DEVELOPMENT OF MOVING DEFORMABLE BARRIER REPRODUCING STRUCK CAR DEFORMATION IN REAL-WORLD CAR-TO-CAR SIDE IMPACT ACCIDENTS IN EUROPE AND JAPAN

Taisuke Fujiwara
Kenji Shigeta
Toyota Motor Corporation
Japan
Paper Number 09-0021

ABSTARCT

The test procedures described in current European and Japanese side impact regulations and assessments involve striking a moving deformable barrier (MDB) into a stationary test vehicle. However, since many car-to-car side impact accidents in the real world occur when the struck vehicle is also moving, the force direction into the struck vehicle in the configurations described by these regulations and assessments differs from that in those actual accidents.
Therefore, to simulate the force into a moving struck vehicle in the current test configuration, i.e., a perpendicular MDB side impact, it is necessary to integrate the stiffness characteristics of the front of the striking vehicle in a side impact accident where both vehicles are moving.
Consequently, a crabbed frontal impact test that simulates the force direction into the striking vehicle in a moving car to moving car side impact test was considered as an evaluation method for the frontal stiffness characteristics. This crabbed frontal impact test was confirmed to be capable of measuring the stiffness characteristics of the front of the striking vehicle occurring in a moving car to moving car side impact.
In addition, an MDB for simulating crabbed frontal impacts was developed based on the frontal stiffness characteristics obtained from the crabbed frontal impact test. It was confirmed that side impact tests using this MDB were capable of simulating the deformation and door moving velocity of the struck vehicle in a moving car to moving car side impact test.
As a result, vehicle safety enhancements based on a side impact test method using this MDB are expected to contribute to the development of appropriate body structures and restraint devices for real-world accidents.

INTRODUCTION

The test procedures described in current European and Japanese side impact regulations and assessments involve striking a moving deformable barrier (MDB) into a stationary test vehicle at right angles. However, in the real world, many car-to-car side impact accidents occur when both the struck and striking vehicles are moving.[1] As a result, the force direction into the struck vehicle in the regulations and assessments differ from that in those actual accidents.
One test method that simulates the force direction when both vehicles are moving is the crabbed side impact test. However, when force is applied at an oblique angle such as in a crabbed side impact, the compressive stress of the honeycomb decreases,[2] and concerns have also been raised about the stability of the stiffness characteristics of the honeycomb. In addition, although an oblique force is applied to the dummy in the struck vehicle, the response of the ES-2 dummy currently in widespread use in regulations and assessments differ depending on whether the impact is oblique or perpendicular.[3]
To resolve these concerns, this paper describes the development method and performance of an MDB capable of simulating force into a struck vehicle in a side impact while both vehicles are moving, while maintaining the configuration of the current perpendicular MDB side impact test.

1. CONSIDERATIONS FOR SIMULATING CAR-TO-CAR SIDE IMPACT ACCIDENTS

1-1 Study of Simulation Method

Many car-to-car side impact accidents in the real world occur as shown in Figure 1-a,[1] generating bending moment in the floor side members as shown in Figure 1-b. This moment causes horizontal bending in each floor side member, which originates in areas with a low modulus of section with respect to the H-axis in the H-W plane of the members.

Impact angle	Perpendicular
Struck vehicle condition	Not stationary
Rough impact velocity ratio	Striking × struck = 2 × 1

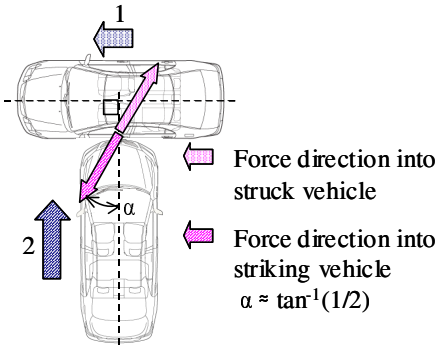


Figure 1-a. Typical form of car-to-car side impact accidents.

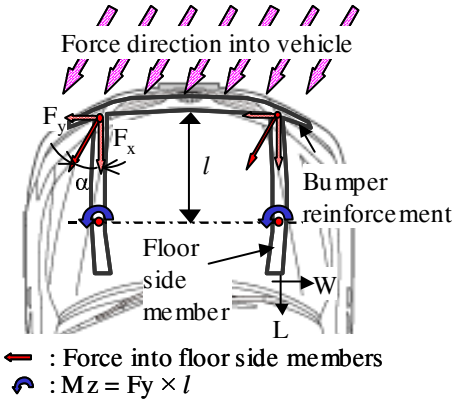


Figure 1-b. Force into floor side members and generated moment.

To simulate force into the struck vehicle in this configuration, force must be applied at crabbed angle α with respect to the front of the striking vehicle so that the stiffness characteristics of the front of the striking vehicle can be identified with the same bending moment generated in the floor side members.
For this purpose, a crabbed frontal impact test was developed using a rigid wall and a vehicle trolley as shown in Figure 2. This test generates bending moment in the floor side members of the vehicle to simulate the deformation modes of the striking vehicle in a car-to-car side impact shown in Figure 1-a.

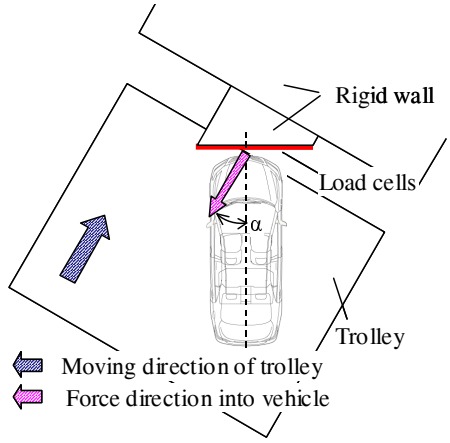


Figure 2. Outline of crabbed frontal impact test.

1-2 Validation of Simulation Method

The appropriateness of the crabbed frontal impact test was validated by comparing its results with those from the striking vehicle in a car-to-car side impact test conducted with both vehicles moving (i.e., a moving car to moving car side impact test). The results from a perpendicular frontal impact, which is the conventional method of examining frontal stiffness, are also shown for comparison in Figure 3.
Table 1 shows the conditions of the crabbed and perpendicular frontal impact tests, and Table 2 shows the conditions of the moving car to moving car side impact test.
Figure 3 shows the frontal deformation of the test vehicles.
Horizontal bending of the floor side members was identified respectively in the vehicle after the crabbed frontal impact and the striking vehicle after the moving car to moving car side impact. In contrast, vertical bending was found after the perpendicular frontal impact.

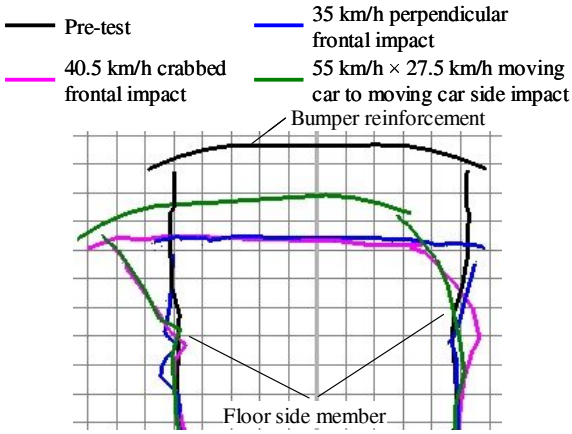


Figure 3. Test vehicle deformation (top view).

Figure 4 shows images of the front of the vehicles after the tests.
Horizontal bending of the left floor side member occurred in the same position of the vehicle after the

crabbed frontal impact and the striking vehicle after the moving car to moving car side impact.
In contrast, although clear horizontal and vertical bending positions in the right floor side member could be identified after the crabbed frontal impact, the position of the horizontal bending that occurred in the striking vehicle after the moving car to moving car side impact could not be clearly identified.
In addition, vertical bending was identified in both floor side members after the perpendicular frontal impact.

Figure 4-a. Left floor side member after crabbed frontal impact.

Figure 4-b. Left floor side member after moving car to moving car side impact.

Figure 4-c. Left floor side member after perpendicular frontal impact.

Figure 4-d. Right floor side member after crabbed frontal impact.

Figure 4-e. Right floor side member after moving car to moving car side impact.

Figure 4-f. Right floor side member after perpendicular frontal impact.

1-3 Discussions on Simulation Method

The results of the crabbed frontal impact and moving car to moving car side impact tests showed different deformation volumes.
This was probably caused by variations in deceleration and post-impact kinetic energy as a result of the different impact targets used in the tests (a rigid wall for the crabbed frontal impact test, and a moving vehicle for the moving car to moving car side impact test).
However, the deformation generated by the crabbed frontal impact was greater than that in the striking vehicle in the moving car to moving car side impact. This is thought to be because the frontal deformation in the moving car to moving car side impact represents only part of the deformation process measured in the crabbed frontal impact test. Consequently, if the volume of deformation were allowed to increase, the horizontal bending of the floor side member in Figure 4-e would approximate the deformation mode shown in Figure 4-d. Therefore, it should be possible to use the crabbed frontal impact test to measure the stiffness characteristics of the front of the striking vehicle in the moving car to moving car side impact more accurately than the conventional measurement method.

2. INVESTIGATION OF FRONTAL STIFFNESS CHARACTERISTICS

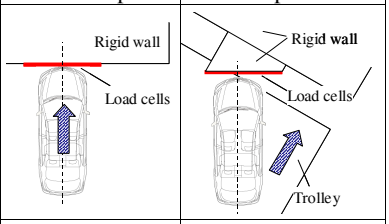
Perpendicular frontal impact and crabbed frontal impact tests were conducted on each vehicle to

compare the frontal stiffness characteristics.
The frontal stiffness characteristics of the Advanced European MDB (AE-MDB) V3.1 currently being developed in Europe and Japan are calculated based on the test results of perpendicular frontal impacts,[(4)(5)] and test methods are being studied where the AE-MDB is collided perpendicularly into the side of a stationary vehicle. Thus, by integrating the comparison results for the crabbed and perpendicular frontal impacts at areas corresponding to each block of the AE-MDB into the AE-MDB V3.1 specifications, it should be possible to simulate the force into the struck vehicle in a moving car to moving car side impact while maintaining the configuration of the perpendicular AE-MDB side impact test. Therefore, the frontal stiffness characteristics of the areas corresponding to each block of the AE-MDB were examined.

2-1 Test Conditions

Table 1 shows the test conditions.

Table 1.
Test conditions

	Perpendicular frontal impact	Crabbed frontal impact
Impact configuration		
Impact velocity	Vehicle 35.0 km/h*1	Trolley 40.5 km/h*2
Vehicle types	Compact car, hatchback, sedan, small SUV	
Vehicle mass	Vehicle mass specified in JNCAP*3 frontal impact tests	
Load cells	40 (size: 200 mm × 200 mm)*4 Plywood boards at impact surface (t: 20 mm)	

*1: Impact velocity in verification test for MDB dynamic characteristics specified by ECE Regulation No. 95[(6)]
*2: Velocity component in vehicle longitudinal direction coincided with perpendicular frontal impact test
*3: Japan New Car Assessment Program
*4: See Figure 5 for the layout of the load cells and AE-MDB.

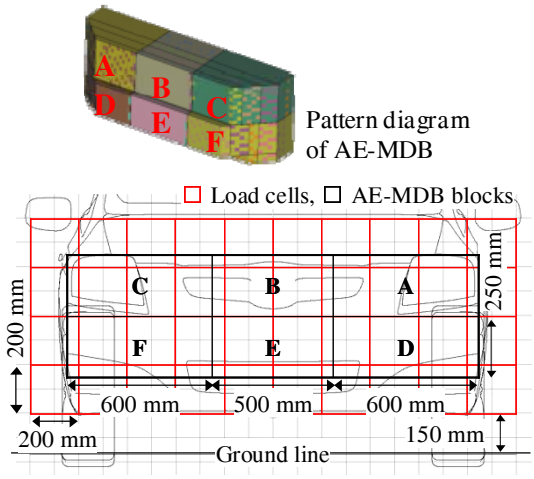
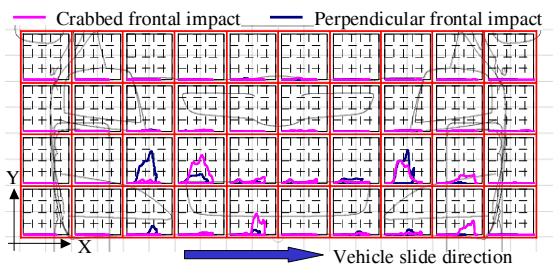


Figure 5. Layout of load cells and AE-MDB blocks.

2-2 Test Results

Figure 6 shows the frontal stiffness characteristics for each load cell block. The results shown below are for the hatchback, and those for the other vehicles are shown in the appendix. The force distribution for the crabbed and perpendicular frontal impacts differs since deformation in the crabbed frontal impact occurs as the vehicle slides to the right into the rigid wall.



X-axis on each graph: maximum displacement = 500 mm,
Y-axis on each graph: maximum force = 200 kN

Figure 6. Vehicle frontal stiffness characteristics.

Figure 7 shows the stiffness characteristics of the whole AE-MDB and the characteristics of the areas corresponding to each block of the AE-MDB, as calculated from the force distribution above. The results for the other vehicles are shown in the appendix.
The force of the whole area generated in the crabbed frontal impact was less than in the perpendicular frontal impact since horizontal bending occurred in the floor side members after the crabbed frontal impact. In particular, force decreased significantly in block F due to the horizontal bending in the floor side members and the rightward shift in force distribution.
In contrast, force increased in block E with respect to the perpendicular frontal impact due to the shift in force distribution from block F.

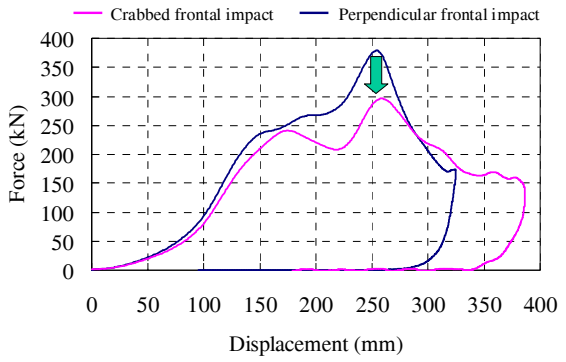


Figure 7-a. Stiffness characteristics of whole area of AE-MDB.

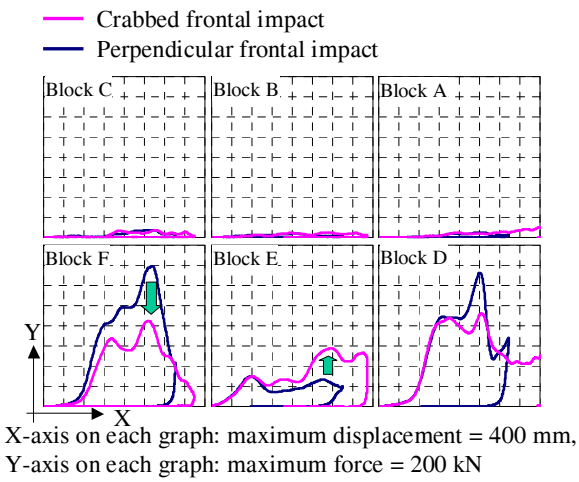


Figure 7-b. Stiffness characteristics for each block of AE-MDB.

The comparison method for frontal stiffness characteristics in the crabbed and perpendicular frontal impacts is defined as shown in Figure 8. Figure 9 shows the averaged force ratio of the four vehicle types. Compared with the perpendicular frontal impact, the frontal force in the crabbed frontal impact was roughly the same in block D, approximately 20% higher in block E, and approximately 20% lower in block F with a deformation volume close to 150 mm.

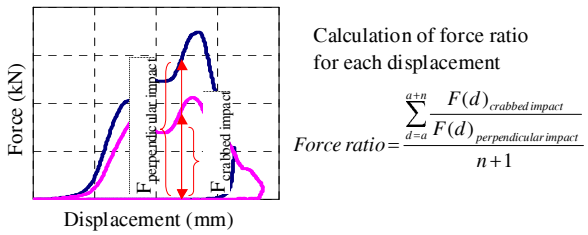


Figure 8. Calculation of averaged force ratio for crabbed and perpendicular frontal impacts.

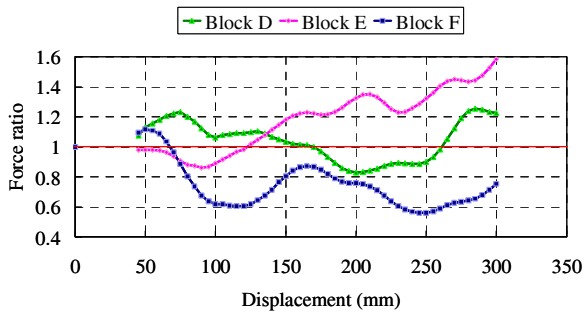


Figure 9. Averaged force ratio for each 5 mm displacement of blocks D, E, and F (averaged for all four vehicles).

3. DEVELOPMENT OF HONEYCOMB FOR CRABBED FRONTAL IMPACT SIMULATION AND VERIFICATION OF PERFORMANCE

3-1 Study of Crabbed Frontal Impact Simulation Corridors

The corridors for the honeycomb to simulate a crabbed frontal impact were created by multiplying the force ratio described above with the existing corridors for AE-MDB V3.1.[5]
Figure 10 shows the created corridors for blocks D, E, and F.
However, the same blocks were used for blocks A, B, and C as in AE-MDB V3.1. This was because this study featured only one vehicle type representing tall vehicles such as SUVs, thereby creating a lack of data for blocks A, B, and C. In addition, since the stiffness characteristics for blocks A, B, and C were set lower than for blocks D, E, and F, it was determined that there was little effect on the stiffness characteristics of the whole area even considering changes in force due to a crabbed frontal impact.

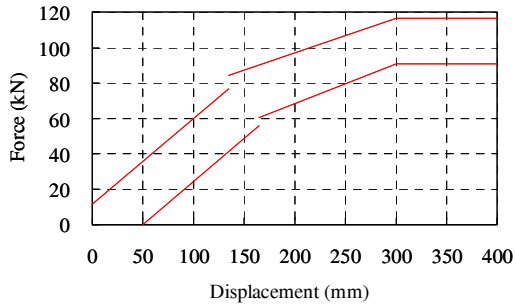


Figure 10-a. Corridor for block D.

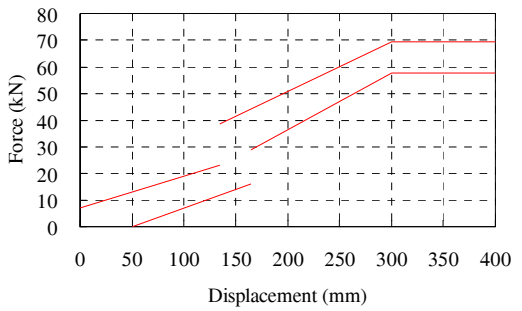


Figure 10-b. Corridor for block E.

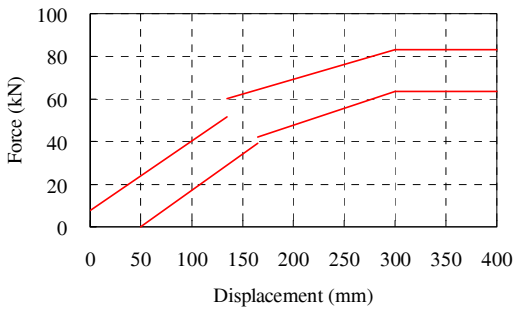


Figure 10-c. Corridor for block F.

3-2 Issues with Crabbed Frontal Impact Simulation Corridors

The following two issues were identified for the corridors shown in Figure 10.

1. Honeycomb asymmetry caused by differences between blocks D and F
2. Difficult honeycomb manufacturing due to the gap of approximately 150 mm created in displacement of block E

3-2-1 Blocks D and F - As an asymmetrical honeycomb is liable to cause usability issues, the left/right characteristics of the honeycomb were averaged to maintain the stiffness characteristics of the whole area (Figure 11).

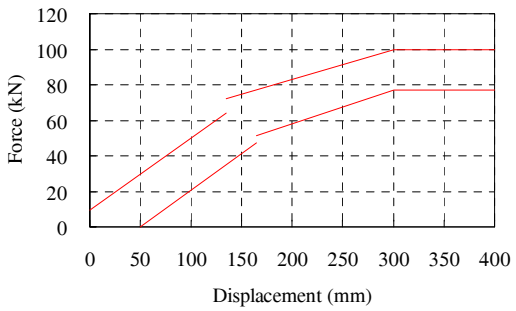


Figure 11. Averaged corridor for blocks D and F.

To verify the effect on the struck vehicle of averaging the characteristics of blocks D and F, perpendicular MDB side impact test simulations (impact point: SRP+250 mm, impact velocity: 55 km/h) were conducted using FEM analysis under two specifications: separate characteristics for blocks D and F, and averaged characteristics. Figure 12 shows the struck vehicle deformation and door moving velocity in these simulations.

Although slight variations in deformation volume occurred in the front and rear parts of the vehicles, no major differences in deformation mode or door moving velocity were identified. As a result, since these variations would not change the approach of vehicle safety enhancements or lead to large differences in dummy injury values, it was judged that averaging the characteristics of blocks D and F would only have a minimal effect.

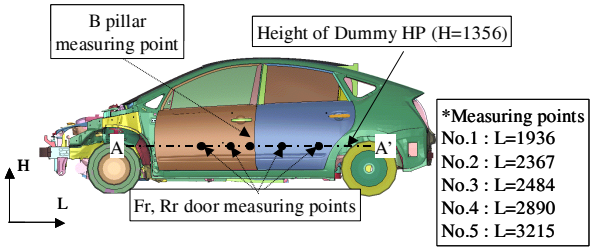


Figure 12-a. Measuring points.

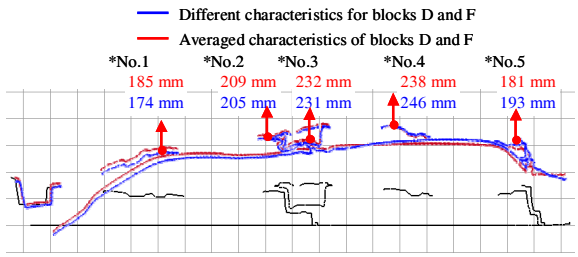


Figure 12-b. Vehicle deformation at section A-A' (time: 140 ms).

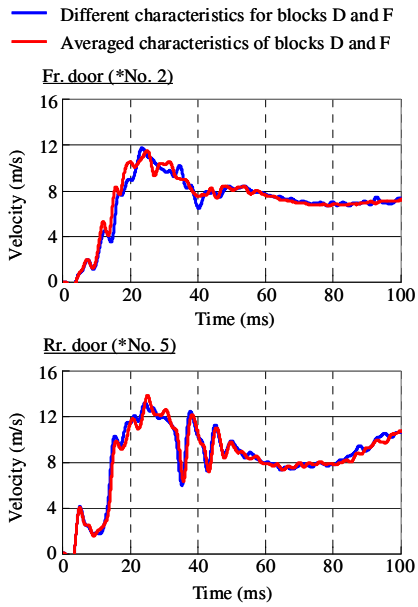


Figure 12-c. Moving velocity of front and rear doors.

3-2-2 Block E -Next, to eliminate the gap of approximately 150 mm in the corridor in block E, the corridor for block E in AE-MDB V3.9 was used,[7] which has almost the same maximum force (Figure 13).

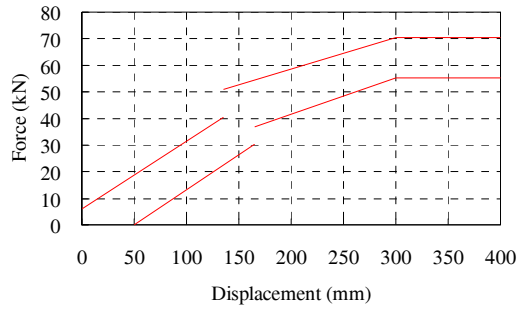


Figure 13. AE-MDB V3.9 block E corridor.

3-3 Development of Honeycomb for Crabbed Frontal Impact Simulation

A honeycomb (AE-MDB V3.10) for simulating crabbed frontal impacts was developed using the corridors shown in Figures 11 and 13. A dynamic test was then conducted to verify its stiffness characteristics. Excluding the mass of the trolley, these tests were implemented in accordance with the barrier certification method specified in ECE Regulation No. 95.[6] The trolley mass was set to 1,500 kg following the AE-MDB specifications. Figure 14 shows the results of the dynamic test. The results of the stiffness characteristics for each block and the whole area of the AE-MDB were confirmed to be within the tolerance range of the corridors.

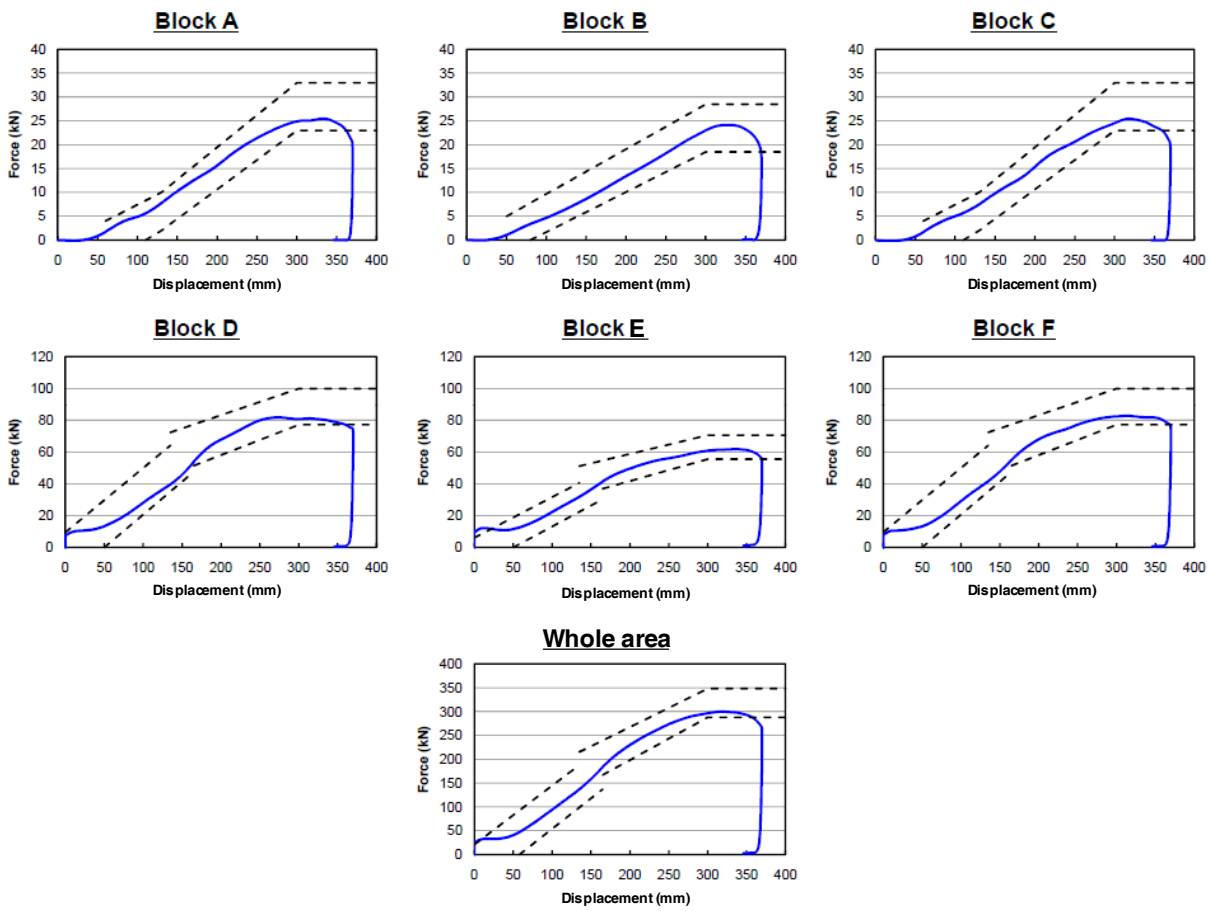


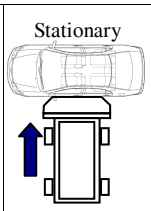
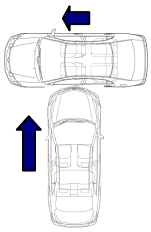
Figure 14. Results of dynamic test for AE-MDB V3.10.

3-4 Verification Test Using Real Vehicle with AE-MDB V3.10

Perpendicular side impact tests were conducted using AE-MDB V3.10 to confirm its performance in comparison to the moving car to moving car side impact test used to simulate real-world accidents.

3-4-1 Test Conditions - Table 2 shows the test conditions.

Table 2.
Test conditions

Impact configuration	Stationary 	
Impact point (mm)	SRP+250	SRP
Impact velocity (km/h)	55	Striking × struck = 55 × 27.5
Striking vehicle	AE-MDB V3.10 1,500 kg	Hatchback 1,500 kg
		Sedan 2,000 kg
		SUV 2,000 kg
Struck vehicle	1,500 kg	
Dummy	Fr: ES-2, Rr: ES-2	

3-4-2 Test Results - Deformation was measured before and after the tests at the door outer and pillar positions shown in Figure 15.

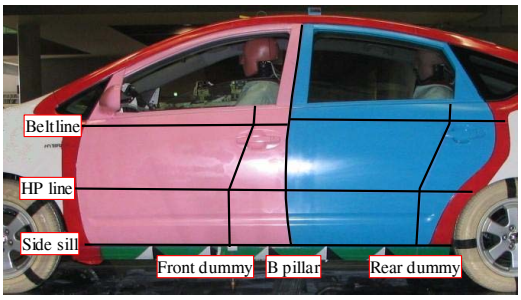


Figure 15. Deformation measuring points in struck vehicle.

Figure 16 shows the measurement results at each position.
At the front dummy and B pillar positions, the deformation volume with AE-MDB V3.10 was between that generated by the SUV and the hatchback. In the rear dummy position, the deformation was larger than with any of the vehicle types.

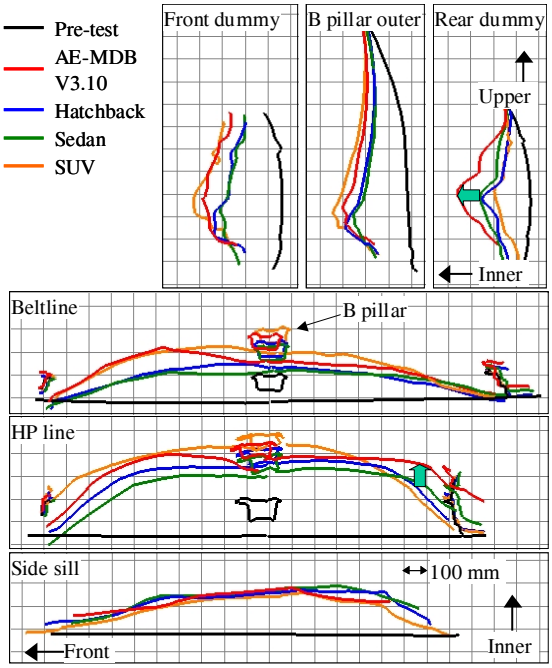


Figure 16. Struck vehicle deformation.

Figure 17 compares the moving velocities at the lateral positions of the front dummy in the beltline and HP line at the front door inner. The door moving velocities were calculated using accelerometers placed on door inner. The door moving velocities in the AE-MDB V3.10 and moving car to moving car side impacts were approximately the same.

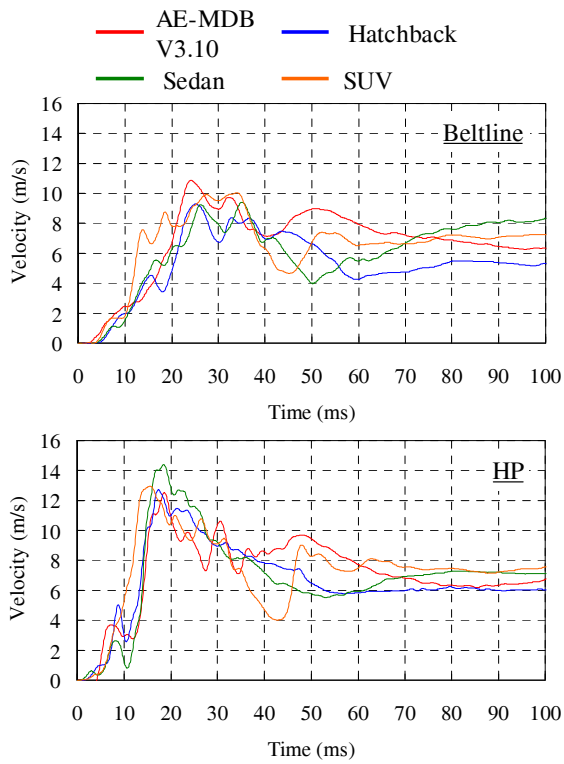


Figure 17. Front door moving velocity of struck vehicles.

3-4-3 Discussions - In the moving car to moving car side impact test, horizontal bending of the floor side members as shown in Figure 18-a prevented direct intrusion behind the rear door in the struck vehicle. However, in the AE-MDB side impact, the right side of the honeycomb intruded directly into behind the rear door (Figure 18-b). This is thought to be a factor in the differences in rear deformation.

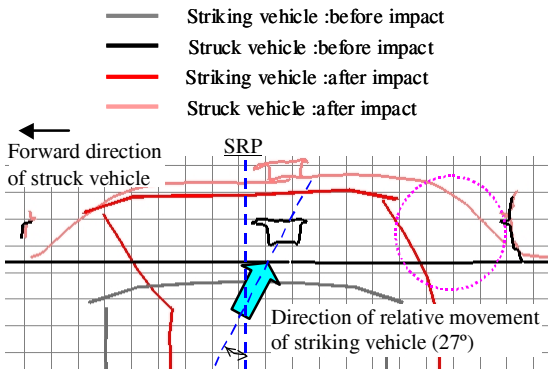


Figure 18-a. Position of striking vehicle in moving car to moving car side impact.

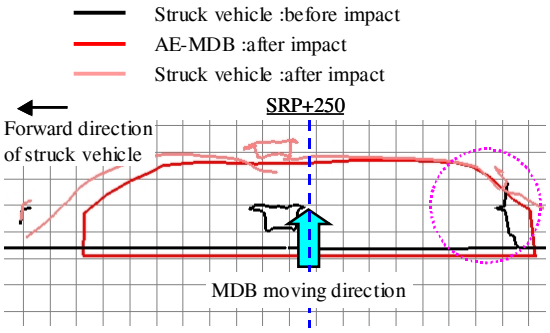


Figure 18-b. Position of honeycomb in AE-MDB V3.10 side impact.

The intrusion volume from the deformed B pillar was also considered. In a side impact test using the conventional AE-MDB V3.1, the deformation mode for door intrusions from the B pillar resembled an M shape. However, in the side impact test using AE-MDB V3.10, the intrusion of the B pillar was greater than that at the front and rear doors, and resulted in a C-shaped deformation mode. This was the same deformation mode as obtained in the moving car to moving car side impact tests (Figure 19).

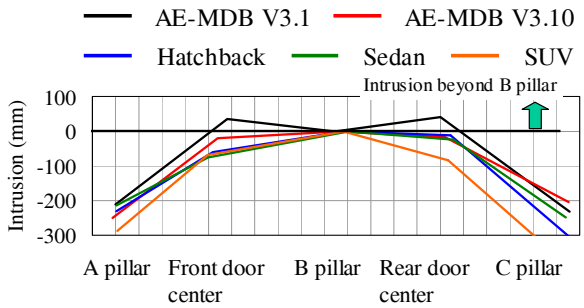


Figure 19. Intrusion volume from B pillar after deformation.

One purpose of the AE-MDB side impact test method is to evaluate the protection performance of the front and rear occupants of the struck vehicle at the same time. Therefore, the volume of rear door deformation in this test can be considered to be acceptable since the rear deformation volume was approximately the same as in the front, while the deformation mode matched that occurring in the moving car to moving car side impacts.
Based on the results and discussions on the struck vehicle as described above, a test using AE-MDB V3.10 is as stringent as the moving car to moving car side impact test based on deformation volume and moving velocity. In addition, in the deformation mode, the B pillar showed the largest intrusion, which approximates the struck vehicle deformation mode in the moving car to moving car side impact test.
This shows that a side impact test using AE-MDB V3.10 is capable of simulating actual moving car to moving car side impact accidents.
As a result, vehicle safety enhancements based on a side impact test method using AE-MDB V3.10 are expected to contribute to the development of appropriate body structures and restraint devices for real-world accidents.

CONCLUSIONS

The following results were achieved in this study.

1. The frontal stiffness characteristics of the striking vehicle were obtained in a side impact in which both vehicles are moving.
2. A honeycomb (AE-MDB V3.10) was developed simulating the frontal stiffness characteristics obtained in point 1 above.
3. An actual vehicle test using AE-MDB V3.10 simulated a car-to-car side impact test conducted with both vehicles moving.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to all those at the Japan Automobile Research Institute (JARI), the Japan Automobile Manufacturers Association (JAMA) Side Impact Working Group, the Japan Automobile Standards Internationalization

Center (JASIC), and Showa Aircraft Industry Co., Ltd. for their assistance and cooperation in this development.

REFERENCES

[1] Fujiwara, T., and Murayama, H. 2007. "Research into New Side Impact Test Based on Accidents in Europe and Japan." 20th ESV, Paper Number 07-0219

[2] Kojima, S., Yasuki, T., Mikutsu, S., and Takatsudo, T. 2006. "A Study on Yielding Function of Aluminum Honeycomb." Society of Automotive Engineers of Japan

[3] EEVC August 2001. "Development and Evaluation of the ES-2 Dummy." EEVC Working Group 12 report

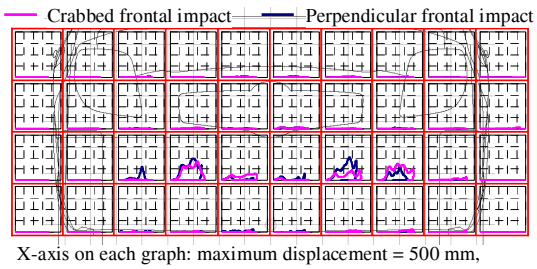
[4] Yonezawa, H., Harigae, T., and Ezaka, Y. 2001. "Japanese Research Activity on Future Side Impact Test Procedures." 17th ESV, Paper Number 267

[5] Ueno, M., Hatano, K., Fukushima, N., and Tsuburai, Y. 2007. "Development of New Generation Mobile Deformable Barrier." 20th ESV, Paper Number 07-0299

[6] ECE No. 95. "Protection of the Occupants in the Event of a Lateral Collision."

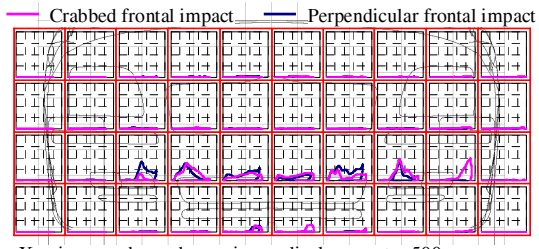
[7] Versmissen, T., Van Schijndel, M., Edwards, M., and Langner, T. 2007. "Development and Evaluation of the Side Impact Test Procedure Proposed by IHRA." 20th ESV, Paper Number 07-0310

APPENDIX



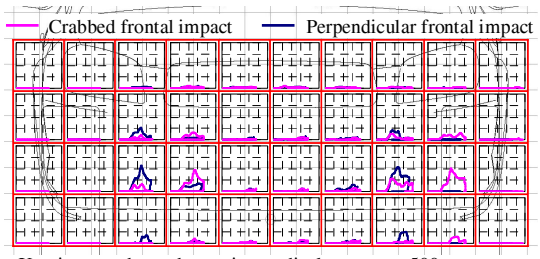
X-axis on each graph: maximum displacement = 500 mm,
Y-axis on each graph: maximum force = 200 kN

Figure 20-a. Frontal stiffness characteristics (compact car).



X-axis on each graph: maximum displacement = 500 mm,
Y-axis on each graph: maximum force = 200 kN

Figure 20-b. Frontal stiffness characteristics (sedan).



X-axis on each graph: maximum displacement = 500 mm,
Y-axis on each graph: maximum force = 200 kN

Figure 20-c. Frontal stiffness characteristics (small SUV).

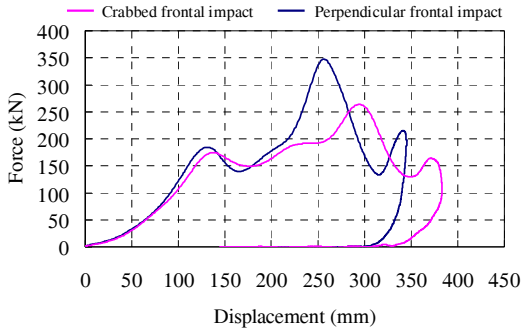


Figure 21-a. Stiffness characteristics of whole area of AE-MDB (compact car).

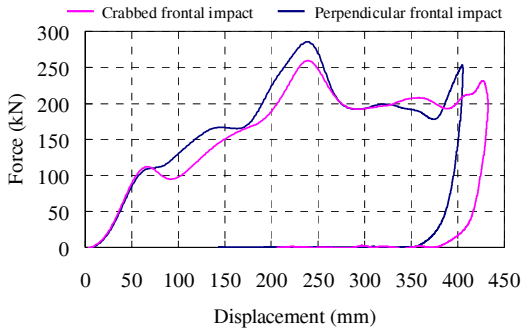


Figure 21-b. Stiffness characteristics of whole area of AE-MDB (sedan).

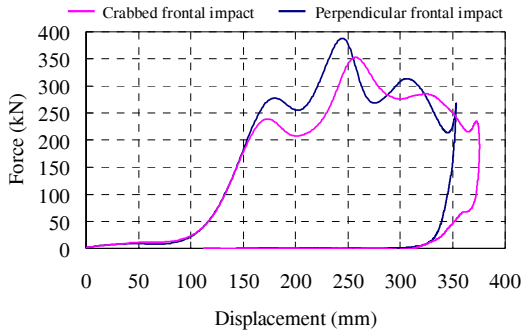
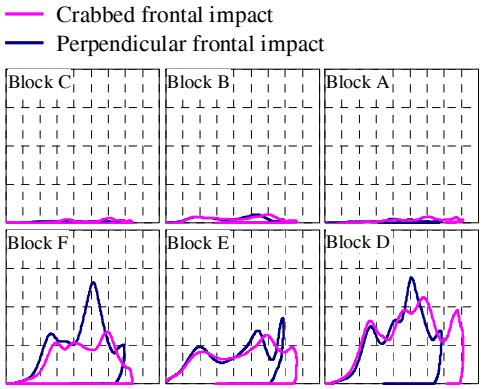
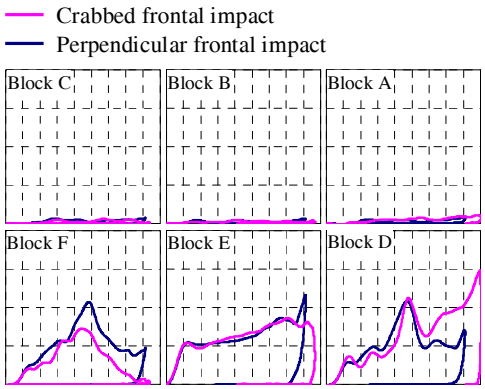


Figure 21-c. Stiffness characteristics of whole area of AE-MDB (small SUV).



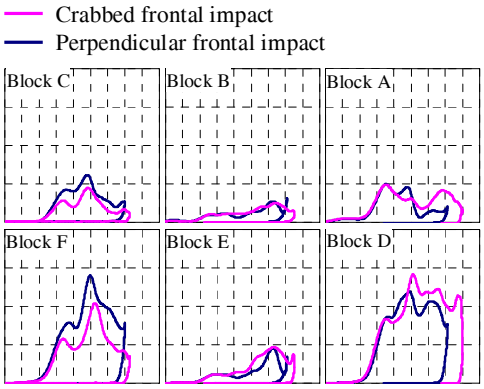
X-axis on each graph: maximum displacement = 450 mm,
Y-axis on each graph: maximum force = 200 kN

Figure 22-a. Stiffness characteristics for each block of AE-MDB (compact car).



X-axis on each graph: maximum displacement = 450 mm,
Y-axis on each graph: maximum force = 200 kN

Figure 22-b. Stiffness characteristics for each block of AE-MDB (sedan).



X-axis on each graph: maximum displacement = 450 mm,
Y-axis on each graph: maximum force = 200 kN

Figure 22-c. Stiffness characteristics for each block of AE-MDB (small SUV).