Simulation of Progressive Deformable Barrier (PDB) Tests

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Abstract

This paper describes the Finite Element (FE) model development of the Progressive Deformable Barrier (PDB). The FE model of the PDB incorporates shear tearing effect and air pressure effect of the honeycomb in the PDB. The developed PDB is used in several vehicle-to-PDB simulations to check its robustness. Five different makes and models of passenger vehicles are selected for the simulation of PDB tests. Finally, the aggressiveness of these vehicles is presented based on the simulation results.

Introduction

The objective of achieving crash compatibility is to minimize injury risks for all occupants involved in the collision. Today, the vehicles are designed to provide adequate protection to its own occupants, but there is no legislation requiring that the vehicles be built to minimize risk of injuries to occupants of other vehicles.

The Progressive Deformable Barrier (PDB) test procedure has been developed by the compatibility and frontal impact working group (WG15) of the European Enhanced Vehicle Safety Committee (EEVC). The PDB test is one of the proposed candidate tests to assess a vehicle's structural interaction, potential frontal force level, and compartment strength [1]. In the PDB test procedure, the post-test barrier deformation is scanned and utilized to evaluate vehicle aggressivity.

The PDB is based on progressive honeycomb blocks to represent different types of vehicles independently of their mass. In other words, it is a vehicle-like barrier. The PDB is deeper than the Offset Deformable Barrier (ODB) to prevent "bottoming out." Due to the longer depth of the PDB, important aspects of modeling honeycomb structure have to be treated carefully in the Finite Element (FE) model.

In this study, the FE model development of the PDB is presented briefly. The readers are referred to another publication [2] where the development and validation of the PDB model has been explained in greater detail. The robustness of the PDB model is studied using different classes of vehicle models. Five different vehicle models, representing the US vehicle fleet, are selected for the full-scale simulation of the PDB test.

The first part of the paper describes the PDB model development. The second part compares the simulations results to the physical test. Finally, the full scale simulations with different vehicle models are presented.

Description of PDB

The PDB as shown in Figure 1 is 1000 mm wide, 700 mm high, and 700 mm deep. The structure of the PDB (version 7.2) is described in Figure 2 and Table 1. This barrier is composed of four aluminum sheets and two honeycomb cores. Between the aluminum sheets and the faces of honeycomb cores, adhesive is applied to bond each to the other. The covering plate and the contact plate are riveted.

Figure 1. Progressive Deformable Barrier

There are two deformable honeycomb cores. The front deformable honeycomb core is the aluminum hexagonal honeycomb with 19.0 mm cell size, and it has constant crush strength, 0.34 MPa. The rear one is also aluminum hexagonal honeycomb, but its cell size is 9.5 mm. The rear honeycomb core is chemically etched in order to provide two progressive resistance areas and two constant resistance areas. The characteristics of crush strength of deformable cores are shown in Figure 3. Adhesive material complies with Economic Commission for Europe (ECE) Regulation 94. A detailed description of the PDB is found in reference [3].

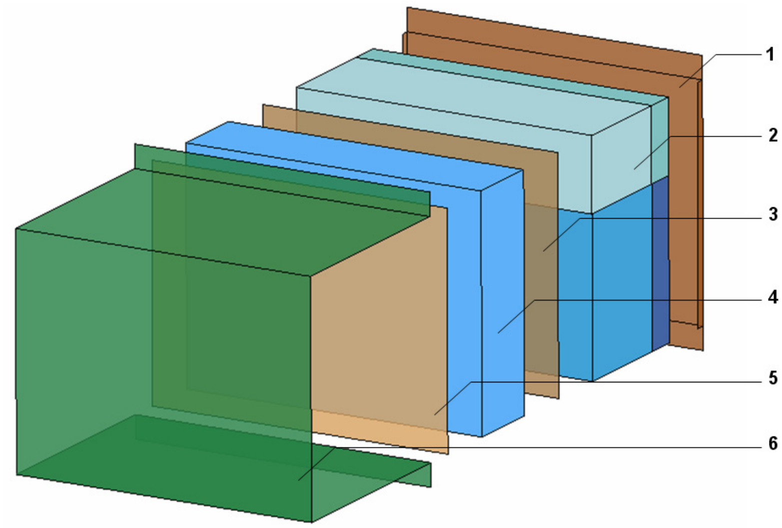


Figure 2. Fragmented view of PDB

Table 1. Name of components

Component number	Name
1	Back Plate
2	Rear Deformable Honeycomb Core
3	Intermediate Plate
4	Front Deformable Honeycomb Core
5	Contact Plate
6	Covering Plate

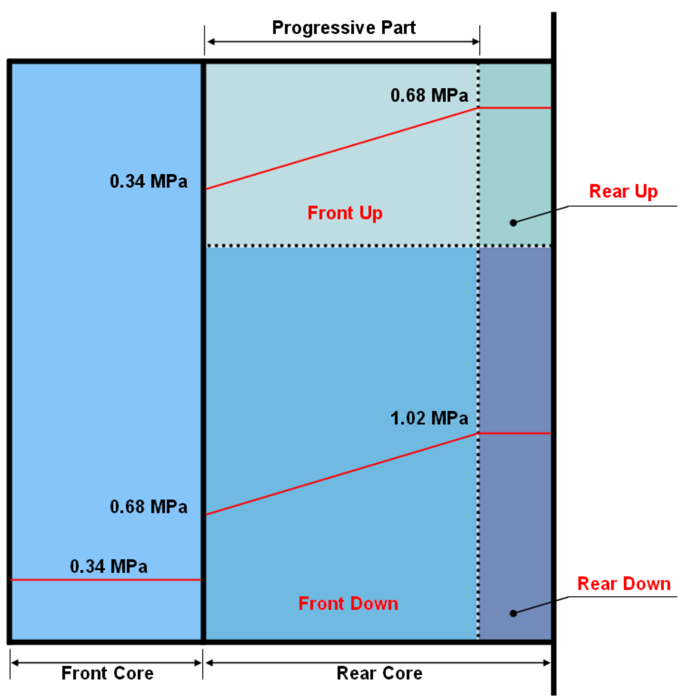


Figure 3. Crush strength of front and rear deformable cores (side view of PDB)

FE Model of PDB

The FE model of PDB is shown in Figure 4. A detailed description of the development and validation of the PDB FE model is presented in reference [2]. Some key aspects of the FE model of the PDB and its validation results are summarized to set a foundation for the full scale simulation study.

Honeycomb modeling

The honeycomb is modeled as solid elements. MAT_MODIFIED_HONEYCOMB (Mat 126) is used as the constitutive material model [4,5]. Material properties, shear tearing and air pressure effects are carefully considered in the FE model of the honeycomb.

Material properties for the progressive honeycomb:

The rear core is etched to have two progressive and two constant crush strengths as shown in Figure 3. The etching process makes the surface of the aluminum progressively thinner. Thus it is important to define the material properties of the honeycomb in various thicknesses of aluminum foil. From the database of honeycomb specification in reference [6], curves for the material properties of honeycomb, such as crush strength, elastic modulus, shear modulus, and density, are obtained in terms of the thickness of aluminum foil. The curves show that those properties are linearly increasing as the thickness of aluminum foil is increasing. These curves are utilized to get the properties in material constitutive equation of the progressive honeycomb cores.

Tearing effect in honeycomb:

Tearing in honeycomb is important since it changes not only the behavior of a barrier, but also the strength of honeycomb. In the PDB test, its importance is emphasized to obtain an accurate deformed shape of the PDB for calculating vehicle aggressivity. In order to represent the tearing effect, honeycomb is modeled using many small column meshes. These columns are connected with breakable discrete beams, MAT_NONLINEAR_PLASTIC_DISCRETE_BEAM (Mat 68), as shown in Figure 5. The failure criteria of discrete beams, such as tearing force and maximum displacement, are calculated by using the results of punch tests from reference [7].

Air pressure effect in honeycomb:

During the PDB test, the honeycomb core experiences a strain-rate of up to 23.8 s^{-1}. Thus a lot of air in the honeycomb core can't escape, and hence gets compressed. This air pressure affects the crush strength of honeycomb. The air pressure effect is obtained from with the results of punch tests from reference [7] by subtracting static punch test result from dynamic punch test result. This effect in the PDB can't be ignorable and is incorporated in the constitutive model of honeycomb.

Adhesive modeling

For simplicity, the adhesive is defined as a tied contact in FE barrier models. In the vehicle-to-PDB test, the vehicle structure penetrates deep into the honeycomb core. Aluminum sheets are debonded from the face of the honeycomb core, and slide down on the honeycomb. So, this phenomenon is treated cautiously in the FE model. In this model, bonding is modeled using discrete beams, MAT_NONLINEAR_PLASTIC_DISCRETE_BEAM (Mat 68). Failure criteria are calculated from material properties of adhesive and a contact area, which is the area between the aluminum sheet and the face of honeycomb core. However, it is difficult to obtain the contact area accurately since this area in a real barrier is a lot wider and very irregular.

Validation

For the validation procedure, three FE models, such as a simple model, an advanced model, and a final model, are created. In the simple model, the honeycomb is modeled with one lump mesh of solid elements. In order to considering tearing of the honeycomb, in the advanced model, the honeycomb is generated with column meshes with connection beams. Finally, the final model is developed with incorporating the air pressure effect into the constitutive equation of the honeycomb.

Two validation tests were performed with the final FE model, and compared with physical experiments [8]. In both experiments, the PDB is impacted by a moving rigid barrier. The results are shown in Figure 6, 7, and 8. From validation test 1, wall forces are relatively well matched in Figure 8(a). However, the behavior of adhesive element between Figure 6(a) and Figure 7(a) is slightly different because of the difficulty in obtaining accurate failure criteria of beam elements. In validation test 2, it can be seen that shear tearing of honeycomb in FE model (Figure 7(b)) has improved because of using honeycomb column meshes and connection beam elements. However, the wall force of the FE model in Figure 8(b) is higher than in the experiment after 300 mm in the deformation of PDB, because there is an inherent limitation of solid elements to describe a tearing effect. Overall, the FE model of the PDB shows relatively good correlation.

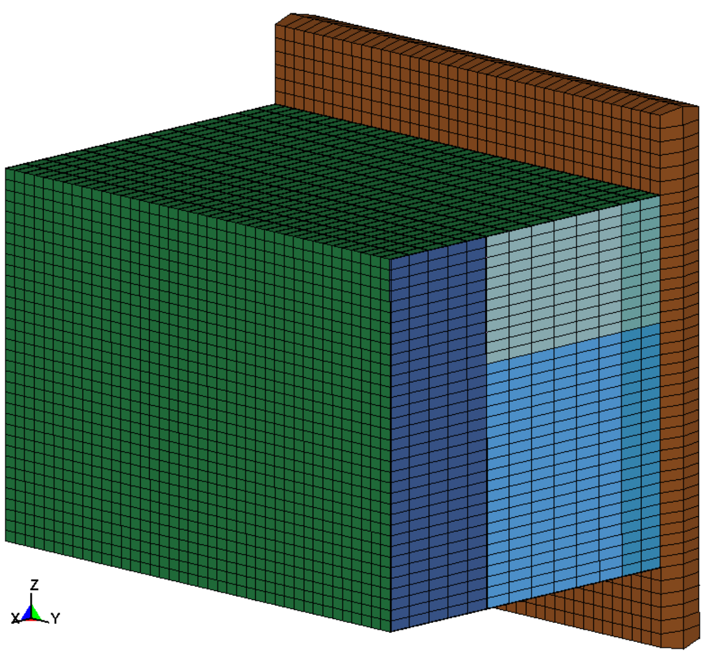


Figure 4. FE model of PDB

Table 2. Size and number of elements of the FE model of PDB

Element Type	Size (mm)	Number
Solid	50×25×25	20,560
Shell	25×25 or 50×25	41,440
Beam	1.0 ~ 1.3	32,808
Node	-	53,459

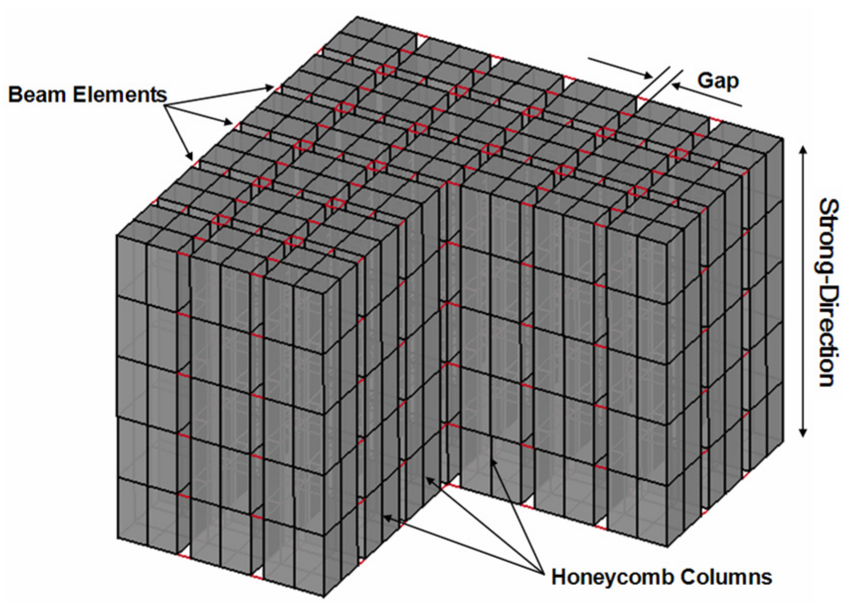
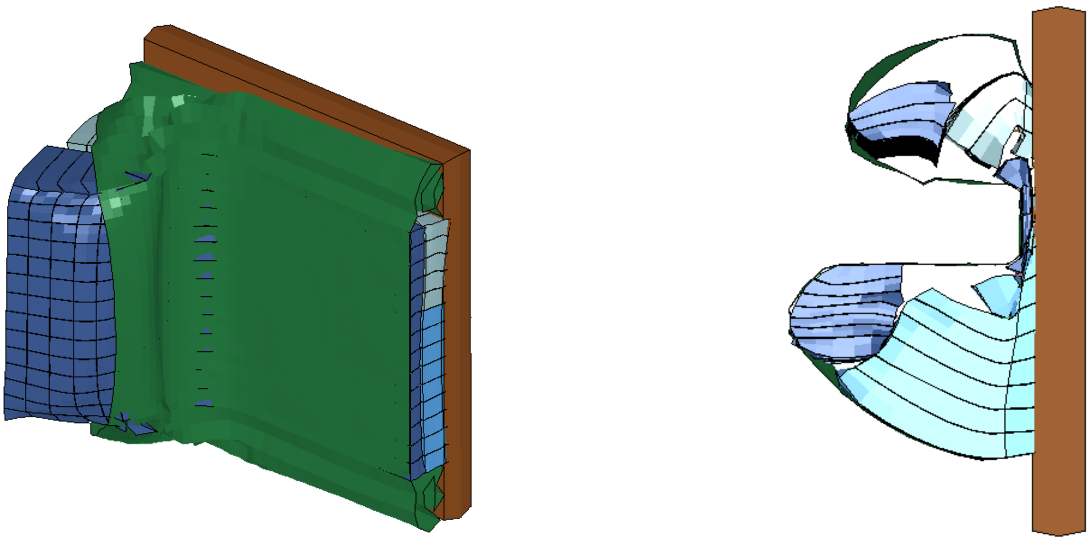


Figure 5. Honeycomb columns and beam connections

(a) Validation test 1

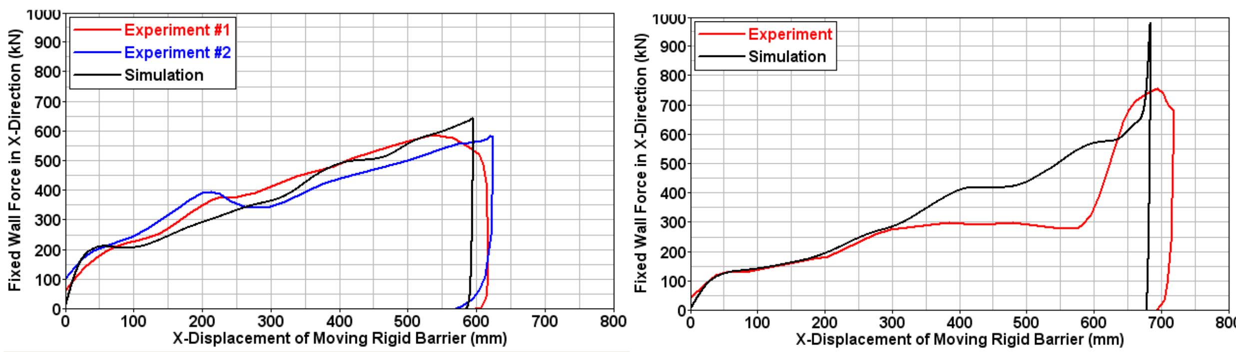
(b) Validation test 2

Figure 6. Deformed shapes of PDB in validation tests



(a) Validation test 1 (b) Validation test 2

Figure 7. Deformed shapes of the FE model of PDB in validation tests



(a) Validation test 1 (b) Validation test 2

Figure 8. Comparison of wall forces in validation tests

Description of PDB Test

Figure 9 shows the setup of the vehicle-to-PDB test. The PDB is mounted on a fixed rigid wall at a height of 150 mm above the ground. The vehicle is oriented such that 50% of the vehicle overlaps with the PDB. The vehicle impacts the barrier at a speed of 60 km/h. The procedure of the PDB test is explained in the references [9,10].

The evaluation method of PDB tests is covered in references [9-11]. Based on the deformation of the barrier, three parameters are judged paramount, such as

- Depth of deformation: X-representative of the stiffness,
- Height of deformation: Z-representative of the geometry, and
- Surface area of deformation.

The partner protection assessment of deformation (PPAD), which is the objective value of aggressivity, is calculated based on these three quantities. The formula of the PPAD is

$$PPAD = \frac{0.52}{10} R^{0.55}, \tag{1}$$

Where $R = \sum_{i=1}^{14} \left(\frac{Z_i}{Z_{\lim}} \right)^4 \left(\frac{X_i}{X_{\lim}} \right)^2 S_i$, i is the index for reference depths (14 ranges in the current proposal), Z_i is the average height for each surface area, X_i is the average deformation for each surface area, $Z_{\lim} = 420mm$ corresponding to average longitudinal height in Europe, $X_{\lim} = 300mm$ corresponding to a certain level of force (300 kN) that represents an average front unit force, and S_i is the surface area for a range of deformation depths. The lower the PPAD is, the less aggressive a car is and the higher the PPAD is, the more aggressive it is. The aggressiveness scale is shown in Figure 10. In addition to the PPAD, the average height of deformation (AHOD), which is comparable to the average height of force (AHOF), and the average depth of deformation (ADOD) are available as well in the PDB tests.

UTAC provides the software for the PDB test, which is PDBSoftV1.0. This program can be downloaded from the reference [12]. Its graphical user interface (GUI) is shown in Figure 11. The input data is the scanned surface of the posttest-PDB. The output of the computer program is 9 quantities, such as

- PPAD is the partner protection assessment of deformation,
- Stiffness means the influence of the stiffness parameter in the formula of PPAD,
- Geometry means the influence of the geometry parameter in the formula of PPAD,
- ADOD is the average of depth of deformation,
- AHOD is the average of height of deformation,
- D_{max} is the deformation maximum,
- $Z(D_{max})$ is the height at the deformation maximum,
- Volume means the calculation of the total volume deformed, and
- Energy means the calculation of the energy absorbed by the barrier based on the volume of deformation and stiffness of the barrier [11].

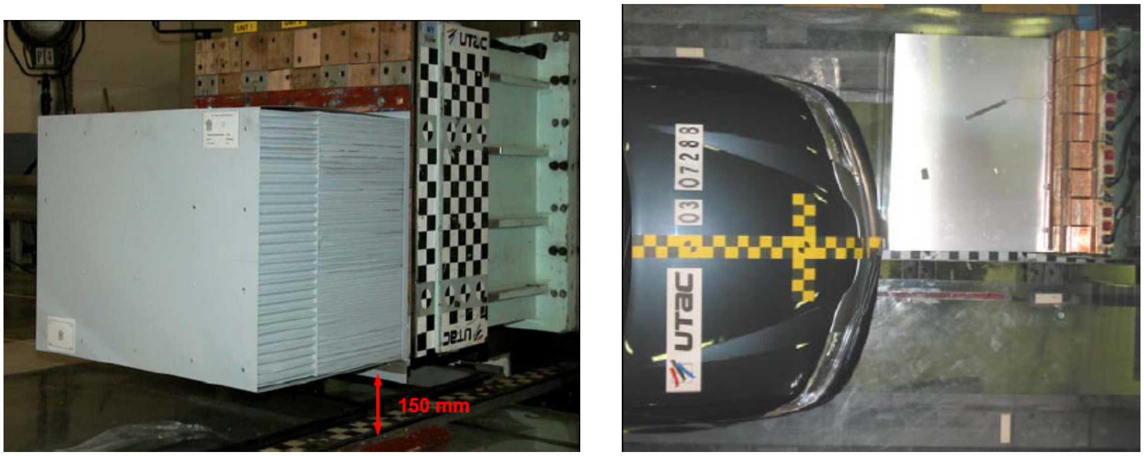


Figure 9. Setup of frontal PDB test

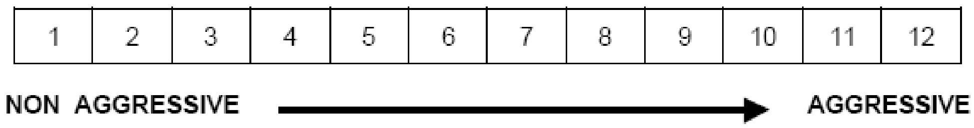


Figure 10. Aggressiveness scale

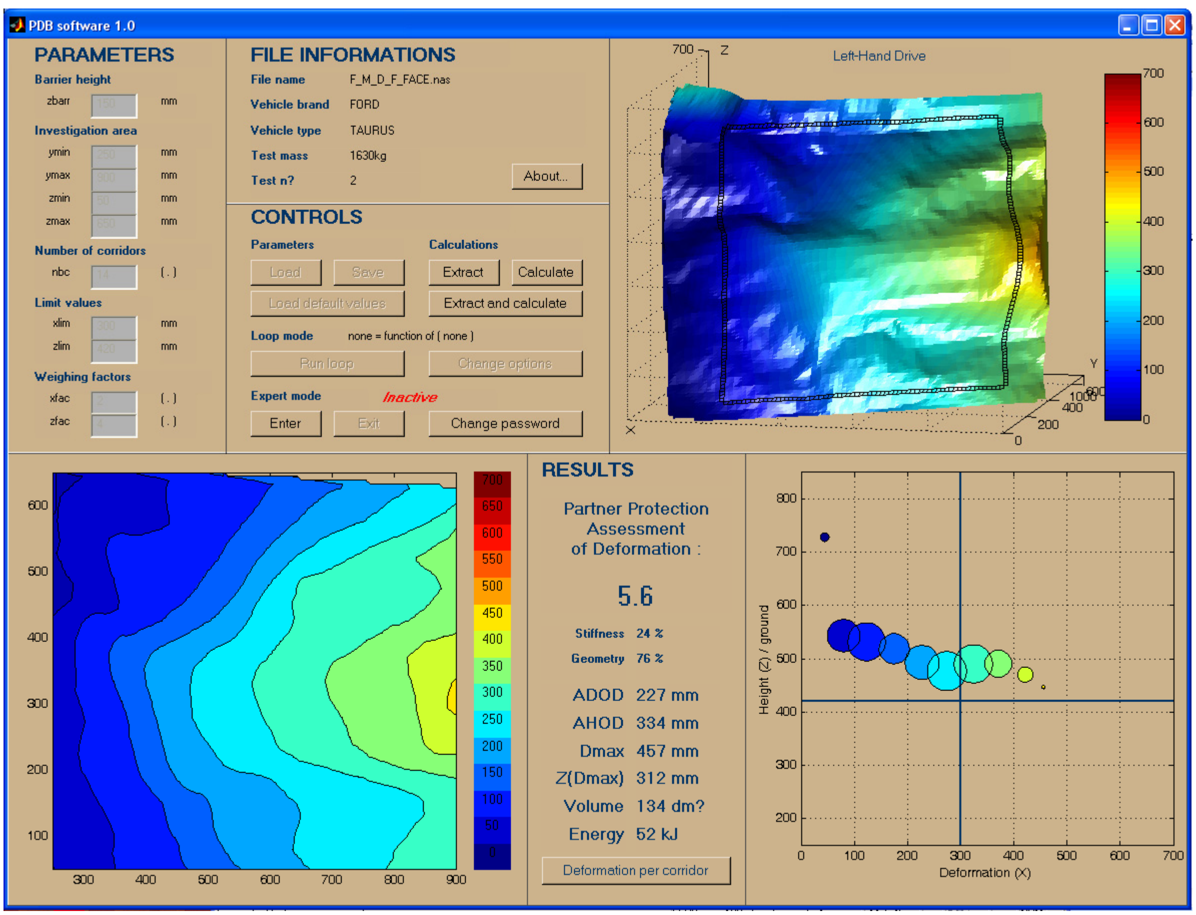


Figure 11. Graphical user interface(GUI) of PDBSoftV1.0

Simulations of PDB Tests

PDB tests are simulated with the PDB FE model developed in the reference [2]. It should be noted that the simulation results aren't validated since there is no available result of PDB test unfortunately. However, the FE PDB model and FE vehicle models are validated [2,13].

The five different sizes of FE vehicle models, Dodge Neon, Ford Taurus, Dodge Caravan, Ford Explorer and Ford F250 shown in Figure 12, are taken from the database of the finite element model archive in the FHWA/NHTSA National Crash Analysis Center (NCAC) at the George Washington University [13]. The vehicle types and weights are listed in Table 3. There are two sedans, one minivan, one Sport Utility Vehicle (SUV), and one pick-up truck. The vehicle model weight ranges from 1204 kg up to 3000 kg. Their structure types are also different. The Dodge Neon, Ford Taurus and Dodge Caravan have unibody structure but the Ford Explorer and Ford F250 have ladder frame structure. Those differences in vehicles make the simulation results comparable quantitatively.

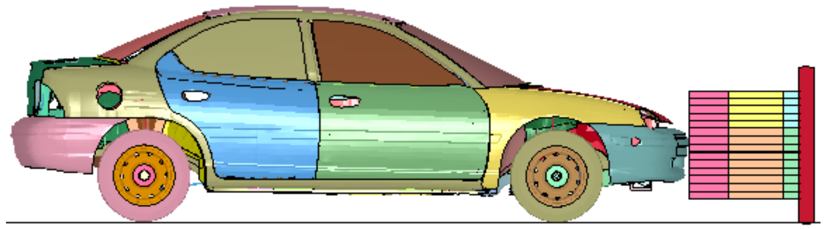
After the PDB tests are simulated, the FE model output is read by the UTAC computer program. The aggressiveness of each vehicle is evaluated by PDBSoftV1.0. These aggressiveness matrices are summarized in Table 3. The deformed shapes of both vehicle and PDB at 200 msec are shown in Figure 13-17(a), (b). Figure 13-17(c) show the 3-D view of deformed face of PDB. The Black square line in Figure 13-17(c) is the investigation area of aggressiveness. The 2-D views of the depth ranges of PDB deformation are shown in Figure 13-17(d) and their bubble views are in Figure 13-17(e). The wall forces of five PDB tests are shown in Figure 18.

None of the simulation results of the vehicle-to-PDB test are validated or compared with experiment results, since comparable experiment data doesn't exist. Therefore, it can't be said that the aggressiveness values in Table 3 are objective. However, from the simulations of the PDB test, some expected results can be confirmed, such as

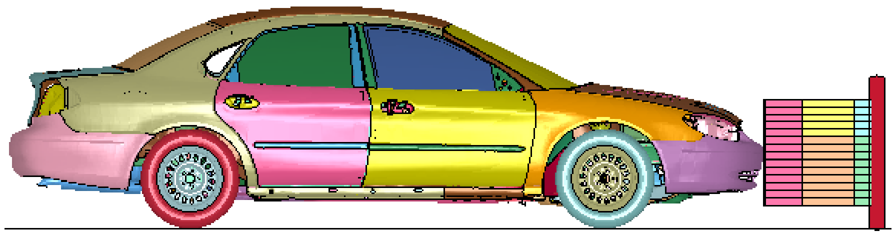
- The heavier a vehicle is, the higher PPAD is, which means that the heavier vehicle is more aggressive.
- The minivan, SUV, and Pick-up truck have higher AHOD and PPAD than the sedan. In other word, the higher AHOD is, the higher PPAD is.
- The vehicle with ladder frame structure has higher PPAD than the one with unibody structure. That is, the vehicle with ladder frame structure is more aggressive.
- The deformed shapes of PDB are quite different between unibody and ladder frame structure vehicles. In the vehicle with the unibody structure, the maximum deformation occurs at centerline of the vehicle. The maximum deformation happens at the position of a ladder frame in the vehicle with ladder frame structure.

The above results show that the FE model of PDB gives quite reasonable results in the simulation of the PDB test. As shown in Figure 16 and 17, the FE models of PDB suffer a very large deformation. However, the FE model gives very stable results.

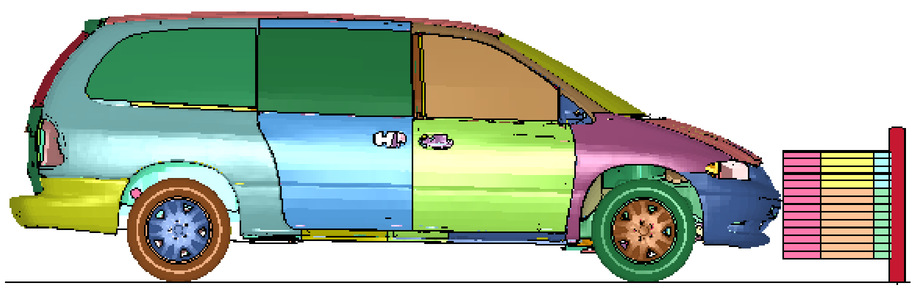
Considering all the results above, the FE model of PDB presented here is quite useful and stable. However, it has to be further validated with an experimental full scale PDB test to obtain accurate values of aggressiveness in the simulation of the PDB test.



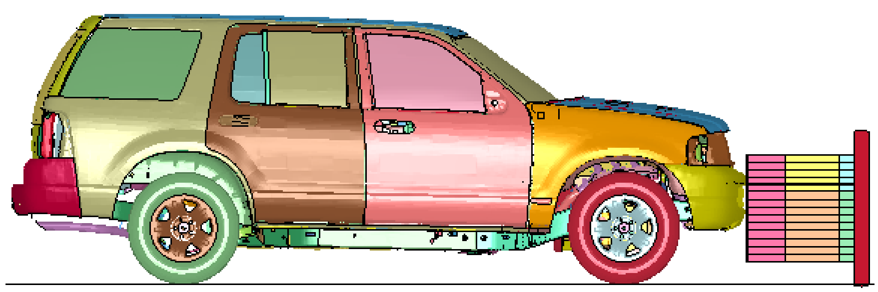
(a) Dodge Neon



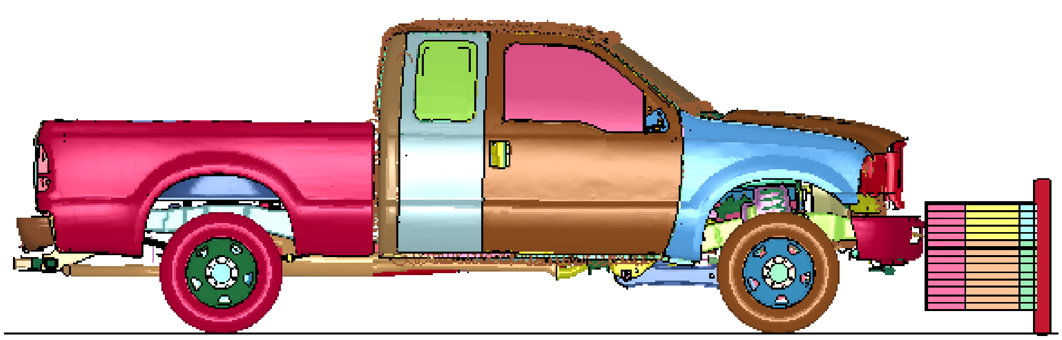
(b) Ford Taurus



(c) Dodge Caravan



(d) Ford Explorer

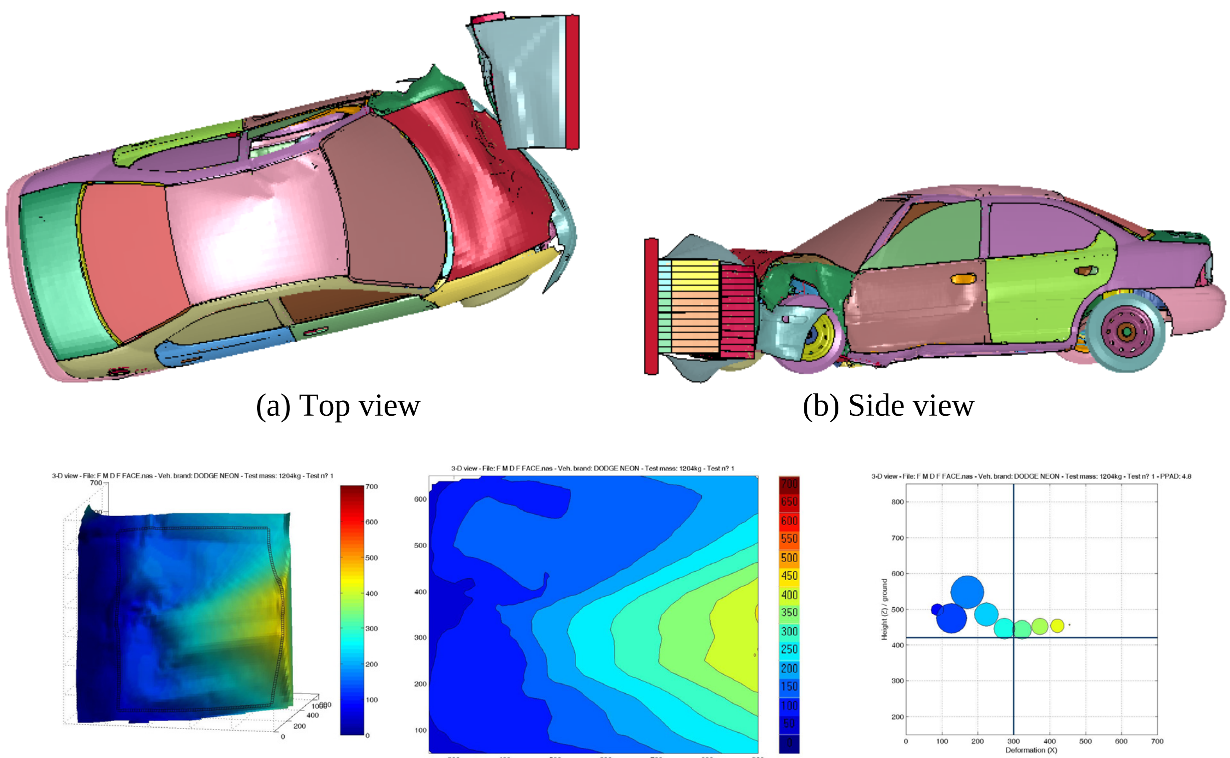


(e) Ford F250

Figure 12. Simulation setup of PDB tests

Table 3. Vehicle weights and results of PDB tests

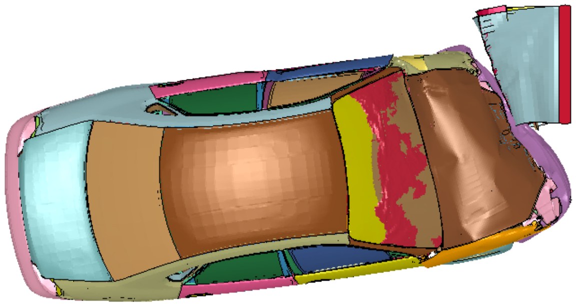
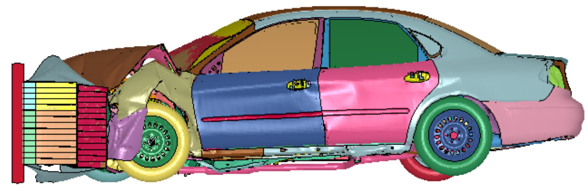
	Dodge Neon	Ford Taurus	Dodge Caravan	Ford Explorer	Ford F250
Vehicle Type	Small-size Sedan	Mid-size Sedan	Minivan	SUV	Large-size Pickup Truck
Weight	1204 kg	1630 kg	2028 kg	2224 kg	3000 kg
PPAD	4.84	5.56	8.88	12.61	14.97
Stiffness	24.1 %	24 %	35.8 %	36 %	28.7 %
Geometry	75.9 %	76 %	64.2 %	64 %	71.3 %
ADOD	214.7 mm	226.8 mm	313.9 mm	367.8 mm	332.5 mm
AHOD	338.7 mm	334.3 mm	367.8 mm	375.7 mm	397.2 mm
Dmax	460.4 mm	456.6 mm	517 mm	564.9 mm	650.2 mm
Z(Dmax)	303.8 mm	312.4 mm	385.8 mm	422.3 mm	627.9 mm
Volume	120.9 dm^3	134.3 dm^3	193.8 dm^3	225.4 dm^3	215.5 dm^3
Energy	47.9 kJ	52.4 kJ	80.4 kJ	96.3 kJ	87.7 kJ



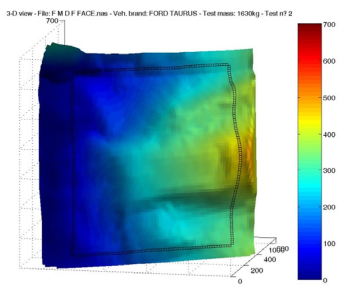
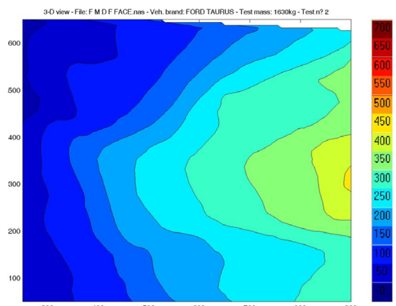
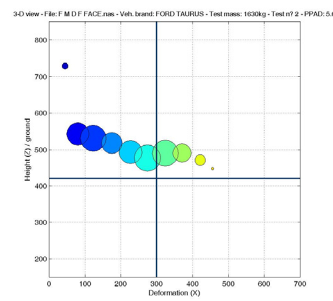
(a) Top view (b) Side view

(c) 3-D view (d) 2-D view (e) Bubble view

Figure 13. Deformations of Dodge Neon and barrier in PDB test at 200 msec

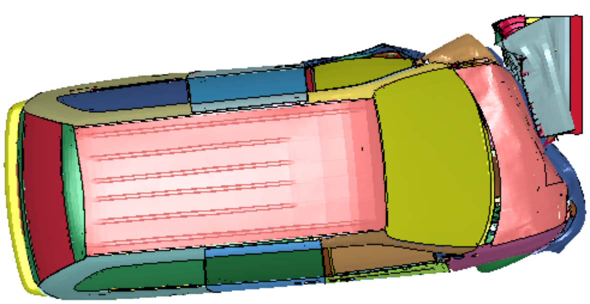
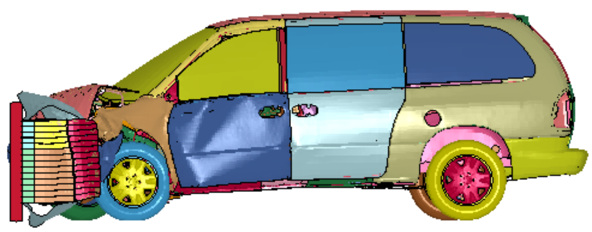



(a) Top view (b) Side view

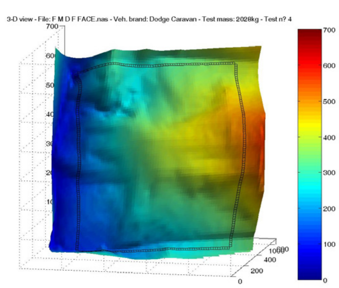
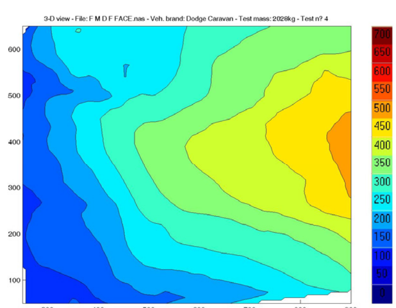
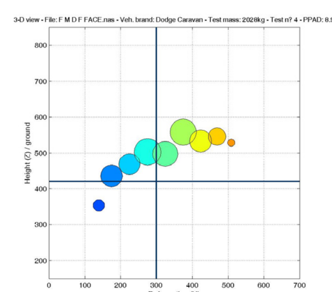




(c) 3-D view (d) 2-D view (e) Bubble view

Figure 14. Deformations of Ford Taurus and barrier in PDB test at 200 msec

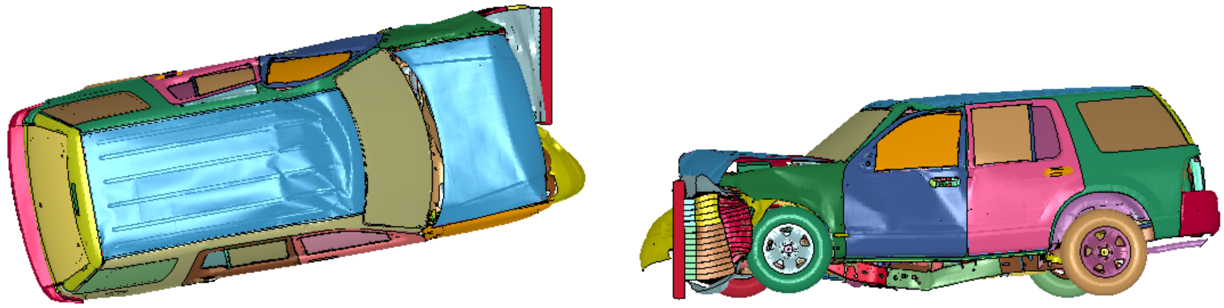



(a) Top view (b) Side view

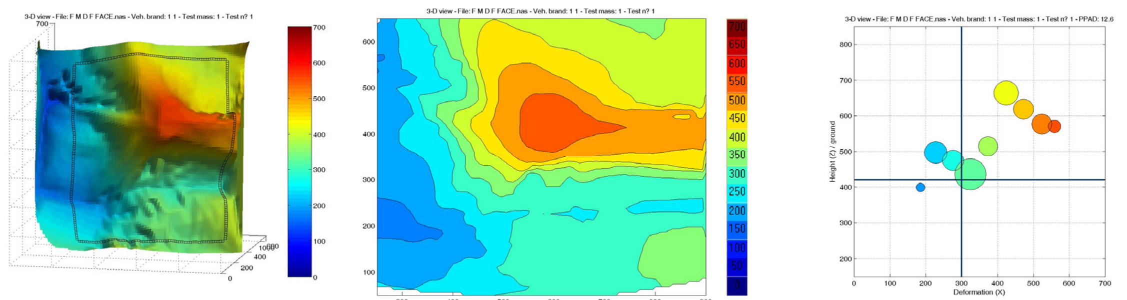




(c) 3-D view (d) 2-D view (e) Bubble view

Figure 15. Deformations of Dodge Caravan and barrier in PDB test at 200 msec

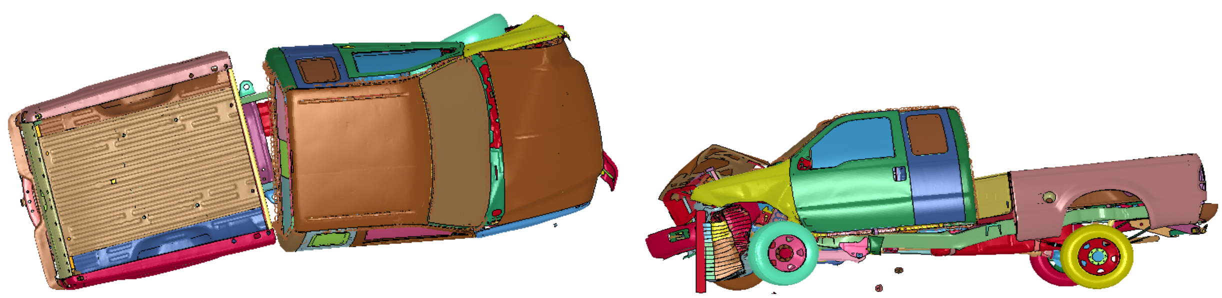


(a) Top view (b) Side view

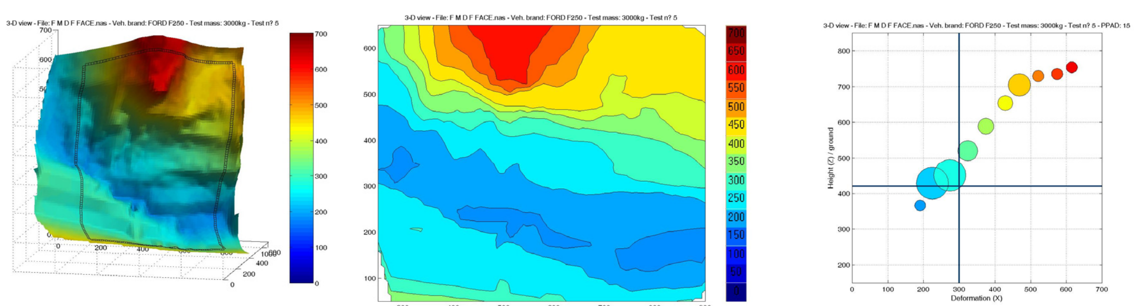


(c) 3-D view (d) 2-D view (e) Bubble view

Figure 16. Deformations of Ford Explorer and barrier in PDB test at 200 msec



(a) Top view (b) Side view



(c) 3-D view (d) 2-D view (e) Bubble view

Figure 17. Deformations of Ford F250 and barrier in PDB test at 200 msec

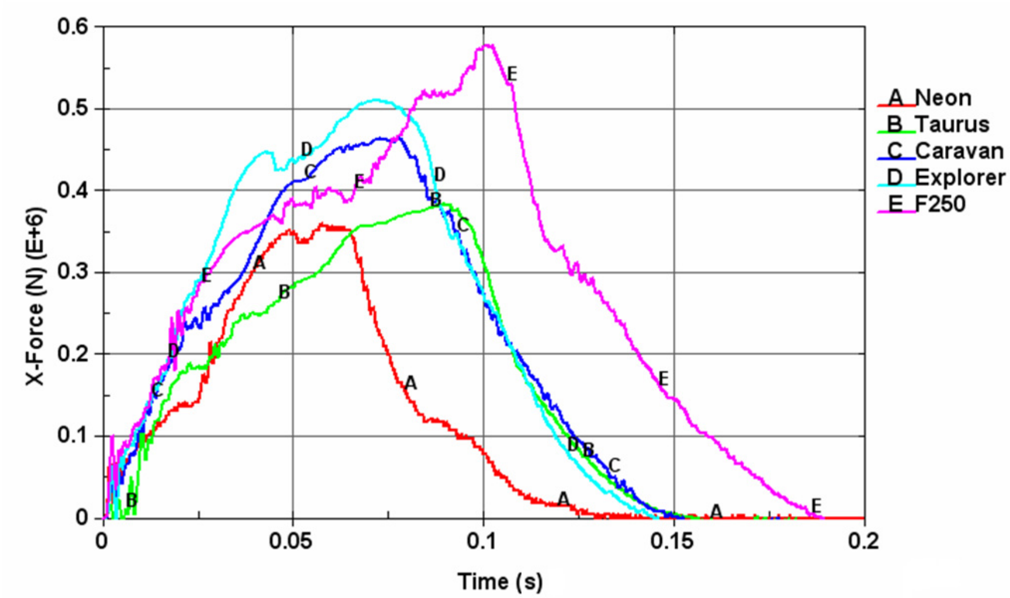


Figure 18. Wall forces in PDB test

Summary

In this paper, a FE model of the PDB and the simulation of PDB tests are described. The usefulness of the FE model of PDB in the simulation of the PDB test is studied.

The FE model of the PDB is developed. The honeycomb is modeled using solid elements. However, honeycomb mesh is divided into many honeycomb column meshes with connection beams in order to consider tearing effect. Air pressure effect is incorporated in the constitutive model of the honeycomb. Adhesive to bond aluminum sheets to the honeycomb core is modeled using discrete beams. In the sub-system validation tests, the FE model shows relatively good correlation.

Five different vehicles are used for the simulation of vehicle-to-PDB tests. These vehicles have different weights, from 1204 kg up to 3000 kg, and structure types, unibody and ladder frame. The simulation results show that the FE model of the PDB is quite useful and stable in large deformation. However, the PDB has to be further validated with an experimental PDB test to obtain accurate values of aggressiveness in the simulation of the PDB test.

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References

1. R Thomson, M Edwards, T Martin, C Zweep, R Damm, and G Valle, 'Car-to-car compatibility: development of crash test procedures in the VC-Compat project,' International Journal of Crashworthiness, 2007 12: 137-151
2. C-K Park, S-W Hong, P Mohan, R M Morgan, C-D Kan, K Lee, S Park, and H Bae, 'FE model Development of progressive deformable barrier (PDB),' International Crashworthiness Conference, Kyoto, Japan, 2008
3. AFL Honeycomb Structures, 'Technical specifications and methods of construction of the compatibility progressive deformable barrier for frontal impact PDB V7.2'
4. Livermore Software Technology Corp., LS-DYNA keyword user's manual – version 971, 2007
5. Livermore Software Technology Corp., LS-DYNA theory manual, 2006
6. Hexcel Corp., 'HexWeb honeycomb attributes and properties,' 1999
7. Q Zhou and R R Mayer, 'Characterization of aluminum honeycomb material failure in large deformation compression shear, and tearing,' ASME Journal of Engineering Material and Technology, 2002 124: 412-420
8. UTAC, 'Report of test validation'
9. UTAC, 'PDB test protocol – version 2.3,' 2006
10. P Delannoy, J Faure, D Coulombier, R Zeitouni, and T Martin, 'New barrier test and assessment protocol to control compatibility,' SAE Technical Paper no. 2004-01-1171, 2004
11. UTAC, 'PDBSoftV1.0 User Guide,' http://wg15.eevc.org/wg15publicdocs/PDBsoftV 1.0_UserGuide.pdf
12. UTAC, PDBSoftV1.0, http://wg15.eevc.org/wg15publicdocs/PDBsetupV10.exe
13. FHWA/NHTSA National Crash Analysis Center, http://www.ncac.gwu.edu/vml/models.html