Barrier Force Distribution Evaluations in Full-Width Impact Tests

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Abstract The structural interaction is prerequisite for compatibility in car-to-car crashes. Full-width tests have been proposed to assess the structural ground-height alignment and homogeneity, which are key factors for structural interaction. In the present research, full-width rigid and deformable barrier tests were compared with respect to barrier force distributions, vehicle deformation and dummy responses. The average height of force was similar between full rigid and deformable barrier tests. Further information on force distribution such as structure homogeneity can be obtained in full-width deformable barrier tests because forces from structures can be clearly shown in barrier force distributions compared with rigid barrier. However, force distribution measurements and homogeneity criteria are dependent on load cell height from the ground.

Key word: Compatibility, Structural interaction, Full-width test, Average height of force, Homogeneity

1 Introduction

Compatibility is defined as the ability to protect not only the occupants, but also other road users as well. Analyses of global accident data of car-to-car collisions from various countries have indicated that there are vehicles with low compatibility, such as cars with poor self-protection and cars with high aggressivity with respect to other cars. The aggressivity of sport utility vehicles (SUVs) has become an issue in the United States and Australia while the self-protection of small cars is important in Europe. In Japan as well, vehicle sizes vary widely, and compatibility is considered an important problem.

For improvement of compatibility, after good structural interaction, the front-end of car structures absorbs impact energy while maintaining passenger compartment intact. Thus, good structural interaction is prerequisite for energy absorption and compartment integrity. Especially for car-to-SUV crashes, structural interaction to prevent override/underride is essential to reduce injury risks to occupants in cars. The ground-height alignment of structures between colliding vehicles, multiple load paths and their shear connection are key factors for structural interaction.

For structural interaction assessment, a full-width test and a progressive deformable barrier test have been proposed. In the full-width impact test, barrier force distribution is measured to assess structural alignment and structure homogeneity [1]. Average height of force (AHOF) is a criterion for longitudinal member ground-height alignment for colliding vehicles to prevent override/underride [2]. The multiple load paths lead to homogeneous front stiffness, and a relative homogeneity assessment is used as the criteria. In order to excite shear connections between load paths, an aluminium honeycomb with two-stage stiffness is proposed to be attached in full-width tests [3].

The present research reports test procedures investigated in a compatibility research project of the Japanese Ministry of Land, Infrastructure and Transport. The full-width rigid barrier test data in JNCAP (Japan New Car Assessment Program) were also used. The full-width tests were examined as a means to improve compatibility since this test configuration has been adopted in the regulation of Japan. The structural interaction is also significant in the Japanese vehicle fleet, which consists of

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various vehicle types including minicars, multi-purpose vehicles (MPVs) and SUVs, and misalignment of ground-height of members between these vehicles can occur.

2 Full-Width Rigid Barrier Tests

In JNCAP tests of FY (fiscal year) 2002 and 2003 and two additional JMLIT tests, force distributions in full-width rigid barrier tests were measured with 125 x 125 mm high-resolution load cells. The impact velocity was 55 km/h. Force distributions from structures and engines were examined, and the relations between these geometrical locations and AHOF were investigated.

The force distributions of vehicles with different structures such as a bumper beam, lower cross member (radiator support) and subframe were investigated. Figure 1 shows contours of peak force in each cell for vehicles with typical structures. For a minicar without a bumper beam, the forces concentrated around the longitudinal members and engine. For a medium car with bumper beam and lower cross member (without subframe), the forces extended from longitudinal members to the center of the bumper beam. There were also force concentrations from the lower cross member at the engine mount location. However, the attachment locations of the lower cross member cannot be seen because these members are not so stiff in the longitudinal direction. For the medium car, which also has a subframe, the forces distributed more widely around subframe attachment locations. The longitudinal members of SUV generate high force concentrations because this SUV has a frame-type structure.

These results demonstrate that the force distributions in full rigid barrier crash tests can provide useful information for evaluating the structural force in impacts. However, in rigid barrier tests, the engine impact force is very large at impact points. Whole structures of lateral beams such as lower cross member or subframe do not appear in the force distribution, whereas structures in the longitudinal direction appear clearly.

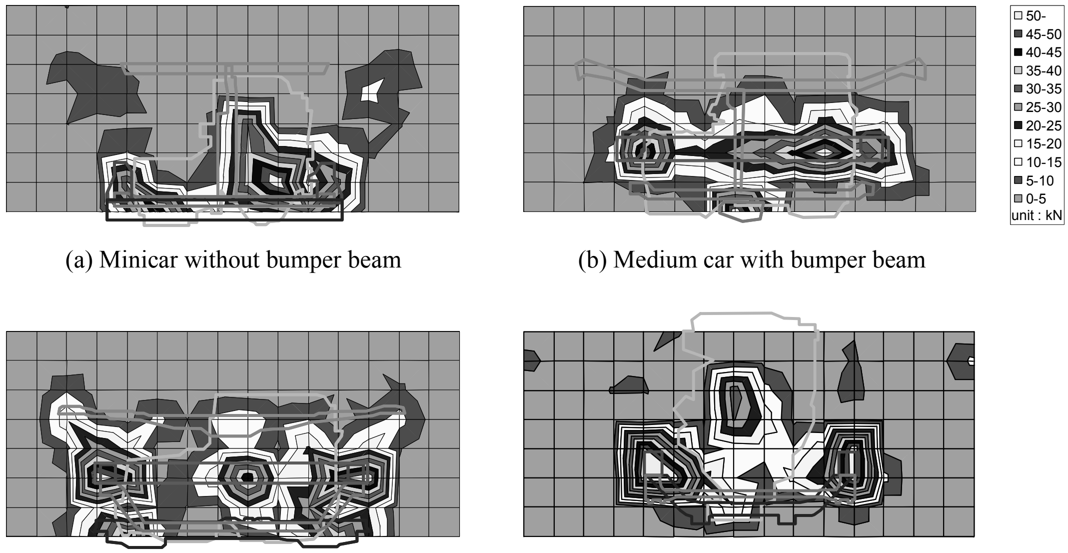
The AHOF has been proposed to predict override/underride in car-to-car crashes. The relations between AHOF and the parameters of vehicle geometry were examined. The AHOF calculation method was based on Summers et al. as follows [2]. The HOF (height of force) is calculated each time from load cell force F_i and its height from ground H_i.

$$HOF(t) = \frac{\sum_{i}^{N} F_i \times H_i}{\sum_{i}^{N} F_i} \tag{1}$$

The AHOF is determined from weighing HOF by the barrier total force.

$$AHOF = \frac{\int_0^t HOF(t) \times F(t)\, dt}{\int_0^t F(t)\, dt} \tag{2}$$

The relation between geometry parameters and AHOF were examined. The ground heights of the longitudinal member and engine have a correlation with the AHOF as shown in Figure 2. Therefore, the alignment of longitudinal member between cars may be controlled if the AHOF is adopted in the requirements.



(a) Minicar without bumper beam　(b) Medium car with bumper beam

(c) Medium car with subframe　(d) SUV

Figure 1. Typical force distributions for vehicles with various structures in full-width rigid barrier crash tests

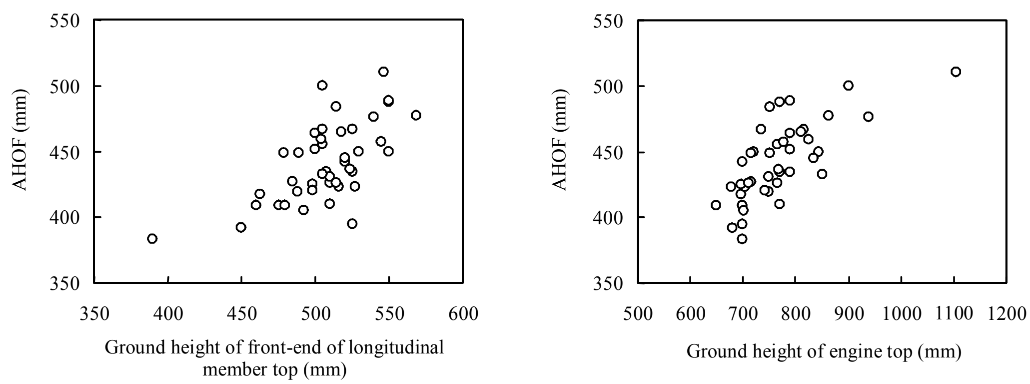


Figure 2. AHOF and ground height of longitudinal member and engine

3 Full-Width Deformable Barrier Tests

Full-width deformable barrier tests were carried out for five vehicles using a deformable element developed by the Transport Research Laboratory (TRL) [3][4]. Figure 3 shows the barrier. The first layer of the deformable element has a crush strength of 0.34 MPa with 150 mm depth, and the second layer has a crush strength of 1.71 MPa with 150 mm depth. The second layer consist of 125 mm x 125 mm honeycombs so as to transfer axial forces to the 125 mm x 125 mm loadcells attached behind the honeycombs. Test vehicles include the minicar (Suzuki Wagon R), small car (Toyota Vitz), medium car (Subaru Legacy), small SUV (Subaru Forester), MPV (Honda Stepwgn), and SUV (Toyota Surf). The impact velocity was 56 km/h.

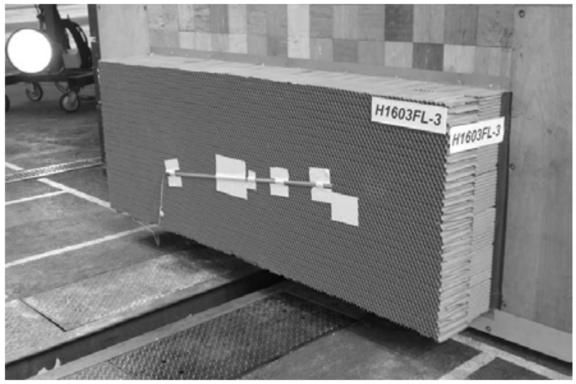
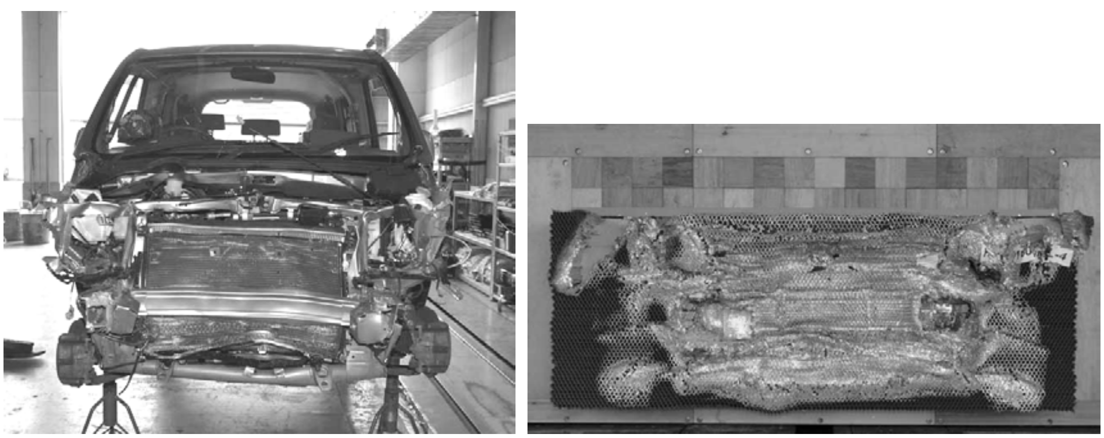


Figure 3. Deformable barrier

3.1 Structure deformation

Figure 4 shows deformation of vehicle and honeycomb after the test. There are honeycomb deformation due to vehicle structures such as longitudinal member, shotgun, bumper beam and lower cross frame. The longitudinal member of Stepwgn bottomed-out the honeycomb, which reflects the high local stiffness of these longitudinal members. The lateral members such as bumper beam and lower cross member can be seen in the honeycomb deformations.

Generally, it has been demonstrated that the deformable element excites shear deformation of structures in the full-width deformable tests, which can be similar in car-to-car crashes [3]. Figure 5 presents the Stepwgn after full-width deformable barrier tests. The lower cross member of Stepwgn deformed backward in full-width deformable barrier tests, which also occurred in car-to-car crashes. Thus, the forces of the lower cross member that can prevent underride of colliding car may be assessed effectively in the full-width deformable barrier tests than in the rigid barrier tests.



(a) Vehicle (b) honeycomb

Figure 4. Stepwgn in full-width deformable barrier test

Figure 5. Shear deformation of vehicle in full-width deformable barrier test

3.2 Barrier force distributions

Distributions of each load cell peak force in the full width tests are presented in Figure 6. The engine impact forces are mitigated by the deformable barrier, and forces of structures can be seen clearly. Especially the local stiffness of longitudinal members is high for Surf or Stepwgn.

The Forester has a subframe, and Surf has a SEAS (blocker beam), and Stepwgn has a stiff lower cross member. These lateral members must to be detected in the force distributions in order to assess the effectiveness for structural interaction. However, it is not still clear that the forces from the lateral members appear in the force distributions, even though there are forces at the load cells which contacted these lateral members. This is because the impact forces are spread due to the thick honeycomb, and the forces in the first row cells can be seen even for other cars which do not have lower force paths.

To evaluate the homogeneity of the vehicle, the relative homogeneity assessment was proposed by the TRL [4]. The homogeneity assessment is variability of peak load from the target load L (the total of peak cell forces divided by the number of cells within the standard footprint), and it is sum of variability of individual cells RH_{cl}, each row RH_r and each column RH_c. The RH_{cl}, RH_r and RH_c indicates the overall, vertical and horizontal force distribution, respectively.

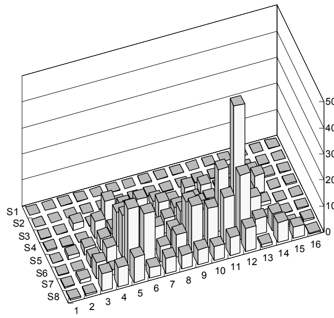
$$RH_{cl} = \frac{\sum_{i=1}^{n_c}\sum_{j=1}^{n_r}\left\{(L - f_{ij})/L\right\}^2}{n_c n_r} \tag{3}$$

$$RH_r = \frac{\sum_{i=1}^{n_r}\left\{\left(L - \frac{1}{n_c}\sum_{j=1}^{n_c} f_{ij}\right)/L\right\}^2}{n_r} \tag{4}$$

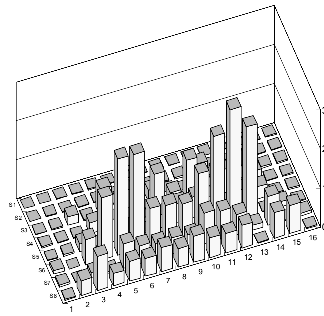
$$RH_c = \frac{\sum_{j=1}^{n_c}\left\{\left(L - \frac{1}{n_r}\sum_{i=1}^{n_r} f_{ij}\right)/L\right\}^2}{n_c} \tag{5}$$

Figure 7 shows the relative homogeneity assessment of the test vehicles. The relative homogeneity is large for the Surf and Stepwgn which have great local forces by longitudinal members. The relative homogeneity assessment is smallest for the Forester which has a subframe, and the force concentrations from longitudinal members are relatively small.

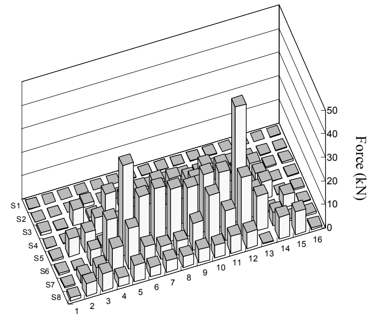
The AHOFs in full-width deformable and rigid barrier tests are compared and shown in Figure 8. The AHOFs measured in both barriers have a strong correlation. The honeycomb may affect the pitching of vehicles during impact, which can lead to higher AHOF. But the AHOFs of Stepwgn and Wagon R in full-width deformable barrier tests are lower than that in full rigid barrier tests, because the upper structures of these vehicles did not contact the whole barrier due to the limited size of deformable element.



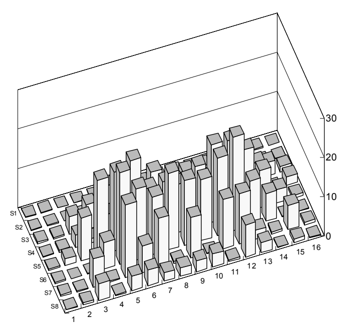
(a) Wagon R



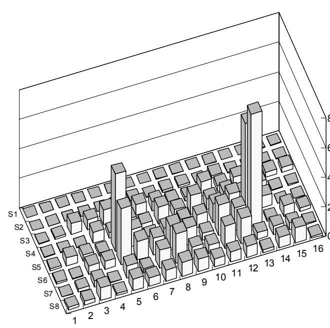
(b) Vitz



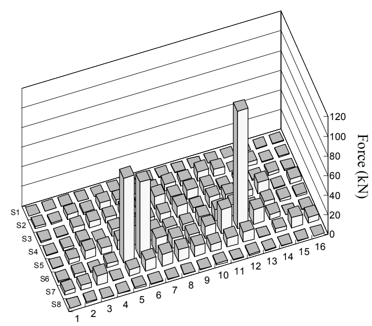
(c) Legacy



(d) Forester



(e) Stepwgn



(f) Surf

Figure 6. Force distributions in full-width deformable barrier tests

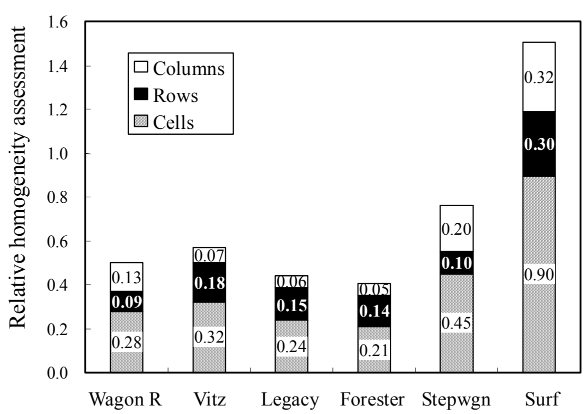


Figure 7. Relative homogeneity assessment in full-width deformable barrier tests

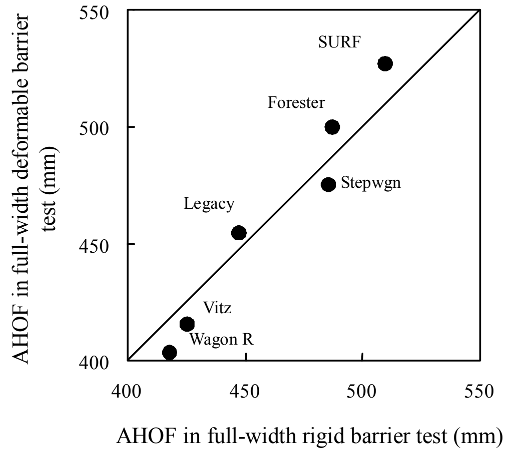


Figure 8. AHOF in full-width rigid barrier and deformable barrier tests

3.3 Load cell alignment

It is shown from mathematical simulations by Jerinsky and Hollowell that the AHOFs are affected by load cell alignment and resolutions [5]. In the present research, the force distributions of the same car models as Toyota Vitz (Yaris) in full-width deformable barrier tests were examined for different ground height of load cells. One ground height of load cell barriers is 50 mm and another barrier is 125 mm with the same load cell size as 125 x 125 mm (see Figure 9).

The force distributions are shown in Figure 10. A front-end of longitudinal member bridges four load cells in the 50 mm ground height load cell barriers, whereas it bridges two load cells in the 125 mm ground height load cell barriers. The force concentrations by longitudinal members are larger in 125 mm ground height load cell barriers. From Figure 9, it is clear that the force distribution measurements are dependent on load cell alignments.

The center of force (COF) with time is shown in Figure 11. The AHOF is 436 mm in a 50 mm ground-height load cell barrier, and it is 416 mm in a 125 mm ground-height load cell barrier. There are large differences of relative homogeneity criteria such as 0.315 for 50 mm ground-height load cell barrier, and 0.567 for 125 mm ground-height load cell barrier (see Figure 9). Since the relative homogeneity assessment is related to the deviation from the target load, it is strongly affected by force distributions measurements.

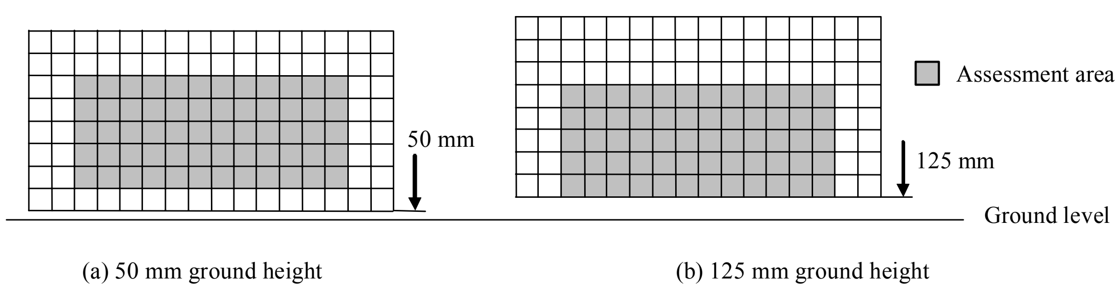


Figure 9. Load cell ground height

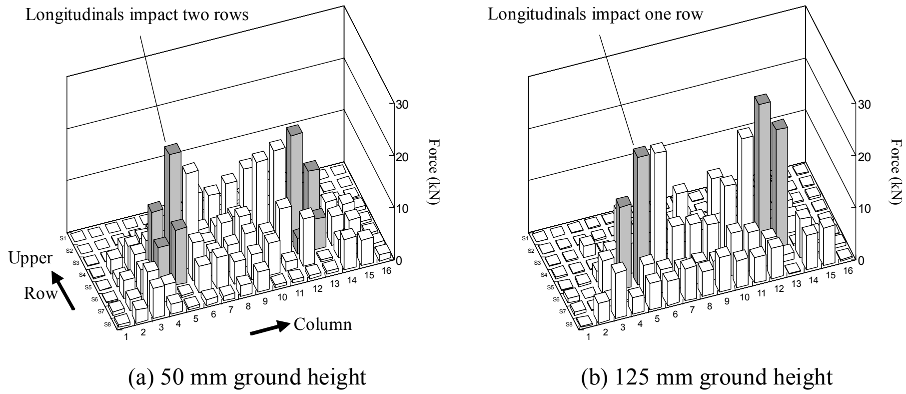


Figure 10. Force distributions of same car models with different load cell ground height

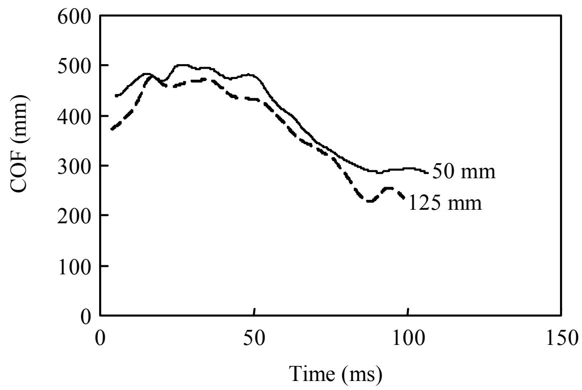


Figure 11. Center of force with time for different ground height of load cell barriers

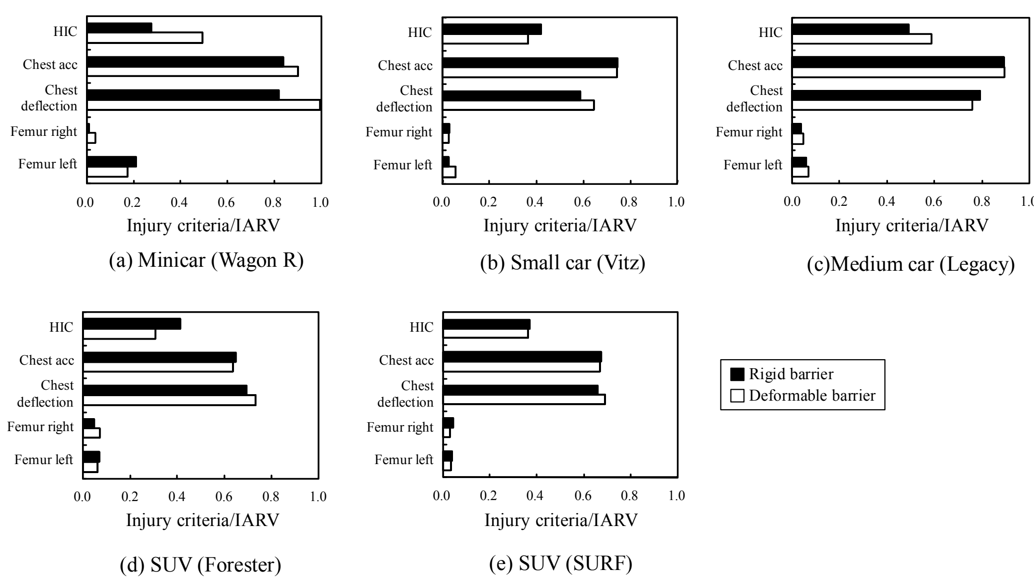


Figure 12. Injury criteria of driver dummy in full rigid and deformable barrier tests

3.4 Dummy responses

Dummy responses were compared between rigid and deformable barrier tests. Figure 12 shows injury criteria of the driver dummy in both tests. Dummy criteria were similar for full-width rigid and deformable barrier tests. The tested cars will be optimized for full-width rigid barrier tests. Because of crash sensing time differences between rigid and deformable barrier tests, the dummy restraint starting time can be later in deformable barrier tests compared with rigid barrier tests. As a result, the interaction of seat belt and airbag with dummies differs for both tests, especially for cars with high acceleration.

4 Discussion

In full-width rigid barrier tests, the force distributions can provide useful information on the impact force of structures. In full-width deformable barrier crash tests, the forces from structures appear clearly in barrier force distributions with mitigating engine impact forces. By the honeycomb stiffness, the shear deformations of vehicle structures are excited, which can also occur in car-to-car crashes. Irrespective of these shear deformations, it is still not clear whether forces from cross members such as SEAS, lower cross member and subframe can be effectively assessed in the full-width deformable tests, though these cross members can be identified in the deformation of the honeycomb.

The occupant responses and injury criteria in full-width deformable barrier tests were similar to those in full rigid barrier crash test. Therefore, the full-width deformable barrier can serve as high-deceleration tests. However, in full-width deformable barrier tests, the crash sensing time can be later compared with rigid barrier tests, and the occupant behavior can be affected, especially with high-acceleration cars.

The AHOFs determined in full rigid and deformable barrier tests are similar. Thus, to determine the criteria such as AHOF and initial stiffness proposed by NHTSA, the force distributions in full-width rigid barrier tests can be available. Further force distribution evaluation will be possible in full-width deformable barrier tests since force distributions without large influence of engine impact can be assessed in full-width deformable barrier tests. Relative homogeneity assessment is a useful criterion to evaluate structure homogeneity. However, the force distribution measurements strongly depend on load cell alignments due to structure bridging on load cells, which can lead to errors of the assessment. Further research will be needed to clarify the effect of load cell sizes and alignments on force distribution and its criteria.

5 Conclusions

In the present research, full-width rigid and deformable barrier tests with high-resolution load cells were investigated for structural interaction evaluation. The conclusions are summarized as follows:

1. In full rigid barrier crash tests, barrier force distributions provide useful information to evaluate the structure. The force distributions are dependent on the structures and engine. The AHOF has a correlation with longitudinal member and engine height.
2. The deformable element in full-width tests is valuable for stiffness evaluations of structures by mitigating an engine impact force and also for exciting shear deformation of structures. Irrespective of different force distributions and vehicle deformations, the AHOFs determined in full rigid and deformable barrier are similar. In full-width deformable barrier crashes, there was a case in which unrealistic deformation of longitudinal member occurred.
3. In full-width deformable barrier tests, further evaluation of force distributions are available compared with rigid barrier tests. However, the force distribution measurements depend on load

cell alignments due to structure bridging load cells, which can lead to errors of homogeneity assessment.

4. The occupant responses in full-width deformable barrier tests were similar to those in full rigid barrier crash tests. Basically the full-width deformable barrier tests serve as high-deceleration tests.

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