient of restitution is set at zero.

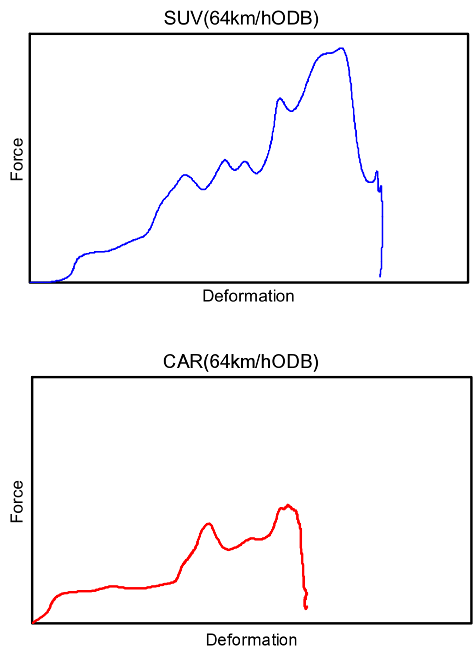

Figure 5.
Calculated force-deformation curve
(MADYMO vehicle model, 64km/h ODB condition).

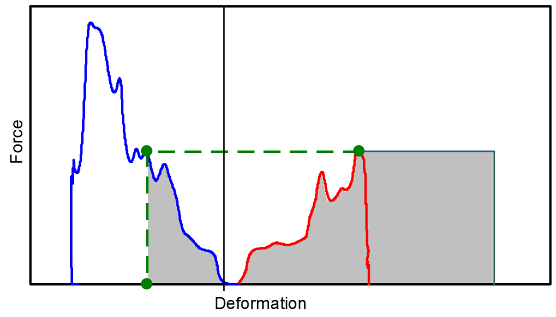

Figure 6. Predicted force-deformation curve (SUV-to-car impact).

The ceiling of impact force F is determined by the car body stiffness therefore car bears unilaterally most of impact energy. Consequently body deformation of SUV is reduced to 56% of 64km/h ODB condition, whereas that of car increases to 196%. This result is not considered compatible. The stiffness mismatch leads to this result.

In this case, there are the following approaches to reduce deformation of car body.

(a) By decreasing the stiffness of SUV, increase the deformation and impact energy absorption of SUV.

(b) By increasing the stiffness of car, increase impact energy absorption of SUV.

It is difficult to adopt approach (a), because this is directly connected to drop of self-protection performance of SUV in fixed-barrier tests. Accordingly, approach (b) is adopted and required amount of stiffness increase to reduce car body deformation is predicted (Figure 7). In this case, the target of reducing deformation as same level as that in fixed-barrier tests is set.

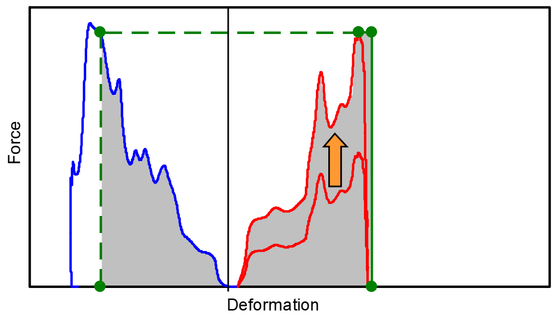

Figure 7.
Predicted force-deformation curve and required amount of stiffness increase (SUV-to-car impact).

Figure 7 shows that the car's deformation in frontal SUV-to-car impact will be comparable to that in 64km/h ODB impact by increasing car's stiffness 1.9 times throughout. This result is considered as compatible.

Here, an attempt to take vehicle stiffness apart to pieces was made. In frontal impact of a vehicle, behavior of power-train and body is quasi-independent. Consequently, it is possible to separate the reaction force of vehicle into two forces generated by each [1]. Generally, the former is called “Mechanical force”, the latter “Structural force”. Based on this approach, the result that force-deformation curve of the car separated into above two forces is shown in Figure 8.

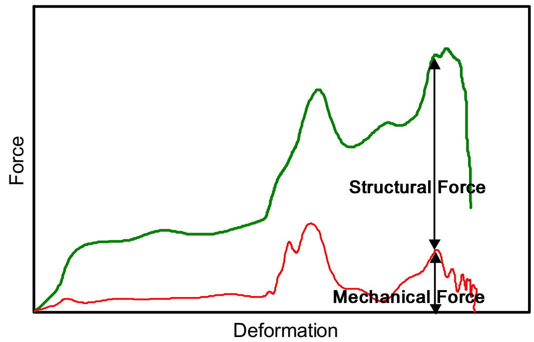

Figure 8.
Force-deformation curve of car and its component (MADYMO vehicle model, 64km/h ODB condition).

At the neighborhood of the peak, nearly 25% of car’s reaction force consists of “Mechanical force” generated by inertia force of power-train. However, it is difficult to control vehicle stiffness by this component in actual car. Consequently, it is necessary to achieve target stiffness mainly by increasing “Structural force”. According to this, required increase of car body stiffness is estimated as 2.2 times by equation (7).

$$\frac{Structural\quad Force(reinforced)}{Structural\quad Force(original)} = \frac{1.9-0.25}{1-0.25} = 2.2 \quad \cdots\cdots \quad (7).$$

3. DETAILED STUDY OF STIFFNESS MATCHING USING SUV-TO-CAR MADYMO MODEL

From the study using simplified method in former chapter, the possibility is shown that required increase of car body stiffness amounts to 2.2 times as much as original car to reduce car body deformation in frontal SUV-to-car impact. In this method, force-deformation characteristic of each vehicle is modeled as single spring with force-deformation curve obtained by the simulation under 64km/h ODB condition. However, because the structure of actual vehicle is more complicated, there is some possibility that those fixed force-deformation characteristics are not always appropriate.

Accordingly, as next stage, simulations in which two MADYMO vehicle models (Figure 1) collide mutually were conducted.

Figure 9 is the calculated result of frontal SUV-to-car impact simulation in which each vehicle collides mutually under the condition shown in Table 1. In case of this simulation, contact definition in MADYMO model is set so that main structural members such as side-frame of both vehicles may transmit impact force mutually and structural interaction become satisfactory. Viewing the result, it is clear that deformation of car body becomes larger than that of SUV, and an unbalance of energy absorption occurs. Body deformation of SUV is reduced to 80% of 64km/h ODB condition, whereas that of car increases up to 150%.

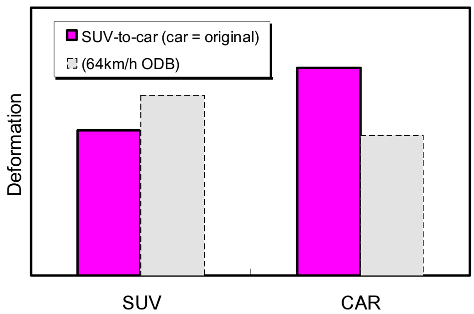

Figure 9. Calculated vehicle body deformation of MADYMO vehicle model (64km/h ODB & SUV-to-car(original) impact).

In the next step, an attempt was made to set deformation of each vehicle compatible by increasing strength of main members of car body. In case of increasing strength, each member is multiplied by its optimized ratio instead of a common ratio, so that the deceleration-deformation curve of the vehicle become close to a rectangle. By this way, occupants will be restrained in earlier stage of impact and this enables to make good use of ride-down effect, and so car body characteristic become favorable from occupant injury point of view.

Result of SUV-to-car (reinforced) impact simulation is shown in Figure 10. With the stiffness increase of car, more impact energy is absorbed by SUV that result in large reduction of car body deformation. As a result, the deformation of both SUV and car become nearly same as that of 64km/h ODB condition and the deformation of each vehicle become compatible.

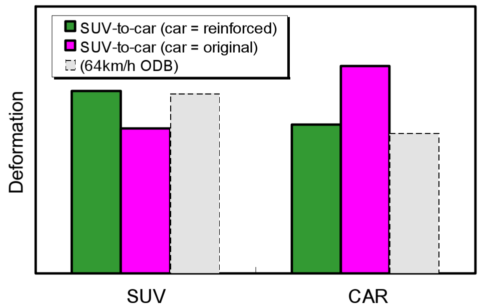

Figure 10. Calculated vehicle body deformation of MADYMO vehicle model (64km/h ODB & SUV-to-car(reinforced) impact).

In Figure 11, strength of each part of main members before/after reinforcement is shown. The ratios of strength increase vary with members and result in the range from 1.3 to 32 times.

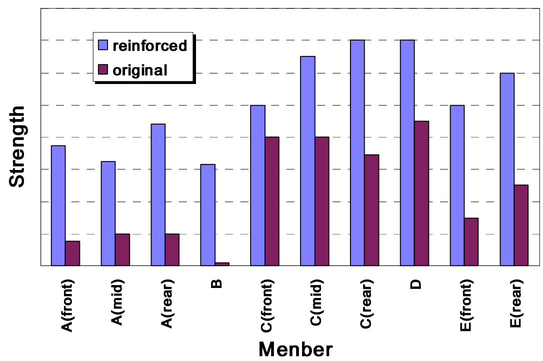

Figure 11. Strength of members of car model.

To estimate the increase of body stiffness, section force of reinforced car body was calculated, by means of adding up strength of members in above per a section crossing x-axis of vehicle. Calculated value normalized by that of original car was 2.2, in the section that affects the peak force of body.

From the study above using SUV-to-car MADYMO model, it is shown that to reduce car body deformation in frontal SUV-to-car impact, required amount of stiffness increase is over 2 times even if structural interaction is satisfactory. This corresponds closely with the result of simplified method in former chapter as a result (See Figure 7-8 and equation (7)). Each result suggests the importance of helping match stiffness in frontal SUV-to-car impact.

4. INFLUENCE OF STIFFNESS MATCHING ON FRONTAL FIXED-BARRIER IMPACT PERFORMANCE

To help keep occupant's compartment space during a frontal impact is one aspect of self-protection process. In case of frontal SUV-to-car impact, it can be achieved by limiting body deformation to an appropriate level. The most effective measure is to match stiffness of both vehicles as mentioned above.

However, once vehicle stiffness is increased, vehicle deceleration in fixed-barrier tests increases in accordance with the relation F=m*a, since mass increase due to reinforcement is generally small in comparison with stiffness increase. In this case, vehicle stops its motion within smaller displacement, and to prevent occupant from hitting cabin inner, it is necessary to strengthen power of restraint system. As a result, occupant injury indexes may become worse in fixed-barrier tests.

So in this chapter, verification of the influence arose from increase of car body stiffness to cope with frontal SUV-to-car impact on occupant injury indexes in fixed-barrier tests was conducted.

In the first place, deceleration-displacement curves of original/reinforced car calculated with MADYMO model under fixed-barrier test conditions are shown in Figure 12-13. As mentioned above, by increasing body stiffness, displacement become small and deceleration increases about 20% throughout.

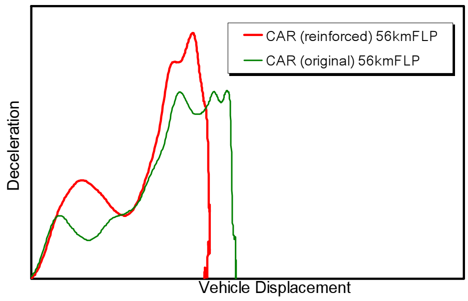

Figure 12. Deceleration-displacement curve of MADYMO vehicle model (56km/h Full-overlap).

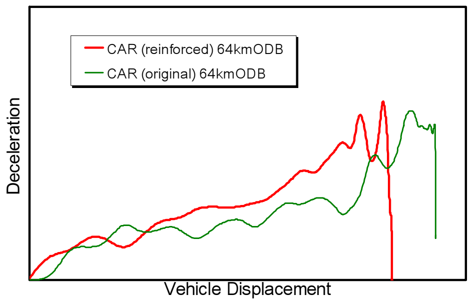

Figure 13. Deceleration-displacement curve of MADYMO vehicle model (64km/h ODB).

Occupant injury indexes were calculated under the condition shown in Table 2. Calculations were performed using MADYMO occupant dummy model (See Figure 2), for driver (AM50, belted) case only. Here, the parameters of restraint system of car (original) were set along to typical specifications of corresponding vehicle class. On the other hand, those of car (reinforced) were adjusted in a realistic range so that injury indexes might become as good as possible. In the concrete, parameters such as air-bag power, steering column absorbing load, seat belt load-limiting force were adjusted.

Table 2.
Calculation conditions of occupant injury indexes

Case	1	2	3	4
body stiffness	Original		Reinforced	
Impact condition	56km/h Full-overlap	64km/h ODB	56km/h Full-overlap	64km/h ODB
Restraint system	Typical	←	Adjusted	←

Calculated results about main injury indexes of car (reinforced) are shown in Figure 14. Values in the graph were normalized using those of car (original). Every item shown in this graph is higher when compared those of car (original). Especially, deterioration of HIC and chest-G is large, and those become 1.85 and 1.36 times each in comparison with that of car (original). Despite adjusting restraint system as much as possible, deterioration of occupant injury indexes was unavoidable as a result.

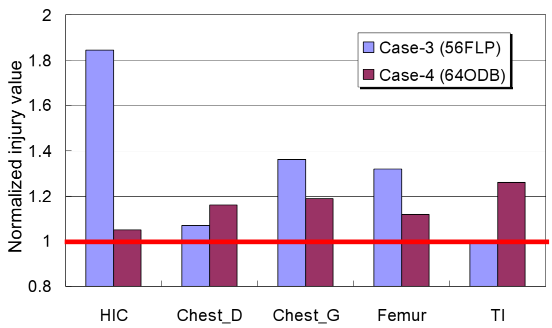

Figure 14.
Normalized injury indexes of occupant dummy.

5. DISCUSSION

The study above shows for the scenarios analyzed that in order to realize good impact compatibility from the viewpoint of stiffness-matching, it would be necessary to increase body stiffness of the car over two times.

It is very difficult to increase body stiffness within realistic mass rise that affects little on fundamental performance of vehicle. Moreover, even if it can be realized, it becomes clear that such body reinforcement increases deceleration of vehicle in fixed-barrier impact tests, and this led to deterioration of occupant injury indexes.

These facts indicates that it is very difficult to cope with both measures to accomplish good impact compatibility in frontal SUV-to-car impact and measures to accomplish sufficiently low occupant injury indexes in fixed-barrier tests.

Since design and evaluation methods for self-protection performance are based on government mandated and to some extent market driven fixed barrier impact tests that consequently require a vehicle stiffness strongly related to mass, it is difficult to simultaneously achieve enhanced compatibility. However, from a purely frontal impact compatibility point of view, it is necessary to harmonize frontal stiffness of vehicles by means of increasing the stiffness of lighter vehicle or decreasing that of heavier vehicle. In efforts to accomplish the enhanced compatibility, it is desirable that such changes to vehicle stiffness will not reduce the self-protection performance.

In order to enhance compatibility while still maintaining self protection performance, harmonizing the use of MDB to imitate vehicle stiffness with government mandated self protection performance test procedures appears to be needed. However, in order to actualize the above, further studies are required about specification of MDB that has meaning as vehicle stiffness standard, and evaluation method for partner protection performance (including structural interaction which is set forth as a prerequisite in this paper).

In this paper, influences by the increase of body stiffness so as to achieve frontal compatibility on other impact modes (i.e. a stiffer car could be impacting the sides of other vehicles) and influences by mass-ratio of each vehicle on deceleration characteristic of smaller vehicle, were not considered. However, these are important matters in an attempt to achieve improved compatibility, and so further research may be needed.

6. CONCLUSIONS

Taking up full-sized SUV and middle-sized sedan, an attempt to quantitatively evaluate the matters mentioned below on 56km/h frontal offset SUV-to-car impact condition was made.

i) Required the increase of the car body stiffness to lower the deformation of car body.

ii) Influence of the increase of car body stiffness on occupant injury indexes in fixed-barrier impact tests.

As a result, following knowledge was obtained.

i) In order to limit deformation of car body as same level as that in fixed-barrier tests, even if structural interaction is satisfactory, stiffness of car body must be increased up to double, based on the models used for this research.

ii) In case of above realized, even if occupant restraint system is adjusted using currently available technology among current vehicles, occupant injury indexes in fixed-barrier impact tests deteriorate in this study.

REFERENCES

[1] Edwards, M., et al., "Development of Test Procedures and Performance Criteria to Improve Compatibility in Car Frontal Collisions." Vehicle Safety 2002.

[2] Delannoy, P., et al., "Proposal to Improve Compatibility in Head on Collisions." 16th International Conference on the Enhanced Safety of Vehicles, Paper No. 98, Windsor, Canada, 1998.

[3] Summers, S., et al., "Design Consideration for a Compatibility Test Procedure." Society of Automotive Engineers, Paper No. 2002-01-1022, 2002.

[4] Delannoy, P., et al., "New Barrier Test and Assessment Protocol to Control Compatibility." Society of Automotive Engineers, Paper No. 2004-01-1171.

[5] Takizawa, S., et al., "Experiment Evaluation of Test Procedure for Frontal Collision Compatibility."

Society of Automotive Engineers, Paper No. 2004-01-1162.

[6] Haenchen, D., et al., " Feasible Steps towards Improved Crash Compatibility." Society of Automotive Engineers, Paper No. 2004-01-1167.

[7] Verma, M.K., et al., "Significant Factors in Height of Force Measurements for Vehicle Collision Compatibility." Society of Automotive Engineers, Paper No. 2004-01-1165.

[8] Hirayama, S. et al., "Compatibility for Frontal Impact Collisions Between Heavy and Light Cars." 18TH International Conference on the Enhanced Safety of Vehicles, Paper No. 454, Nagoya, Japan, May 2003.