A FUNDAMENTAL STUDY OF FRONTAL OBLIQUE OFFSET IMPACTS

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ABSTRACT

Vehicle crashworthiness in frontal collisions is often evaluated using a procedure that simulates a full frontal crash between two vehicles. In the real world, however, many of the accidents regarded as frontal collisions are oblique offset impacts. Such impacts may differ from full frontal collisions in terms of vehicle body deformation and occupant behavior, owing to differences in the position and direction of the input crash energy. The distribution of occupant injuries in real-world accidents tends to vary depending on the impact angle. Accordingly, researching occupant protection measures based on a good understanding oblique offset impacts is a useful approach to help enhance vehicle safety performance further. In this work, vehicle body deformation and dummy behavior were analyzed in frontal oblique offset impacts, involving car-to-car crashes of ordinary medium-size passenger vehicles, and in FEM simulations. A fundamental research study was then made of the results to identify the characteristics of frontal oblique offset impacts. The collision test results revealed that cabin deformation tended to increase when crash energy was applied at an oblique angle. It was observed that the struck vehicle also moved sideways, causing the force of inertia to act on the dummy. As a result, the dummy's upper torso translated sideways and ankle inversion/eversion occurred. In the FEM simulations, it was seen that the front side member of the struck vehicle sustained less axial deformation and that the engine compartment absorbed less energy than in the full frontal collision, resulting in the cabin structure needing to absorb larger proportions of the crash energy.

FEM simulations showed that providing a subframe to connect the front side members and the floor panel increases the energy-absorbing capacity of the engine compartment. Additionally, MADYMO (Mathematical Dynamic Model) simulations showed that side-impact airbags on the struck side reduce the lateral translation of the near side dummy's upper torso. These simulations also showed that applying a control load that acts on the thighs and lower legs in the lateral direction reduces ankle inversion/eversion.

INTRODUCTION

The number of traffic accident fatalities in Japan has been on a downward trend since 1993, dropping to 8,747 deaths in 2001, which marked the first time in 13 years that the figure fell below the 9,000 level. However, both traffic accidents and injuries have been consistently increasing in number, with the latter reaching 1.18 million in 2001. Vehicle manufacturers strive to find new means to help reduce the injuries that occur while maintaining this downward trend of fatalities.

Crash compatibility is an example of an issue that has been examined in recent years as an area for further improvement of vehicle safety. This issue was taken up by one of the six working groups formed under the International Harmonized Research Activity (IHRA) project at the 15th ESV Conference. At the time research was launched, attention was focused on the question of vehicle mass. At IBEC '97, Steyer et al.[1] presented a report concerning the vehicle body strength characteristics that were needed to ensure compatibility with respect to vehicle mass differences. At the 16th ESV Conference, Zobel at al.[2] also reported on body structural requirements (i.e., the bulkhead concept), in addition to body strength properties. However, at the 17th ESV Conference, the IHRA Compatibility WG[3] indicated that the vehicle mass alone was not necessarily the only factor that influences the risk of occupant injury. They pointed out that passenger compartment integrity is a key factor in reducing the risk of occupant injury and that a favorable structural interaction between the colliding vehicles must first be ensured in order to secure cabin integrity. At the same ESV Conference, Edwards et al.[4] and Delannoy[5] reported different methods for evaluating the homogeneity of the stiffness distribution of the front-end structure, which is thought to be an important element in securing a favorable structural interaction between the front-ends of colliding vehicles.

Another issue in the consideration of improving front-end crashworthiness is oblique offset impact performance. Based on the results of an accident analysis using National Automotive Sampling System (NASS) data, Stucki et al.[6, 7] reported at the 1995 SAE Congress and at the 15th ESV Conference that frontal oblique offset impact tests conducted with a moving deformable barrier (MDB) were suitable for covering the accident patterns not included in the FMVSS 208 test procedures. At the 16th ESV Conference, Ragland[8] reported the results of a detailed study of an oblique offset impact test procedure in which the MDB was crashed into a subject vehicle. In addition, on the basis of NASS data, Ragland et al.[9] reported at the 17th ESV Conference that the largest number of leg injuries occur in frontal oblique offset impacts on the driver's side and that offset impacts represent the most common crash mode. At the 16th ESV Conference, Sugimoto et al.[10] also presented the results of oblique offset impact tests together with a test procedure in which they crashed their independently developed MDB into a subject vehicle.

It is anticipated that performance in oblique offset impacts is closely related to crash compatibility. Improving the robustness of vehicle crashworthiness in relation to the impact angle should be studied. The compatibility evaluation procedures[4, 5] being investigated at present would be very useful in relation to real-world accidents. However, although the reports seen in the literature so far have described the results of oblique offset impact tests and the results of analyses of real-world accident patterns, they have not presented any details concerning studies of safety measures actually applied to vehicles.

The purpose of this research is to present technical issues involved in oblique offset impacts and to show a direction for implementing measures to improve vehicle safety, with the aim of enhancing the robustness of vehicle crashworthiness in relation to the impact angle in frontal collisions. This research paper presents the results of crash tests and FEM simulations that were conducted to analyze vehicle deformation and dummy behavior in oblique offset car-to-car (CTC) impacts involving ordinary medium-size passenger vehicles as an example. It also presents the results of a basic examination of the technical issues that were revealed on the basis of this analysis.

ACCIDENT ANALYSIS

In the U.S., NASS makes public accident data in which the impact angles are indicated. Figure 1 shows the results of an accident analysis based on NASS Crashworthiness Data System (CDS) statistics. This analysis looked at accidents involving belted drivers. Accidents that occurred at impact angles having an absolute value of 10° or less were the most numerous, accounting for approximately 40% of the total. Excluding the accidents for which the details were unknown, those having an impact angle greater than 10° accounted for approximately 50% of this NASS accident database.

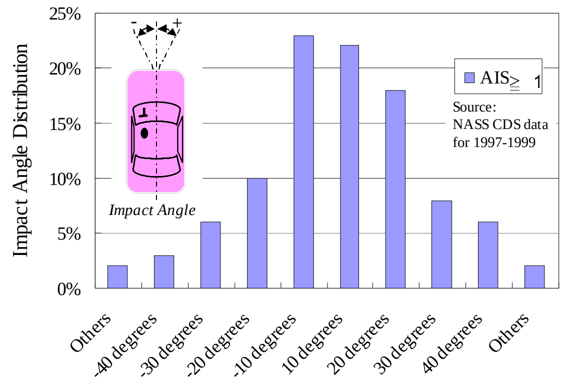

Figure 1. Impact angle distribution.

CLARIFICATION OF FRONTAL OBLIQUE OFFSET IMPACT CHARACTERISTICS

Impact Tests

Car-to-car (CTC) impact tests were conducted to study the characteristics of frontal oblique offset impacts and to identify the technical issues that should be investigated. The circumstances at the time of the impact are illustrated in Figure 2. The subject vehicle and the bullet vehicle used were two identical prototypes representing ordinary medium-size passenger cars. The angle of impact was set at 30°, taking into account the impact angle distribution seen in the analysis of real-world accidents in Figure 1 and the data given in the literature.[8-11] A 50th percentile Hybrid III (AM50) dummy was placed in the driver's seat to obtain injury value measurements, and a high-speed video camera was also used to record the kinematics during the impact.

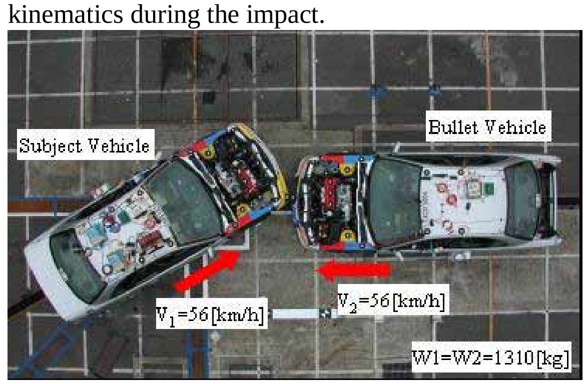

Figure 2. Oblique offset crash.

Vehicle Deformation Behavior

Figure 3 is a photograph of the subject vehicle following a frontal oblique offset impact test, and Figure 4 shows the vehicle with the same specifications following an offset deformable barrier impact test at 64 km/h (64K-ODB). Figure 5 shows the deformation ratios (oblique offset impact/64K-OBD) found for representative locations of the vehicle body.

Figure 3. Prototype vehicle after oblique offset crash.

Figure 4. Prototype vehicle after offset deformable barrier crash.

The lower portion of the cabin, including the floor panel and the lower part of the A-pillar, displayed larger deformation in the oblique offset impact test than in the 64K-ODB test. It appears this is due to the pronounced crash force applied to these locations by the tire that was pushed directly inward on account of the oblique impact. In addition, the side member, which is a principal absorber of crash energy, was crushed to a lesser extent in the oblique offset impact than in the 64K-ODB impact. It is deduced from this lesser amount of crushing that there is a decrease of engine compartment crash energy absorption.

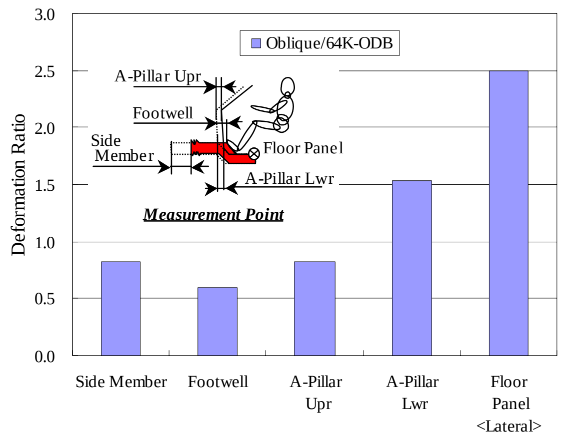

Figure 5. Deformation ratios.

Dummy Kinematics

The injury values recorded for the dummy in these tests satisfied the ECC protocol standards.(11) However, certain dummy kinematics were observed that have not been reported previously, notably that the upper torso translated laterally (See Figure 6) and the ankles suffered inversion or eversion (See Figure 7).

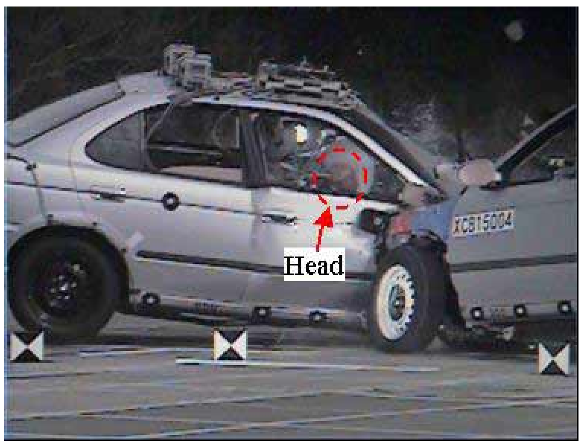

Figure 6. Lateral translation of dummy's upper torso in oblique offset crash.

Figure 7. Ankle inversion/eversion in oblique offset crash.

The upper torso's translation to the side is attributed to the force of inertia acting on the dummy as a result of the lateral movement of the struck vehicle during the impact. Friction force between the floor panel and the soles of the dummy's shoes also appears to influence ankle inversion/eversion (See Figure 8).

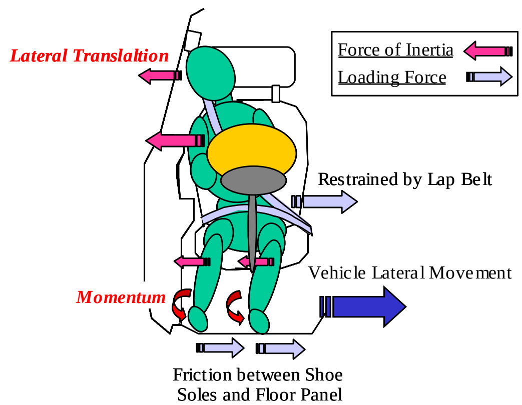

Figure 8. Schematic illustration of dummy's kinematics.

FEM Simulations

FEM simulations were run in order to analyze the deformation behavior of the vehicle body in more detail. The model utilized in the analysis modeled the prototype vehicle used in the impact tests. Figure 9 compares the measured and simulated deformation ratios for the oblique offset impact and the 64K-ODB impact. The simulated deformation ratios agreed well with the measured results for the most part, indicating that this simulation procedure could be used to help study the characteristics of oblique offset impacts. In order to make a more detailed comparison, a simulation was also run for an inline CTC impact with a 50% offset, in addition to the 64K-ODB impact (See Figure 10). Figure 11 shows the distribution of energy absorption by the subject vehicle in each impact mode. In the oblique offset impact, the energy absorption rate of the engine compartment, which is designed to absorb crash energy, was lower and that of the right side of the cabin was higher in comparison with the results seen for the other two impact modes. Energy absorption by the engine compartment in the oblique offset CTC impact was only 78% of that in the inline CTC impact.

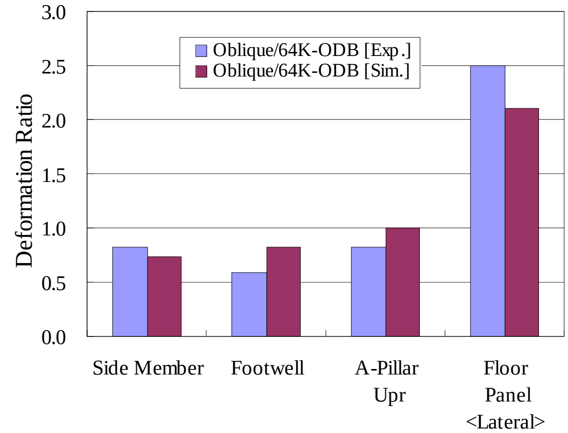

Figure 9. Comparison of deformation ratios.

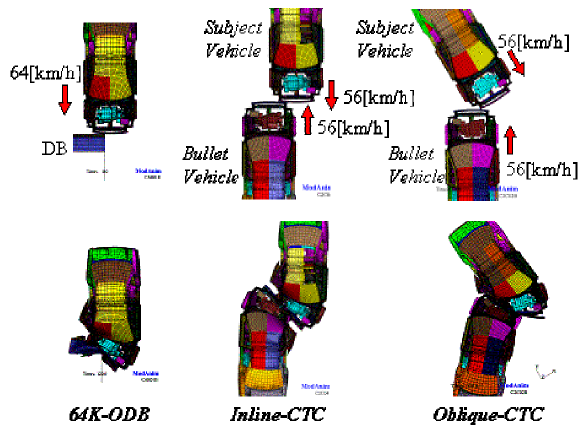

Figure 10. FEM simulations.

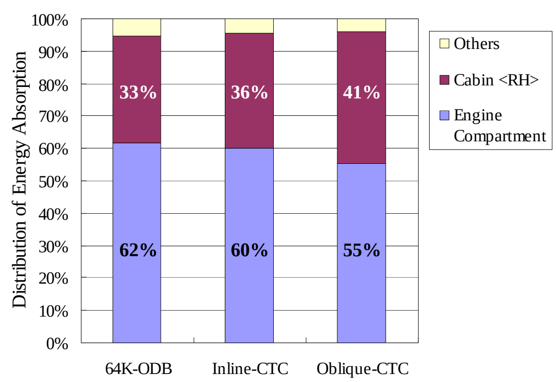

Figure 11. Distribution of energy absorption.

This decrease in energy absorption coincided with the energy absorption level that was predicted from the smaller extent of side member crushing in the oblique offset impact than in the 64K-ODB impact. This decline in energy-absorbing capacity may be due to the oblique impact angle, as the front part of the side member on the struck vehicle was bent inward, and the force acting to push the front part rearward decreased. Another contributing factor was a decrease in the dispersion of the load to the non-impacted side, because the engine was not pushed directly rearward. Figure 12 compares the side member deformation modes in the inline CTC impact and the oblique offset CTC impact. It is seen that the front part of the side member was bent inward in the oblique offset impact and also that the side member itself suffered less deformation.

Based on the foregoing analysis results, it is thought that the lower portion of the cabin displayed larger deformation in the oblique offset impact than in the 64K-ODB impact because of two factors. One was the pronounced energy input from the tire, and the other was the reduced level of energy absorption by the engine compartment.

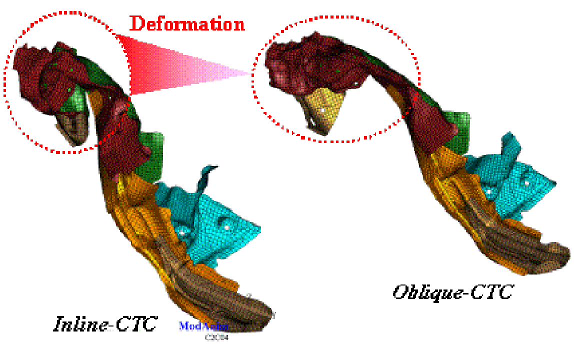

Figure 12. Comparison of side member deformation.

EXAMINATION OF TECHNICAL ISSUES

Increase in Cabin Strength

The same impact tests were conducted using a reinforced vehicle body that was built by adding structure to the above-mentioned baseline prototype vehicle. Figure 13 illustrates the areas of the body that were reinforced. Reinforcement was mainly applied to the lower portion of the cabin, including the floor panel, the lower part of the A-pillar and the side sill. A photograph of the reinforced vehicle body following an oblique offset impact test is shown in Figure 14. The deformation ratios of the reinforced body in relation to the original body are given in Figure 15. As a result of the reinforcements applied, cabin deformation was substantially reduced compared with that of the original body. These results show that reinforcement of the lower portion of the cabin can help reduce deformation in oblique offset impacts.

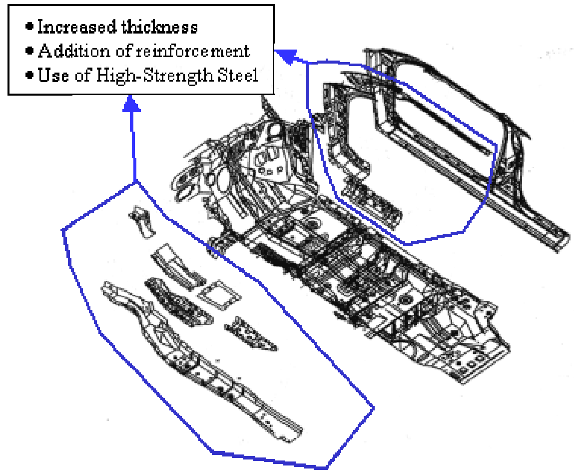

Figure 13. Reinforced areas of improved body.

Figure 14. Reinforced vehicle after oblique offset crash.

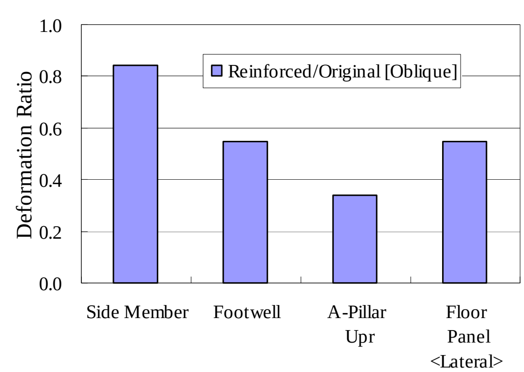

Figure 15. Deformation ratios.

On the other hand, because the amount of crushing exhibited by the front side member did not increase, it is thought that improvement of the energy-absorbing capacity of the engine compartment is an issue that must be addressed separately. It is desirable for the engine compartment to absorb as much crash energy as possible. This is because the amount of energy that the engine compartment has to absorb may increase in real-world accidents when vehicle incompatibility is seen. Additionally, although the measured dummy injury values satisfied the ECC protocol standards,(11) it was observed that the dummy's upper torso still translates laterally and that ankle inversion/eversion still occurred, as was seen in the earlier series of tests. Accordingly, it was concluded that measures for dealing with these behavior patterns must be addressed separately from those intended to control vehicle body deformation.

Improvement of Engine Compartment's Energy-Absorbing Capacity

As one measure for improving the energy-absorbing capacity of the engine compartment, FEM simulations were conducted to confirm the effect of applying the #-type frame that has generally been used on large cars. Figure 16 shows the front-end of a vehicle with the H-type frame that was used on the prototype vehicle in the impact tests. Figure 17 shows the front-end of a vehicle built with the #-type frame.

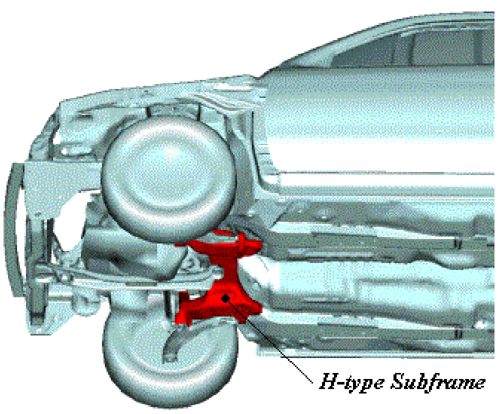

Figure 16. H-type frame model.

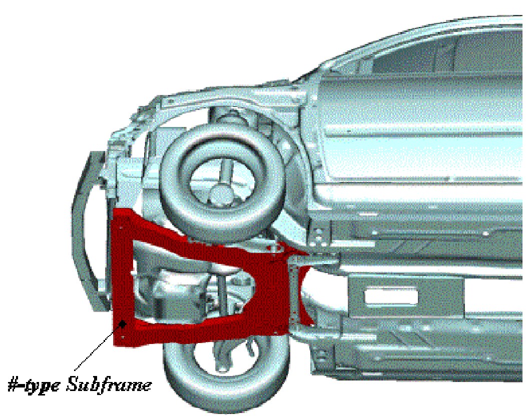

Figure 17. #-type frame model.

The #-type frame includes a subframe that connects the front part of the side members and the front part of the floor panel, which is thought to help disperse the load applied to the engine compartment. A comparison was made of the deformation modes of the two frames in frontal impacts. It was found that the vehicle with the H-type frame showed pronounced deformation of the portion on the outer side of the engine in an oblique offset CTC impact, and the deformation mode differed from that seen in an inline CTC impact (See Figure 18). On the other hand, for the vehicle with the #-type frame, the deformation mode of the engine compartment was nearly the same in both the inline and oblique offset CTC impacts (See Figure 19).

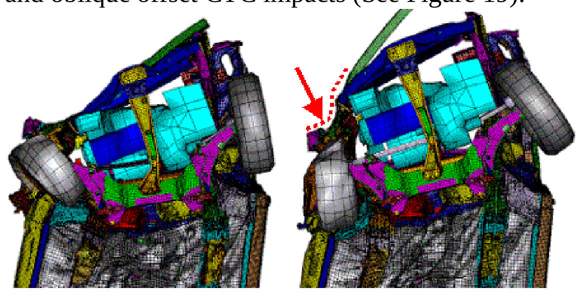

Figure 18. Comparison of deformation modes with H-type frame.

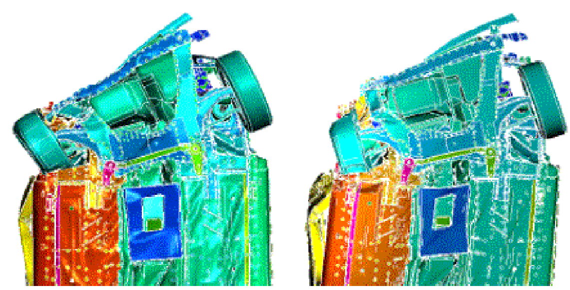

Figure 19. Comparison of deformation modes with #-type frame.

In addition, for the vehicle with the #-type frame, energy absorption by the engine compartment in the oblique offset CTC impact was 88% of that in the inline CTC impact (See Figure 20). This figure was 10% higher than that of the vehicle with the H-type frame. Together with the results of the above-mentioned deformation mode comparison, this showed that the #-type frame can help increase the energy-absorbing capacity of the engine compartment in this oblique offset impact test condition.

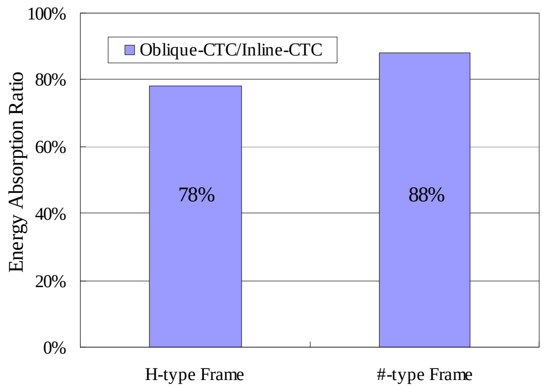

Figure 20. Comparison of energy absorption ratios.

Controlling the Lateral Translation of Dummy's Upper Torso

A simulation was run in which an attempt was made to prevent the dummy's upper torso from lateral translation by means of a side-impact airbag system on the struck side occupant. The MADYMO (Mathematical Dynamic Model) code was used in the simulation. Figure 21 illustrates the airbag used to inhibit the sideways fall of the upper torso. The airbag was designed to inflate fully at the moment the dummy began to move laterally. When the airbag was positioned so as to inhibit lateral movement of the dummy's head, it substantially reduced the lateral movement of the head, but had little effect on the chest region. When positioned next to the chest region so as to inhibit the lateral movement of the chest region, it was found that it was equally effective in controlling the sideways movement of both the head and chest region (See Figure 22). In attempting to inhibit the sideways fall of the upper torso, it is thought that support should be provided for the chest region or for the chest region and the head together.

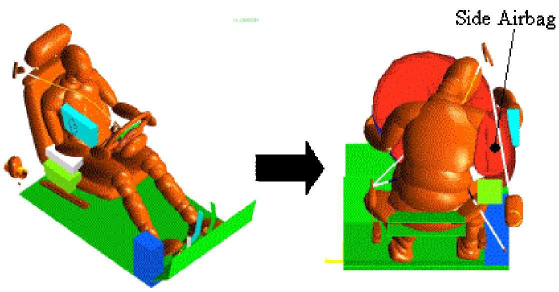

Figure 21. Reduction of lateral movement.

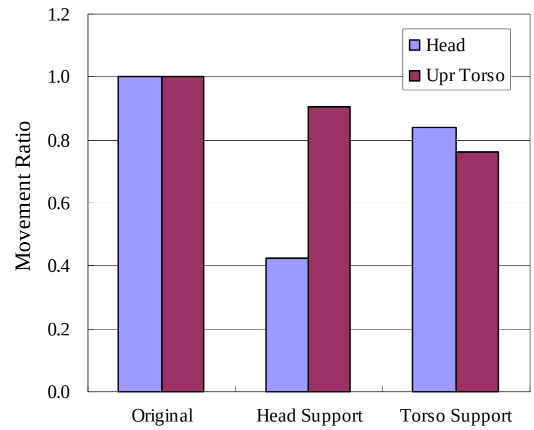

Figure 22. Movement ratios.

Controlling Ankle Inversion/Eversion

Simulations were also run to examine measures for preventing ankle inversion/eversion. The MADYMO code was also used in performing these simulations. The basic approach considered for controlling ankle inversion/eversion was to use the seats, door trim, A-pillars, floor panel and other places to apply a lateral load to the legs and thereby prevent relative displacement of the feet and lower legs (See Figure 23). The places considered for applying a load to the legs were the feet, the lower legs and the thighs.

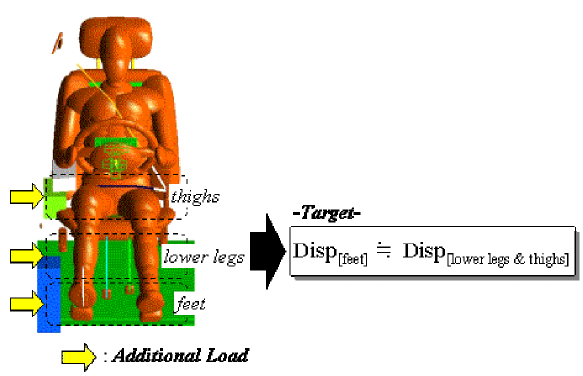

Figure 23. Method of reducing ankle rotation.

An investigation was made of the effect of applying a load to these three locations on inhibiting ankle inversion/eversion. It was found that loads could be applied to two locations, i.e., the feet and the lower legs or the thighs, in order to obtain stable behavior. Furthermore, in a comparison of the lower legs and the thighs, it was observed that the thighs tend to govern leg movement because of their larger effective mass. Accordingly, it was found that using the thighs as one of the load input locations had a larger effect on inhibiting ankle inversion/eversion (See Figure 24).

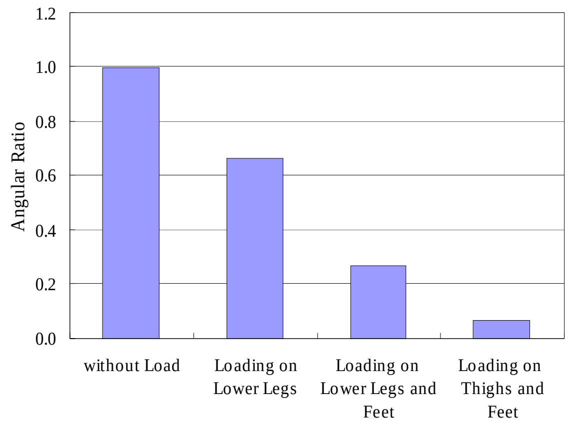

Figure 24. Angular ratio of ankle rotation.

However, the lateral movement of the upper torso, which was discussed in the previous section, and ankle inversion/eversion are both behavior patterns that are especially characteristic of oblique impacts. At this point, not enough research has been done on the corresponding injury criteria for these body locations or on methods of measuring such injuries. Therefore, further research needs to be done on these behavior patterns in future studies.

SUMMARY

Car-to-car (CTC) crash tests and FEM simulations were conducted to analyze vehicle deformation and dummy behavior in frontal oblique offset impacts. The results raised the following four technical issues:

- Increase in cabin strength
- Improvement of the energy-absorbing capacity of the engine compartment
- Controlling the lateral movement of the upper torso
- Controlling ankle inversion/eversion

Measures for addressing these issues were examined in CTC crash tests and FEM simulations and their effectiveness was studied. The results indicated certain directions to take in implementing measures to address these technical issues.

CONCLUSIONS

This research has raised several technical issues involved in frontal oblique offset impacts under certain conditions and has indicated some directions to take in addressing those issues. However, further R&D work would need to be undertaken in order to implement measures for dealing with such issues on production vehicles. With regard to such occupant behavior as the lateral movement of the upper torso and ankle inversion/eversion in particular, accident analyses have to be conducted to examine the actual incidence of injuries and research must be done to clarify the corresponding injury criteria. In addition, more concrete and detailed R&D work must be done on the proposed measures examined in this study. Specifically, the control logic, including an occupant detection method needed for deployment of the side-impact airbag system, must be developed and studies must be undertaken to examine a mechanism for triggering the application of a desirable load and a method of applying the load to occupants' legs.

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