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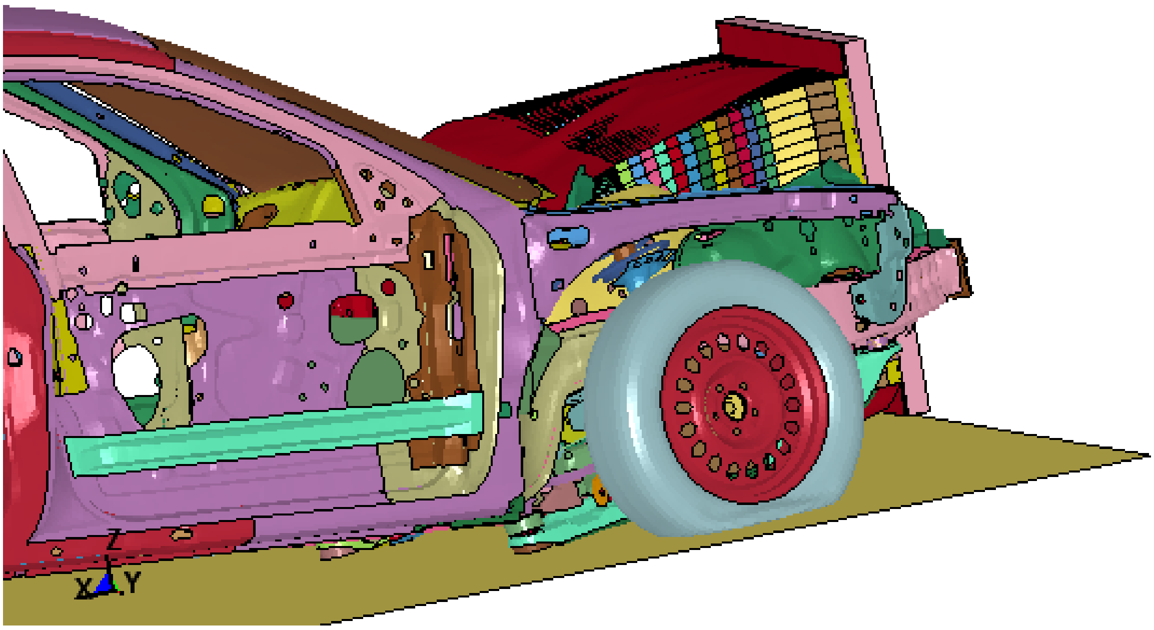

Influence of the different vehicle subframe configurations in the PDB assessment

Master's Thesis in the Automotive Engineering International Master's Program

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Cover:
Crash simulation of the simplified Ford Taurus 2001 to the PDB barrier

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ABSTRACT

There is no consideration for crash compatibility of passenger vehicles in safety regulations. The EU Project FIMCAR is investigating different frontal crash tests that can assess a vehicle's frontal crash performance for both self and partner protection. Existing candidates need further development in establishing an objective measurement from the test data. The PDB (Progressive Deformable Barrier) is one of the candidates with ability to detect load distribution of a vehicle frontal structure in a crash. Deformation of the PDB barrier surface is used to evaluate vehicle performance. The proposed PDB barrier and evaluation process needs further investigation before acceptance for vehicle regulatory or consumer testing.

The PDB's ability to detect different front end structural configurations of a vehicle was evaluated by simulations. A finite element model of the vehicle (2001 Ford Taurus) and the PDB were used. The vehicle performance benefits of different sub-frame configurations were indentified with car-to-car simulation results that were used as the reference for car-to-PDB simulations. A new protection criterion of a partner vehicle in crash was also developed using available PDB test results.

The performance differences of various sub-frame configurations were detected through the car-to-car simulations. Initial car-to-PDB simulation results were not able to detect these differences because of issues with components of the PDB. For this reason, the PDB model was modified to improve lower structural interaction detection. The modified PDB showed better results.

The results of the physical PDB and the FE PDB simulations were evaluated with the developed criteria. The new PDB criteria worked well with scanned physical PDB deformation faces, but not with the unmodified PDB simulation results. This discrepancy may be due to the removal of covering structures in the vehicle FE model that created a more aggressive car structure than a true production car.

The PDB was able to detect different sub-frame configurations. The car-car results showed that the longer sub-frame configuration increases self protection because structural interaction starts earlier in the crash. Due to the limitations of the PDB and vehicle models used in the project, the proposed criteria did not properly assess the different subframe configurations. Further work is needed to confirm the criterion is robust to apply in frontal crash compatibility evaluation.

Key words: Compatibility, PDB, Self-protection, Structural Interaction, Fork Effect, Finite Element

Contents

Preface

This thesis project was carried out between January 2011 and June 2011 at SAFER (Vehicle Safety Division in Chalmers University of Technology). The modifications of the FE models were made by ANSA and LS-PrePost. The FE simulations were made by LS-DYNA solver on the Chalmers super computer service BEDA. This project is part of the project FIMCAR (Frontal Impact and Compatibility Assessment Research) conducted by European Union.

We would like to show our high gratitude to our supervisor Dr Robert Thomson. Thanks for all his support and guidance. Also we would like to thanks Linus Wågström and Aleksandra Krusper for their technical support throughout all the stages of the project. We finally want to thank Dr Johan Davidsson for his leading advice and comments about our work and report.

Göteborg June 2011

Amir Reza Riazi

Darius Simkus

Notations

EX	Car model with extended sub-frame configuration
BA	Car model with basic sub-frame configuration
SH	Car model with shortened sub-frame configuration
WO	Car model with without sub-frame cross beam
C2C	Car to car crash scenario
C2PDB	Car to PDB crash scenario
C2PDB1	Car to standard PDB crash scenario
C2PDB2	Car to modified PDB crash scenario
FWDB	Full Width Deformable Barrier
FWRB	Full Width Rigid Barrier
ODB	Offset Deformable Barrier
PDB	Progressive Deformable Barrier
FIMCAR	Frontal Impact and Compatibility Assessment Research
NCAC	National Crash Analysis Center
VC-COMPAT	Improvement of vehicle crash compatibility through the development of crash test procedures

1 Introduction

1.1 Background

Annually, a huge number of people are being killed on the roads of the European Union. There were about 54300 deaths in 2001 which decreased by about 36 percent until 2009 (based on the statistics from European Commission of Road Safety) [1]. This positive trend shows promising future for road traffic safety and more work is needed to help improve the trend. In the future, active safety would play a significant role in vehicle safety, however passive safety will remain important for a long period.

In the passive safety area of the vehicles, crash compatibility is one of the most important parameters. Each vehicle manufacturer has its own strategy to improve crash compatibility of their cars and there are no considerations in legislation. Different ideas have been proposed for evaluation of crash compatibility.

The PDB (Progressive Deformable Barrier) concept was developed to represent vehicle frontal structures similar to a partner vehicle as a tool to assess partner protection. The stiffness of the barrier increases progressively in the longitudinal direction and it has two stiffness configurations vertically. The barrier allows detecting the front end structure and load paths of the vehicle. Also, the PDB represents the vertical car force distribution, because the vehicles usually have stronger lower front load path than the upper ones [2].

1.2 Compatibility

Structural interaction is achieved when energy absorbing structures in a vehicle are efficiently deformed by structures in the collision partner. The best condition is for all of the main frontal structures of a vehicle like longitudinals and sub-frame to contact their pairs from the partner car in the impact. In this scenario, the main load paths (Figure 1.1) of the colliding cars would absorb the impact energy. The load paths of a vehicle, like the Ford Taurus, are the sub-frame, lower rails and upper rails in the front. They are direct loads through the sills and A-pillars to transfer the crash load to the compartment.

Accident analysis in FIMCAR identified fork effect and small overlap in frontal collisions. If the impact happens with fork effect (horizontal misalignment of load paths evolved during collision, Figure 1.2) or a small overlap, there is a risk that strong parts interact with soft parts of the partner vehicle and cause big intrusion to the compartment.

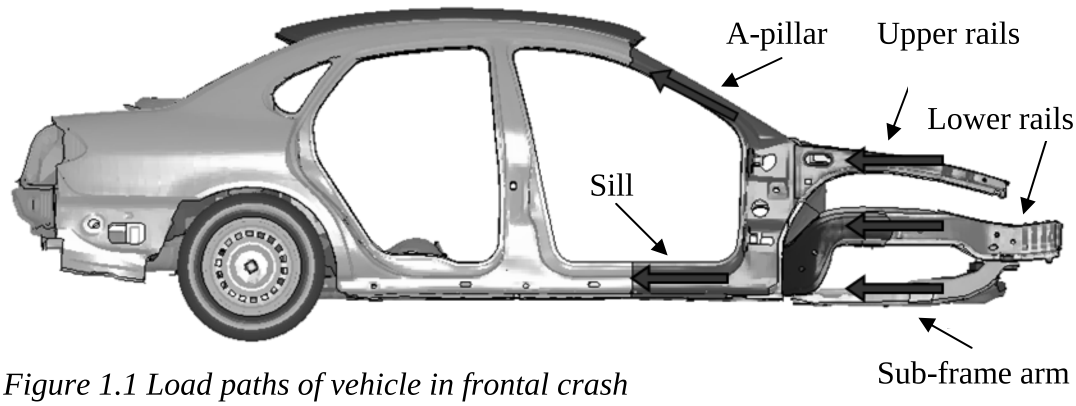

Figure 1.1 Load paths of vehicle in frontal crash

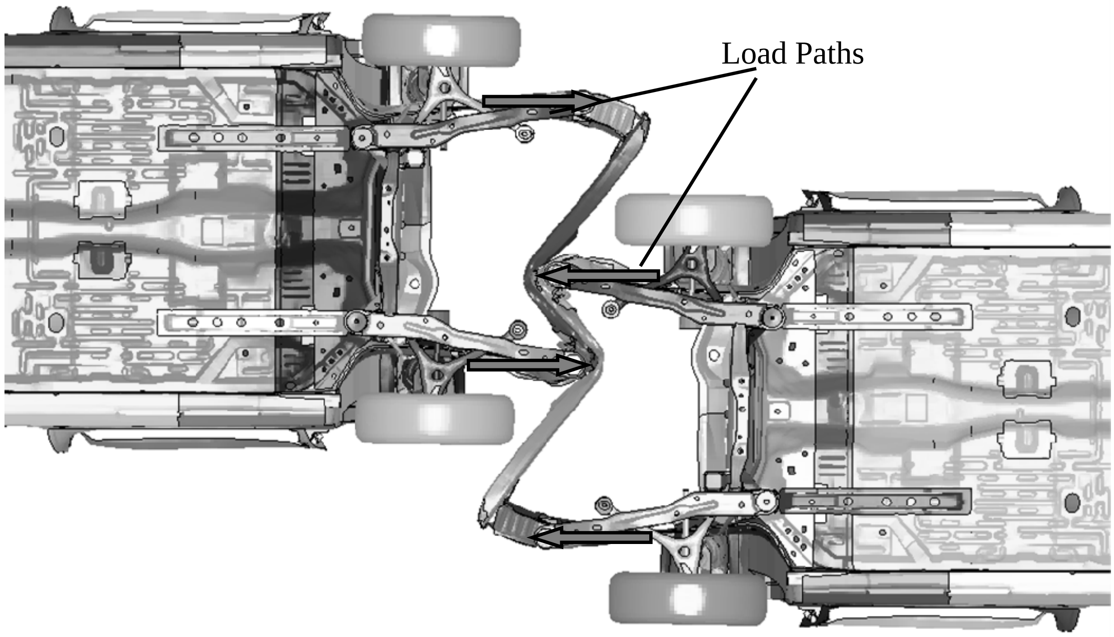

Figure 1.2 Fork effect

FIMCAR also identified problems when the vehicles are not aligned vertically. This causes over/underriding. Similar compatibility issues occur where stiff structures overcrush softer structures in the partner vehicle.

Crash compatibility of vehicles refers to how well structure of two vehicles counterpart in frontal collision and amount of damage to the colliding vehicles. For crash compatibility adjusted force level, structural interaction, optimized passenger compartment strength are indispensable.

Mass is an important parameter in compatibility of the colliding vehicles, because according to the law of conservation of momentum in an impact, the lighter vehicle in front-to-front crash would experience bigger velocity changes than the heavier vehicle. It means that the passenger of the lighter vehicle would experience higher accelerations. The mass of the vehicles are not possible to be adjusted because of the different masses in current vehicles on the street and the demand of the market for different vehicle types.

The difference between the frontal structural stiffnesses would cause incompatibility in the crash. The vehicle with a less stiff front structure would experience more front deformation and the stiffer vehicle would have less deformation in the front structure. Thus the softer vehicle is always more vulnerable to compartment intrusions and passenger injuries. The global stiffness of front structures in a vehicle is highly dependent to the structural interaction and distribution of the forces between load paths of vehicles involved in a crash. If the load paths are interconnected with all framing elements of the longitudinal and vertical force resisting vehicle front structure, the contact forces can be well distributed in the vehicle. The ideal extension of this property is for the loadpaths to be evenly, or homogeneously, distributed throughout the vehicle.

As a more distributed deformation of a vehicle is considered as better car front structure design, the assessment of homogenous vehicle deformation should be studied. Thus to assess compatibility, a test method to evaluate homogenous vehicle deformation should be developed. One promising candidate is the Progressive Deformable Barrier (PDB).

1.3 PDB

The PDB barrier is shown in Figure 1.3. It is 797 mm deep, 1000 mm wide and 702 mm high. It is composed of the front deformable core, 250 mm, the progressive deformable core, 450 mm and the back deformable core, 90 mm depth.

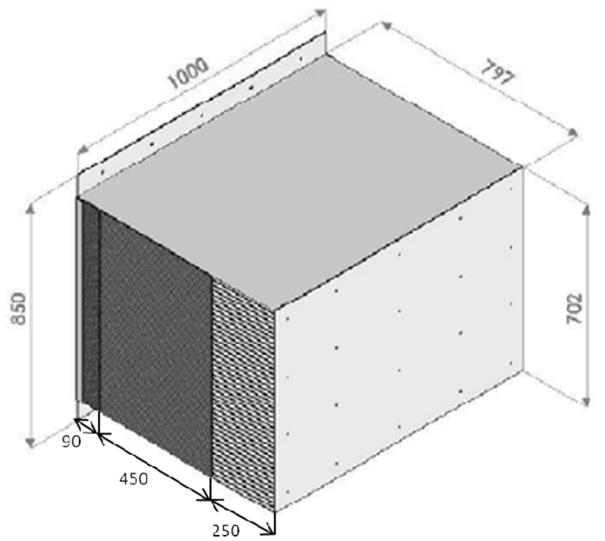

Figure 1.3 PDB barrier dimensions

The PDB is composed of three deformable cores, four plates, cladding, blind rivets and epoxy resin as shown in Figure 1.4 and Figure 2.6

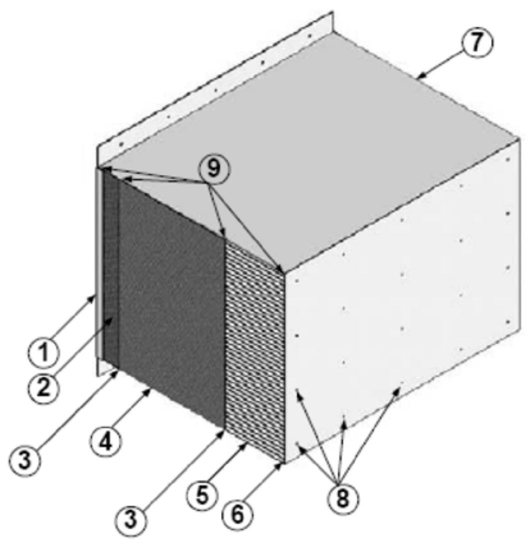

Figure 1.4 PDB components [3]

1 – Back plate,
2 – Back deformable core,
3 – Two intermediate plates,
4 – Progressive deformable core,
5 – Front deformable core,

6 – Contact plate,
7 – Outer cladding,
8 – Blind rivets,
9 – Epoxy resin.

The first 250 mm deep crushing strength area has a constant crush load. The second 450 mm deep progressive crushing strength area has a progressive crush load. The third crushing strength area is progressive and has the same depth as the second one, but is weaker. The fourth, back crushing strength area, is 90 mm deep and keeps constant load, it is implemented to avoid bottoming out of the barrier [4]. These crushing strength areas and strength specifications represent the strength of a vehicle front structure and are shown in Figure 1.5

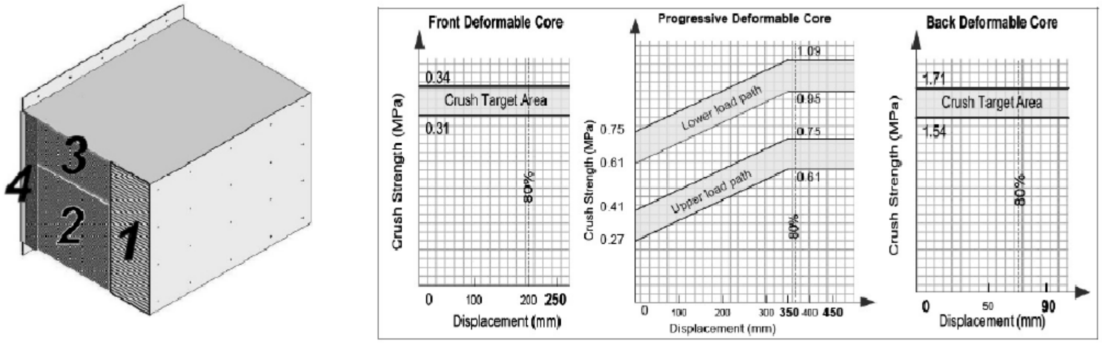

Figure 1.5 PDB cores and crush strength [4]

The PDB model should make equally severe crash test for light and heavy passenger vehicles as shown in Figure 1.6. EES – energy equivalent speed is the energy absorbed by PDB excluded from total vehicle kinetic energy before car to PDB collision. This energy is recalculated to a speed and represents the energy amount absorbed by the vehicle – the crash severity for the vehicle itself.

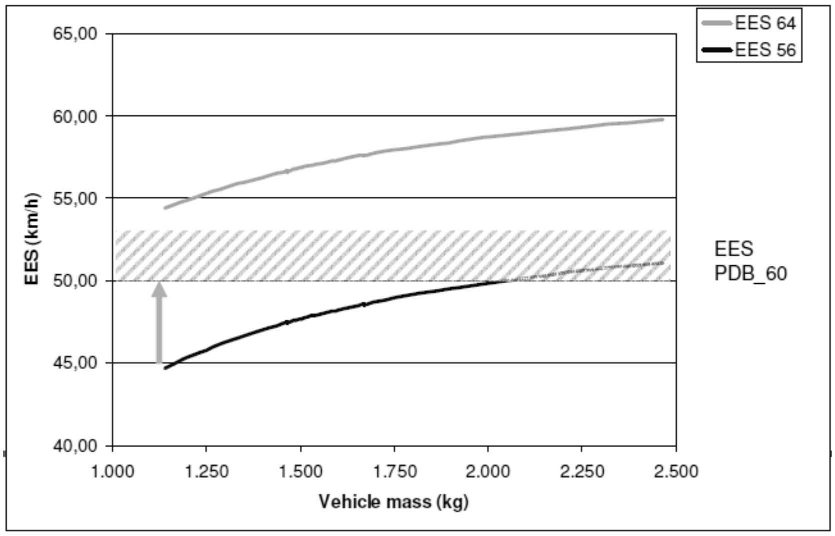

Figure 1.6 EES with different vehicle weight configurations [5]

One of the abilities of the PDB barrier is to detect structural interaction of the vehicle. PDB structure are deformed by the frontal structures of the impacting vehicle, thus, the PDB deformation analysis gives data about the vehicle structural architecture and should thereby evaluate structural interaction.

1.4 PDB measures

PDB analysis was the most important part of the project. The PDB structure is deformed during crash by a vehicle, the deformation amount and variation of the barrier front surface is analyzed as the distribution of the barrier deformation is affected by the front end structure of the vehicle.

The latest PDB assessment criteria was developed by FIMCAR. A front end of a vehicle has three different stiffness areas vertically: from underneath to lower rails, from lower rails to upper rails, above upper rails (Figure 1.1). For this reason, to analyze the crushed PDB model, the front surface was divided to 3 vertical areas (Lower, Middle and Upper) as described in the "Off-set Test Procedure" [5] presentation at FIMCAR workshop January 19th 2011 (Figure 1.7). An example of a PDB deformation pattern is shown in Figure 1.8.

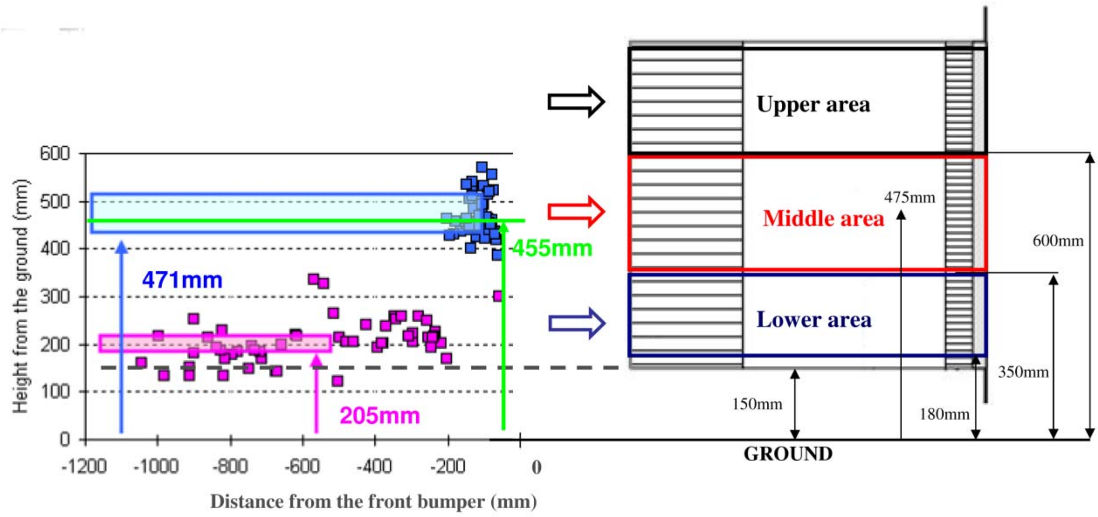

Figure 1.7 Average position of lower and subframe issue from VC-COMPAT WP15 (left) and consideration of three vertical areas (Right)

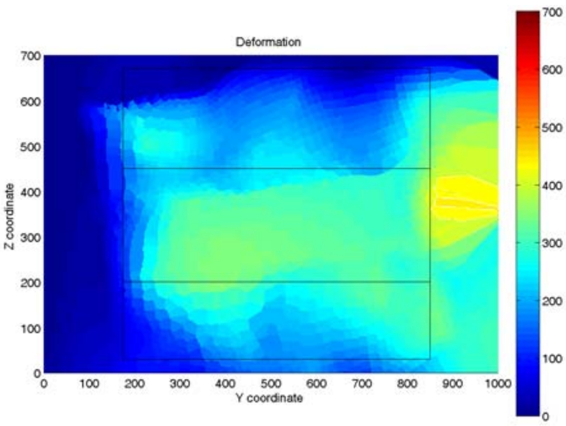

Figure 1.8 A sample PDB deformation

The PDB deformation caused by a vehicle is scored by longitudinal deformation criteria in these vertical areas, Figure 1.9.

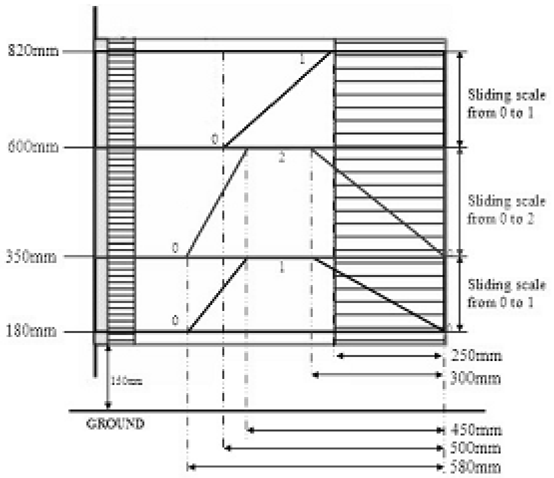

Figure 1.9 Longitudinal deformation criteria limits [5]

Deformation of the PDB was measured with different methods. Percentiles, maximum, minimum, mean and most common value of the deformation measured from the crushed PDB face were determined for analyzing the compatibility criteria. The aim was to have the amount of deformation of the PDB in each area, independent of the shape of the deformations and irregularities in the PDB crushed face.

A homogeneity criteria [5] is also proposed. Homogeneity is defined as the quality of deformed surface being uniform. If the surface is smooth, it will be considered as homogenous, if the surface is rough, it will be considered as inhomogeneous. Homogeneity of the crushed PDB surface was always the point of interest, because the aim of replacing the current ODB barrier to PDB was to detect the structural interaction of the vehicle and PDB is supposed to detect it. There were proposals for how evaluate the homogeneity of the PDB surface, but some are not used anymore and there are controversies about some of them.

A candidate to assess homogeneity is using total variations which is a mathematical concept used to distinguish between the homogenous and inhomogeneous surfaces. Total variation shows the deformation variations of each cell to its neighbor. The sum of all of the deformation variations in the PDB surface could evaluate the homogeneity of the deformations. A surface could be called homogenous when it is more similar to a flat surface than a wavy surface.

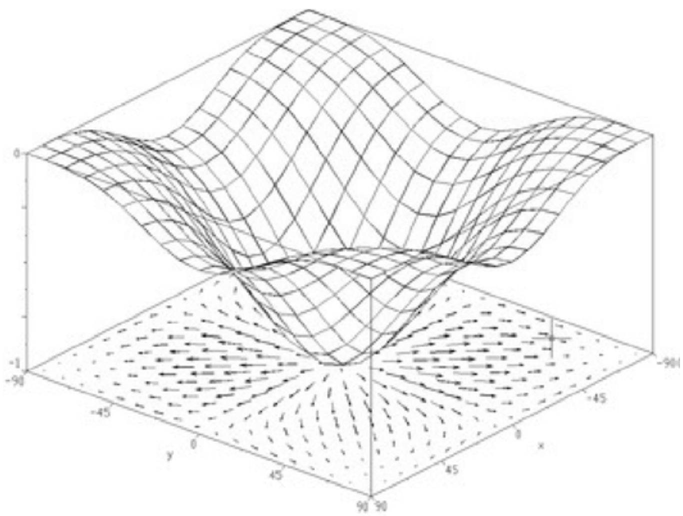

Figure 1.10 Visualization of the variations in a surface [6]

1.5 Some previous analysis have been done on the PDB model by considering the whole surface of the PDB, but that caused the mixing the interaction of the front vehicle structures in the different vertical levels [7]. Literature review

A review of the subject of vehicle crash compatibility and PDB assessment has been performed. The study was focused on exploring the research on physical tests and FE simulations. Physical tests were more reliable than the simulations because they were based on the real models and simulations had more variables and analysis data. There were mainly five resources, EEVC WG15 (Enhanced European Vehicle-safety Committee Working Group 15) [8], VC-COMPAT (Supported by European Union) [3], ACEA-EUCAR [9], NHTSA (National Highway Transportation Safety Administration) in US and DSCR (Directorate for Road Traffic and Safety) in France [10] and Nissan Motor Company [11].

During several projects at Chalmers, the crash compatibility of the vehicles was investigated with FE simulations with different crash scenarios. Avramov and Rachid [12] performed extensive car to car crash simulations with different impact angles and vertical and horizontal overlaps. Park, et al. [13] conducted simulations of car to car and car to rigid barrier. Vehicle models with different sub-frame lengths were used to evaluate the different vehicle front structure in the vehicle crash compatibility. Wu and Chhim [14] modified and introduced extra load paths in the front structure of the vehicle and performed crash simulation scenarios for evaluating the idea. The aim of all of the above projects was to investigate the crash compatibility of the vehicles in different configurations of the position and structure interaction which would cover more real life accident situations.

PDB is a new barrier proposed by France to be used instead of the current ODB barrier in Regulation No. 94 [4] as an update for frontal impact legislations. The criteria for assessing the crash compatibility of cars described by Delannoy, et al. [15].The EEVC WG15 members performed research project [16] to analyze and improve the car crash compatibility and frontal impact. Two approaches for assessing the crash compatibility were evaluated by the partners of the project, using FWDB and ODB test together or FWRB and PDB test together. Several physical tests and FE simulations were performed to evaluate the assessment approaches.

Physical crash tests been performed for evaluating the PDB abilities for assessing the crash compatibility. Meyerson et al. [17] conducted several car-to-PDB and car-to-car crash tests. Delannoy et al. [18] performed crash test comparisons of the ODB and the PDB barriers in crash compatibility and self protection. The ability of barriers has been discussed in comparison. They concluded that even with the lower generated deceleration of the PDB barrier; the test procedure could represent the real world accident because intrusion and acceleration is combined in the test. Tatsu et al. [11] from Nissan motor of Japan, performed several crash test for comparing the ODB and PDB barriers with different types of vehicles. The mentioned researches investigated the performance of the PDB barrier with physical tests for crash compatibility evaluation using PDB deformation, intrusion and dummy injury measures.

Park et al. [7] conducted FE simulation studies of the PDB with 5 NCAC vehicle models. The proposed criterion for crash compatibility by Delannoy [15] was applied to the results of the simulations to evaluate the performance of the criteria for different types of vehicles. FE simulations were performed by the German industry (VW) for criticizing the PDB [16] by making the main load path of the vehicle rigid. The research showed that the PDB would absorb more energy if the vehicle's front structure becomes more rigid. The French industry (PSA) responded to the criticism by simulation studies. They showed that it is not a proper strategy to use the energy absorption capacity of the PDB because it would decrease the self protection and increase the mass of the vehicle.

The literature review showed there were several positive results to improve and assess the crash compatibility of cars and evaluation of the controversy methods. The research used physical tests and FE simulations. The PDB barrier is a candidate for revising the legislation. Based on the physical tests and simulations, using PDB in the legislation would be beneficial if an appropriate and validated evaluation method come in the legislation also. Lack of a proper criteria for assessing the crash compatibility of cars with the help of the PDB barrier, led us to conduct FE simulation of a vehicle with different sub-frame configurations and evaluate the results with a new proposed crash compatibility criteria.

1.6 Objective

The objective of the project is to investigate the abilities of the PDB barrier for distinguish front end structure performance of different vehicles through the crash test. Also, the ability of Car to PDB results should be evaluated as a method to test both self protection and partner protection in one test. For achieving this goal, car to car and car to PDB crash simulation scenarios were performed. The car models had different sub-frame configurations to reveal the sensitivity of the PDB to different structure interactions. The comparison of measurements (acceleration pulse, deformation modes, and firewall intrusions) between car-to-car and car-to-PDB crash simulations would show how PDB could assess the crash compatibility.

A criterion for evaluation of the vehicle crash compatibility by using the PDB barrier is needed to be applied on the results. It should show how the different structural interactions could be examined by the PDB barrier with an organized procedure.

1.7 Limitations

The PDB FE model provided by FIMCAR was a simplified model. Solid elements were used for modeling the honeycomb layers in the PDB model instead of the shell type, for decreasing the simulation time.

The vehicle model used in the project did not have any physical crash test to the PDB barrier. Thus, the validation of the crash simulations of the vehicle model to the PDB model was not possible. Other physical PDB validation methods used instead, for example the tubular impactor test which is explained in the Appendix A. PDB Model Validation. The vehicle model was validated to the frontal physical US NCAP test and it was mentioned that the model could be used for all impact scenarios.

The PDB performance and ability to detect structural interaction of the front structures of the vehicle were investigated, but development and improvement of the PDB was not within scope of the project.

The project investigation has been done for analyzing just the front structures of the vehicle, because PDB is supposed to evaluate the interaction of the frontal structures.

The crash dummies were not used because the vehicle to the PDB structural interaction and the car body performance were more the focus and using the dummy in the crash simulation would add to the complexity.

2 Methodology

The methodology of the project is described in this chapter. The FE model of the vehicle and PDB are also explained.

2.1 FE models

There were two types of models used in this project, finite element models of vehicle and progressive deformable barrier (PDB). FE models are described in this section.

2.1.1 Vehicle model

A Ford Taurus 2001 FE model was selected, because it can represent a European mid-size vehicle and the model is available on the web site of the National Crash Analysis Center (NCAC). The model contains 778 parts and is divided to 1.057 million elements; it is shown in Figure 2.1 [6].

Figure 2.1 Ford Taurus FE model

The NCAC model was changed to a simplified version developed at Chalmers University of Technology (by Rachid, Ebbinger, Park, Avramov, Krusper) Figure 2.4. Less time was needed for running crash simulation with the simplified Ford Taurus.

2.1.2 Vehicle model modifications

An extra beam was introduced into the firewall of the simplified Ford Taurus model (Figure 2.2). This modification stiffened vehicle's crash response, because the motion of the longitudinals is restricted upwards and force is transferred to the A-pillars and sills instead of the firewall.

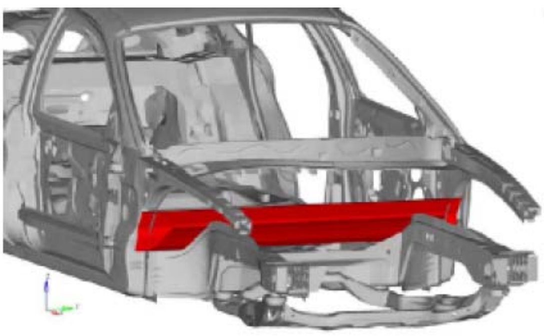

Figure 2.2 Extra beam in the firewall of the Taurus model [13]

The crash pulse of the simplified model represents US-NCAP crash pulse of the modified vehicle models are shown in Figure 2.3. The figure shows the corridor of the acceleration pulse of midsize vehicles in US-NCAP test (56 km/h to the rigid barrier). Taurus_Henrik and Taurus_RA were two other modifications of the Taurus model during previous research at Chalmers and Taurus_CK is the Taurus model that has been used in the current research.

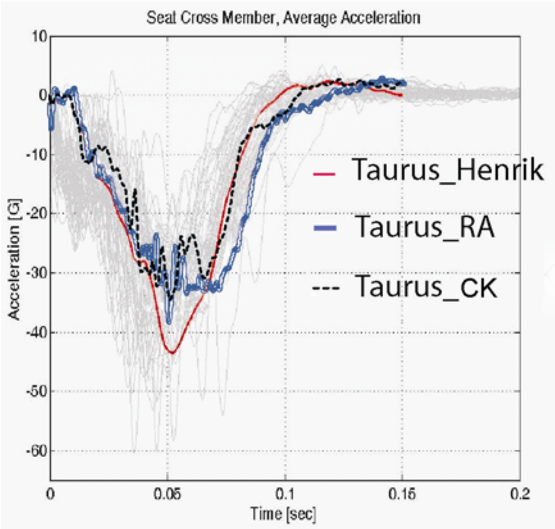

Figure 2.3 US-NCAP crash pulses

The low priority parts like front bumper cover and hood were excluded from the front end of the model in the simplified model thus this model has more exposed frontal structures for interacting with PDB model. All components from the rear end to the B-Pillars were made rigid. The simplified Ford Taurus is shown in the Figure 2.4.

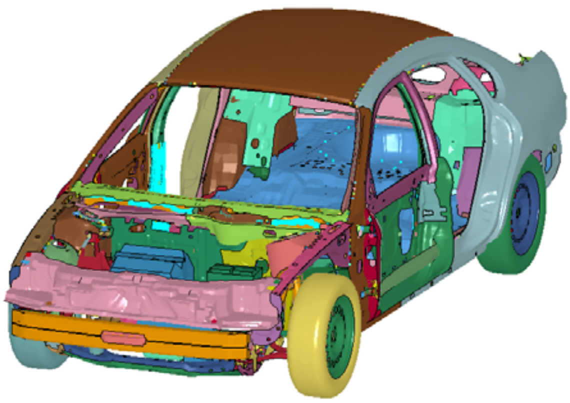

Figure 2.4 Simplified Chalmers Ford Taurus

The weight of the simplified vehicle is around 1390 kg. A failure criterion for the sub-frame mountings to the compartment floors was defined. The sub-frame would be released when load peak reaches 50 kN [13].

Sub-frame Configurations

The Ford Taurus sub-frame carries the engine and lower frontal suspension mounting points as shown in Figure 2.5 (1). Four different sub-frame configurations were used: shortened (2), basic (3), extended (4) and without sub-frame (5) as shown in Figure

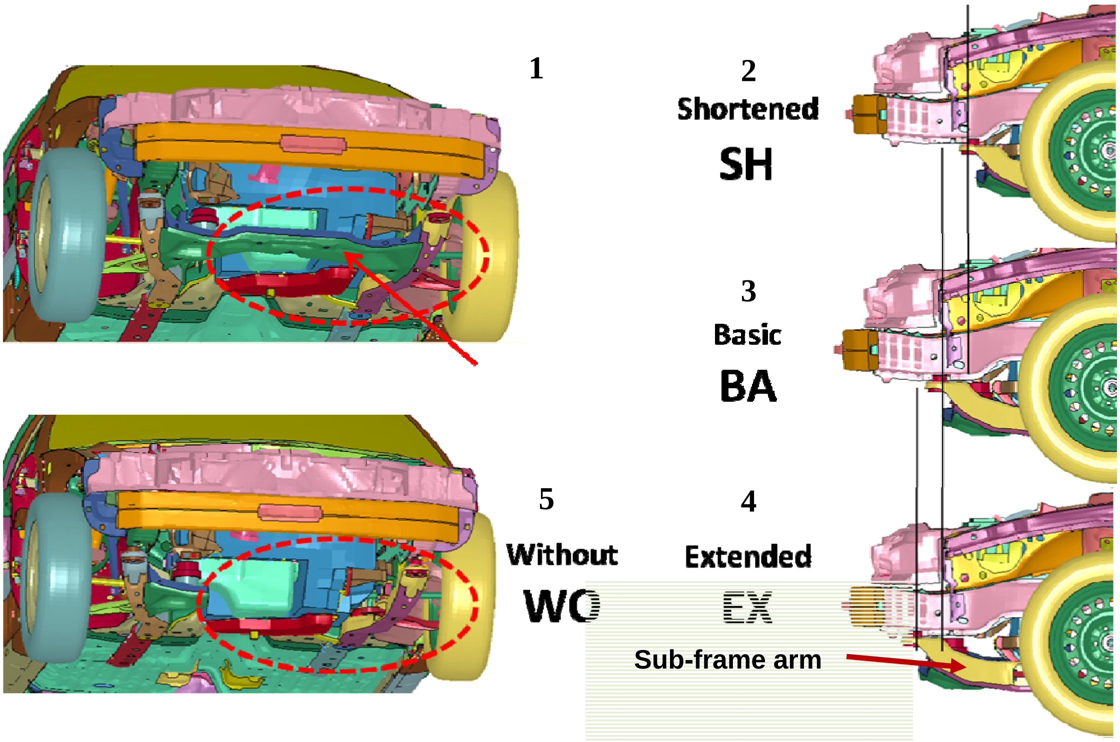

Figure 2.5 Different Taurus sub-frame configurations

2.1.3 PDB model

In this section the PDB model is described. This model is used for car to barrier crash tests simulations. The FE model of PDB is shown in Figure 2.6 was developed by General Motors Europe and released on February 2011. Solid elements used instead of shell elements for defining the honeycomb cores in this PDB model.

The MAT_MODIFIED_HONEYCOMB material model is used for aluminum crushable honeycomb foam material with anisotropic behavior [19]. Thus aluminum honeycomb cores are modeled as solid elements with aluminum honeycomb solid material.

CONTACT_AUTOMATIC_SINGLE_SURFACE_ID card, the interaction, recommended by FE of PDB developer, between disjoint parts, is used during simulations.

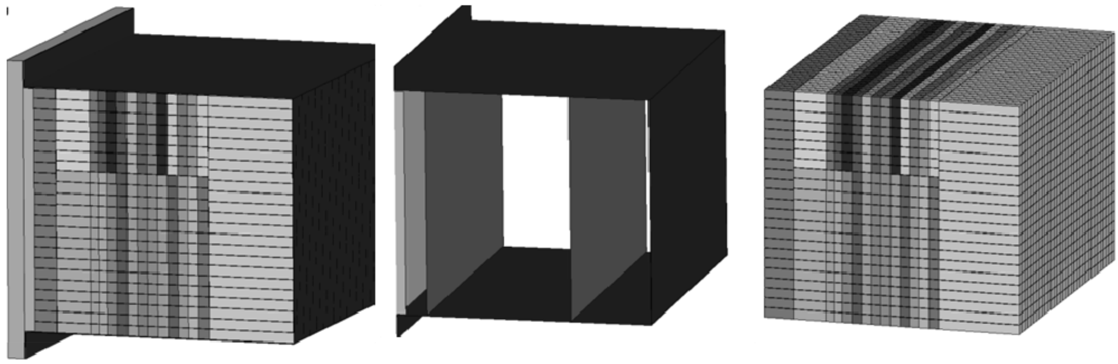

Figure 2.6 The FE model of the PDB

2.2 Simulation matrix

Dynamic crash analysis is necessary for better understanding of the crash compatibility of the vehicles. In order to investigate the effect of the different sub-frame configurations in crash compatibility and ability of the PDB barrier for representing that effect, a simulation test matrix arranged in Table 2.1. The bullet vehicle which is the vehicle model with 4 sub-frame configurations would crash to the target which is either the PDB model or the vehicle with the basic sub-frame configuration.

Car to PDB simulations have been conducted with 60 km/h and 50% horizontal overlap. This is the speed and overlap required by the PDB protocol by Delannoy [15]

Car to car tests have been done with the speed of 56 km/hr which is from the accident study by PENDANT [16] that showed that 85 % of all types of injuries was with the velocity of 56 km/hr. The horizontal overlap was 50% and is based on the car to PDB crash test.

Table 2.1 Simulation Matrix

Bullet	Target	Velocity(km/hr)	Abbreviated Simulation Name
SH	PDB	60	C2PDB1_SH
BA	PDB	60	C2PDB1_BA
EX	PDB	60	C2PDB1_EX
WO	PDB	60	C2PDB1_WO
SH	Basic	56	C2C_SH
BA	Basic	56	C2C_BA
EX	Basic	56	C2C_EX
WO	Basic	56	C2C_WO

2.3 Vehicle Performance measures

In this section, the measurements that have been used for the analysis in the project are described.

2.3.1 Intrusion measurements

The amount and shape of intrusions to the firewall and driver's footwell was measured for investigating self protection. The measurement points are shown in the Figure 2.7. The intrusions have been measured related to the local coordinates in the backseat of the vehicle model. Because the rear part of the vehicle was rigid and mounting the accelerometer far from the front, in the rigid area, allowed having the crash pulse of the occupant compartment recording during crash. This method of measurement allows for monitoring the progress of intrusion through the whole crash time.

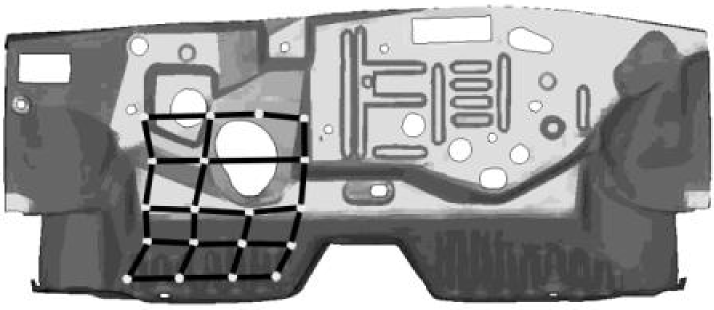

Figure 2.7 Measurement intrusion points at firewall [20]

2.3.2 Acceleration pulse

The acceleration pulse of the crash was measured from the accelerometers on both sides of the backseat. The average acceleration between the two accelerometers used for analysis. The average acceleration multiplied by the mass of the vehicle model was used as the crash force. This acceleration pulse was useful for comparison of car to PDB with car to car and analyzing the behavior of PDB.

2.3.3 Deformation modes

The behavior of deformation of the front structure and other structures of the vehicle model during different crashes (shown in Table 2.1) was analyzed. This analysis of the deformed bumper beams shape helped to assess the ability of the PDB to represent the interaction of another car in the crash.

3 Results and discussion

In this chapter, the results of the crash simulations are presented and discussed. Car-to-car simulations are described in the beginning and Car-to-PDB simulations afterwards. Some issues about the PDB model would be described and some modifications to the PDB model in order to fix the issues are proposed and simulated.

3.1 Car to car

The investigation of the C2C crash simulations shows different front structure interactions. These interactions are presented in Figure 3.1. The EX model (Taurus with extended sub-frame) sub-frame structure starts to interact earlier during the collision, for this reason, the deformation is higher for the sub-frame arm. The BA (Taurus with basic sub-frame) and SH (Taurus with shortened sub-frame) versions have less sub-frame arm deformation, but as could be seen in Figure 3.20 the bumper beam is deformed more in these two cases in comparison to EX version. WO model (Taurus without a sub-frame) does not have sub-frame interactions, thus the bumper beam deformation was the biggest.

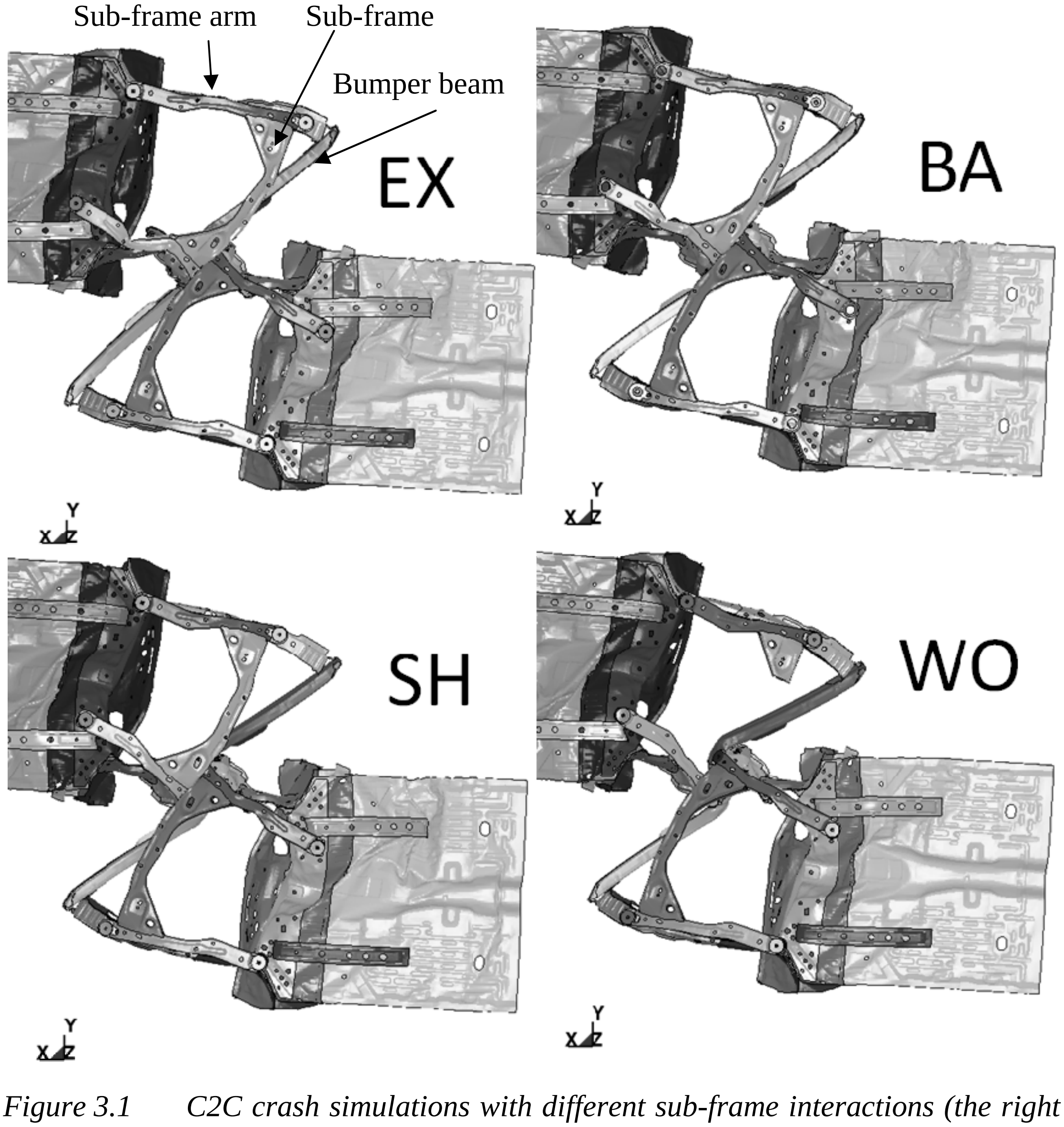

Figure 3.1 C2C crash simulations with different sub-frame interactions (the right vehicles have BA sub-frame configuration)

Figure 3.2 shows the deformation of the bumper beam and longitudinals. The bumper beam in the EX model has the smallest fork effect amount and in the WO model the biggest fork effect amount could be noticed because amount of intrusion of the longitudinal is higher into the bumper beam of the target vehicle. Because the lower load path was extended in the EX model and was loaded earlier in the crash, more energy was absorbed by the sub-frame parts and less energy absorbed by lower rails. For this reason, the EX had the smallest fork effect.

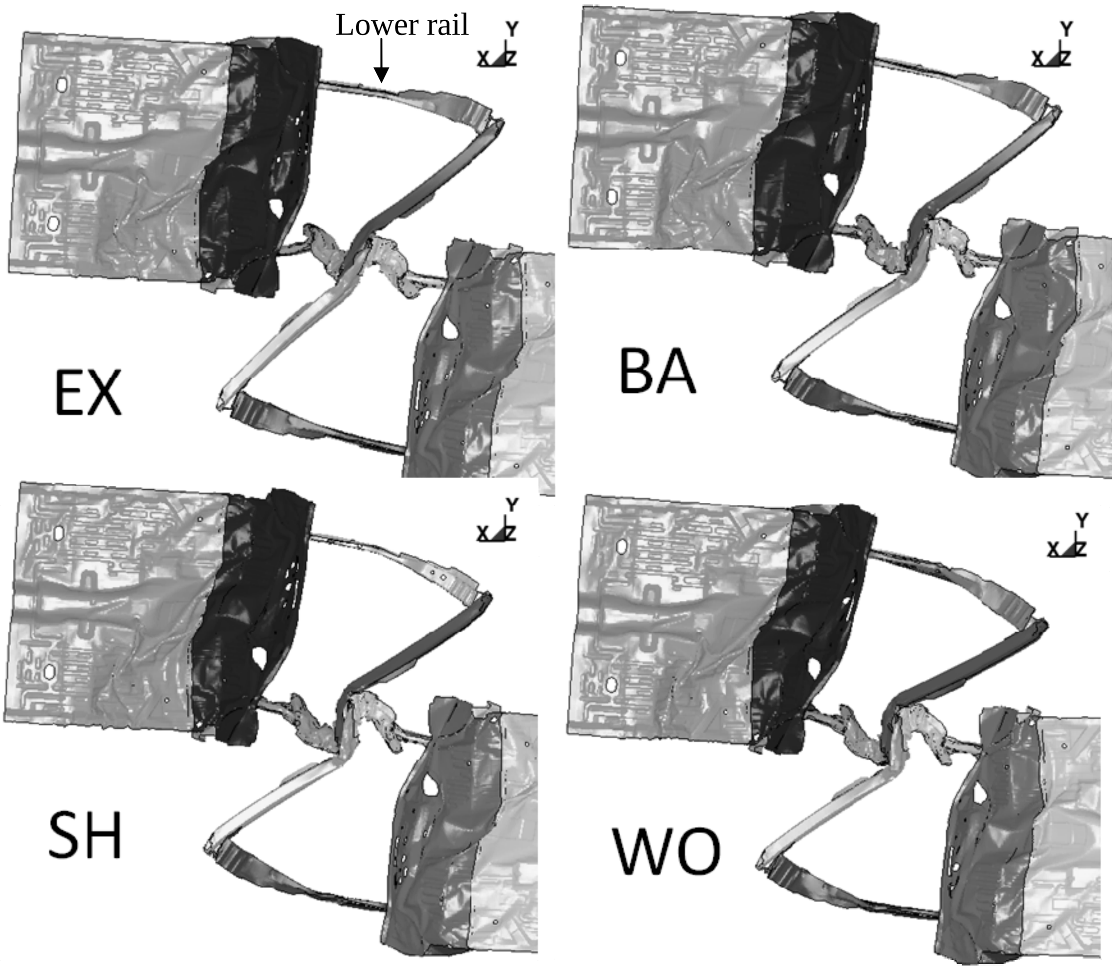

Figure 3.2 C2C crash simulations with different sub-frame interactions and hidden sub-frame (the right vehicles have BA sub-frame configuration)

Figure 3.3 shows that the amount of displacement of the vehicle is related to the length of the sub-frame. In the EX model we have the lowest amount of displacement and when the length of sub-frame is decreasing, the displacement amount of the vehicle would increase and we have the maximum displacement in the WO model. Also, we could notice that the sub-frame interaction starts between about 400-600 mm of the vehicle displacement in the Figure 3.3, marked by the circle. We can notice that the latest structure interaction is in the WO vehicle at around 560 mm. Increasing the length of sub-frame led earlier sub-frame interactions. The EX sub-frame started interacting with the other car around 100 mm earlier than SH.

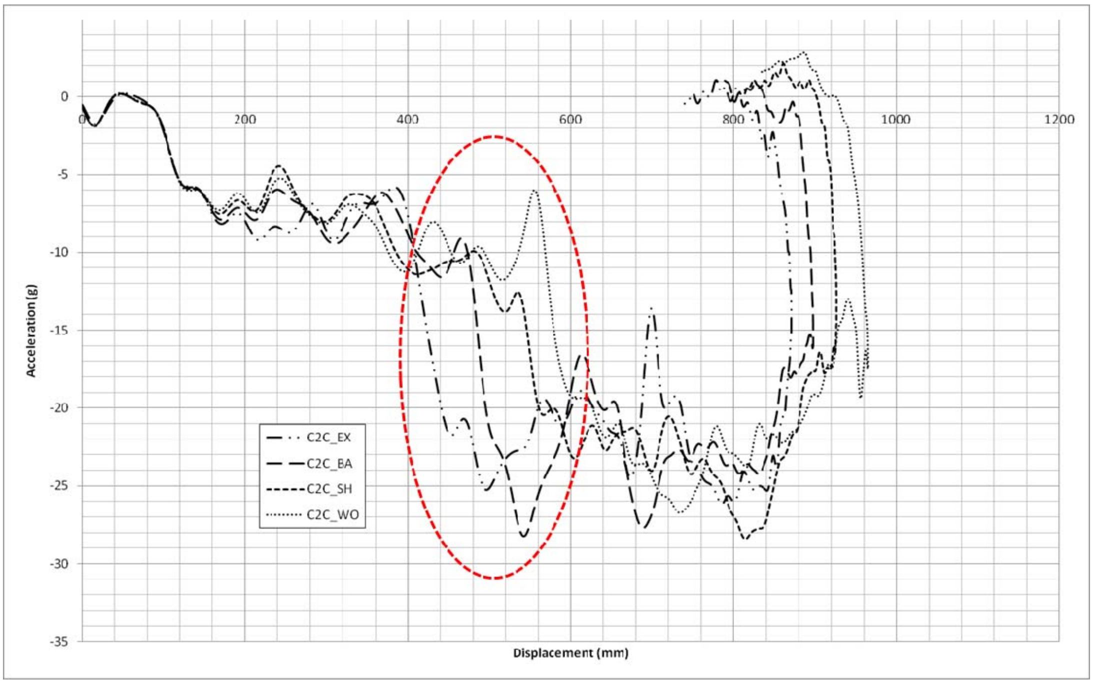

Figure 3.3 Acceleration comparison between car-to-car crash simulations with different subframe configurations

Figure 3.4 shows the same trend as in Figure 3.3 for the bullet cars (cars with varying sub-frame configurations). The increasing length of the sub-frame caused lower intrusions to the firewall. WO had the highest intrusions, especially in the upper area. The longer sub-frame had a better self protection. The target vehicle in crash to the bullet vehicle with WO configuration showed the best self-protection (Figure 3.4 right side).

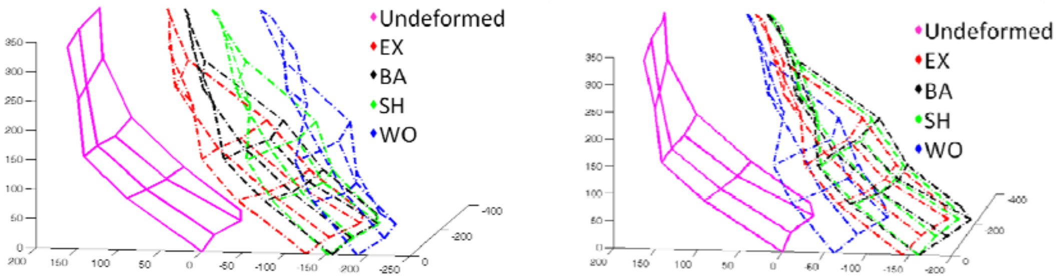

Figure 3.4 C2C firewall intrusions to the bullet cars (left) and target cars (right)

The average firewall intrusions of the target and bullet vehicles are shown in Table 3.1. The longest sub-frame configuration had the lowest average intrusion in bullet, target and total vehicles firewalls during crash. The WO had the biggest average firewall intrusion in the bullet vehicle as well the average difference between bullet and target vehicles.

Table 3.1 Average firewall intrusion

Sub-frame	Average bullet firewall intrusion, mm	Average target firewall intrusion, mm	Total firewall intrusion (bullet + target), mm	Difference in firewall intrusion [bullet – target], mm
BA	202	179	380	23
SH	183	177	360	6
EX	134	161	294	27
WO	230	122	353	108

Discussion

The crash simulations of the C2C were evaluated and described in this section. The deformation modes, acceleration pulses and amount of the firewall intrusion have been compared. The results showed that the longer sub-frame had less fork effect (Figure 3.1 and Figure 3.2), as well as overall vehicle displacement (Figure 3.3) and firewall intrusion (Figure 3.4). Furthermore, the structural interaction of the vehicles started for smaller displacements (Figure 3.3). This trend should be compared with the car to PDB crash test results. The SH, BA and EX had low average difference in firewall intrusion, the WO had the biggest average difference in firewall intrusion between the bullet and target vehicle, so it was the least desirable configuration. The EX configuration had the lowest average total firewall intrusion. The EX case had the best performance in self, partner and total average firewall intrusion performance.

3.2 Car to standard PDB model

Car to standard PDB crash test simulations were conducted with four different sub-frame configurations. Figure 3.5 shows the front structure interactions with PDB from bottom view. In the upper row the pictures represent sub-frame interaction (outer cladding sheet is removed from view for better visualization of honeycomb layers deformation). The lower row of pictures shows the same bumper cross beam deformation (PDB is removed from view for better visualization).

In all cases the sub-frame arm had interactions with the PDB face, while the sub-frame crossbeam did not interact with the front honeycomb layer and slid under it. The sub-frame then started to interact with the middle honeycomb layer. For this reason, the sub-frame interaction area in PDB was unreasonable. The bumper cross beam had a similar amount and shape of deformation; we can see this trend in Figure 3.20, Section 3.4. This trend occurred because the sub-frame crossbeam did not interact with PDB. Thus the different sub-frame configurations did not influence the crossbeam deformation and the bumper cross beam was loaded by similar loads through the collisions.

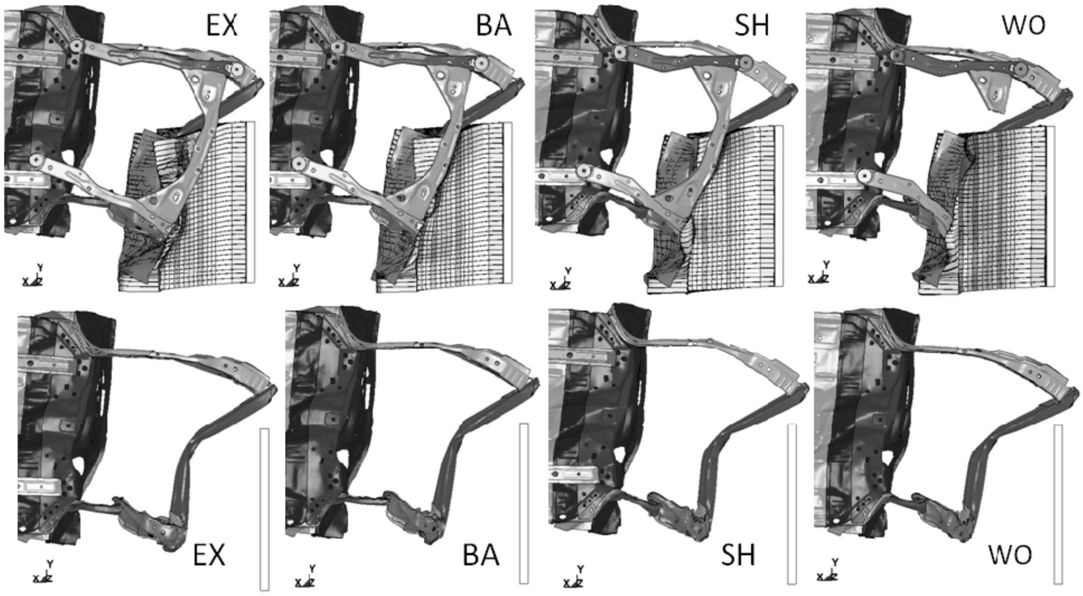

Figure 3.5 Front structure deformation during collision with standard PDB

Figure 3.6 shows deformation of the PDB with four different vehicle configurations. The investigation areas of the PDB are shown by the black lines (as described in the section 1.4). The lower rails and front bumper beam had interaction with the middle area of standard PDB, while the sub-frame structure interacted with the lower area of the PDB.

The sub-frame cross beam of the EX model slid under the front and middle honeycomb layer. As a result of the sub-frame sliding under the barrier, the lower area of PDB was deformed upwards, but not in the longitudinal direction. The effect of the sub-frame interaction could not be noticed in the lower area of the PDB deformation (Figure 3.5 and Figure 3.6 EX). The WO model did not have the interaction with the lower are of PDB, because of the absence of the sub-frame cross beam. The BA and EX sub-frame had a small interaction with the middle honeycomb layer which could be noticed in the Figure 3.5 and Figure 3.6.

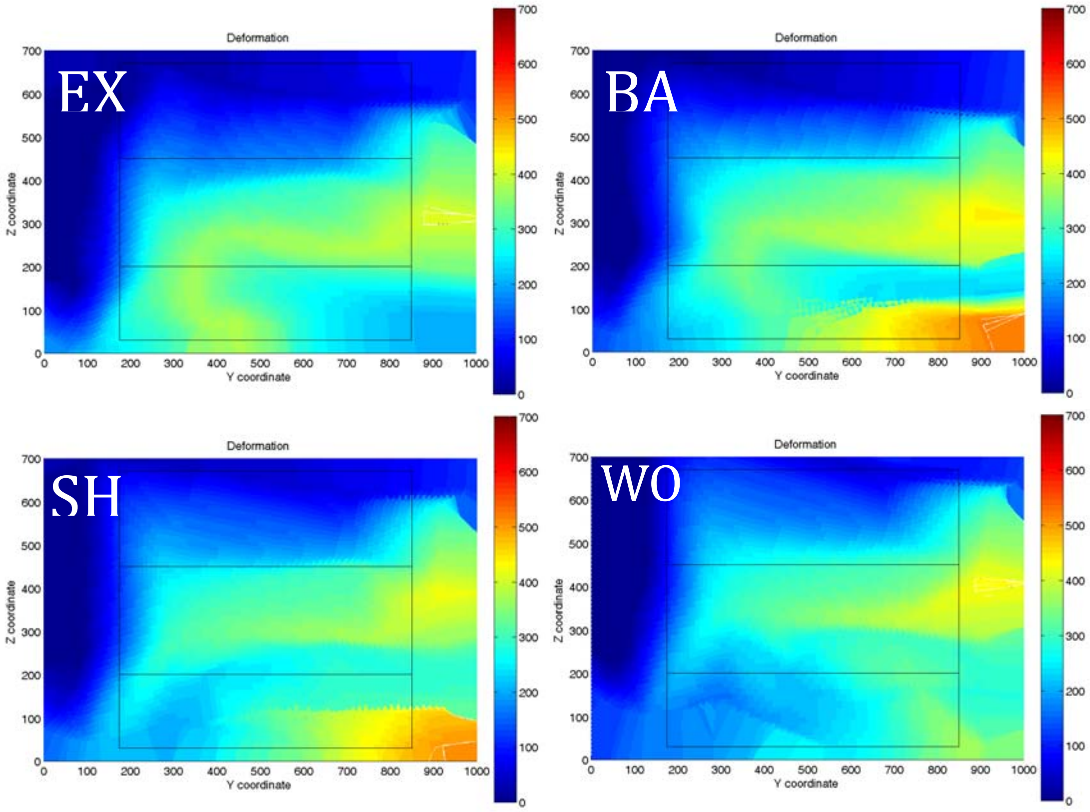

Figure 3.6 Standard PDB deformation comparison

Figure 3.8 shows the 99th percentile of the deformation of the three different areas in standard PDB. The amount of 99th percentile for the middle area was about the same for the different sub-frame configurations. The 99th percentile increased for the lower area and decreased for upper area of the PDB by increasing the length of the sub-frame, because the longer sub-frame absorbed more energy and caused more deformation in the lower area. The lower area of the EX model had the same amount of 99th percentile as the WO model and that was because of the insufficient interaction of the sub-frame cross beam with the lower area of the PDB. The 99th percentile was smaller for the longer sub-frame configuration in the upper area, because the longer sub-frame arm prevented lower rails to be pulled up, while the WO model did not have the stabilizing effect of the sub-frame cross beam (Figure 3.7).

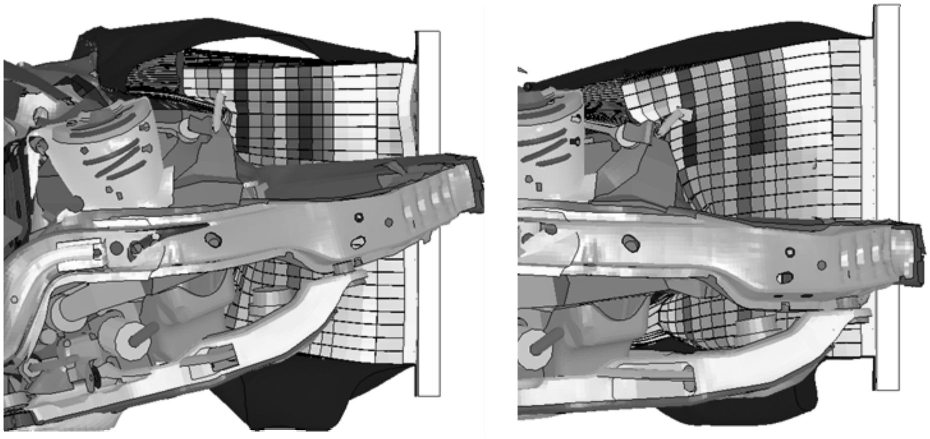

Figure 3.7 Deformation comparison of the lower rails (the left view-WO, the right-EX sub-frame configuration)

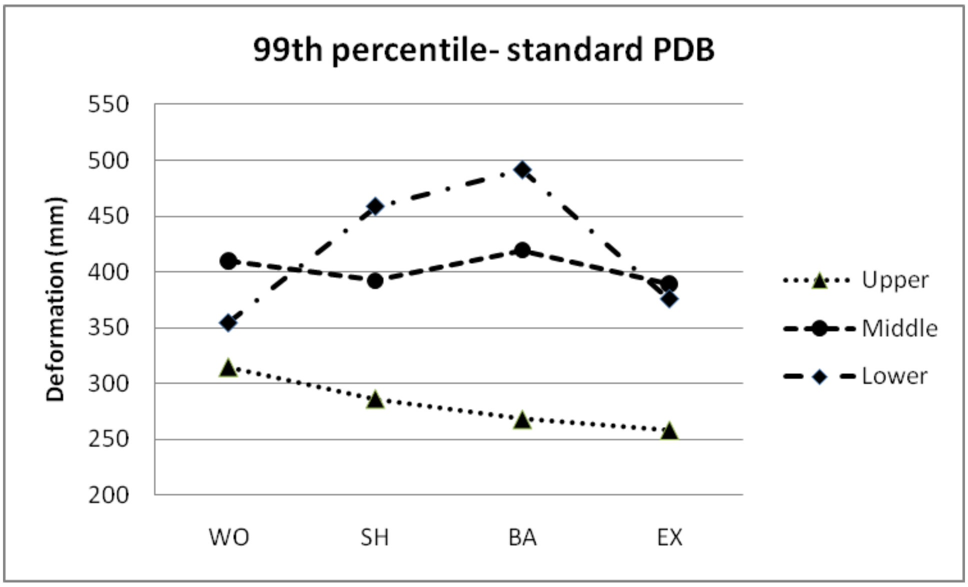

Figure 3.8 99th percentile deformation comparison of PDB areas

Figure 3.9 shows the crash acceleration for the different vehicle configurations versus displacement. The elongation of the sub-frame caused smaller overall displacement of the vehicle. The trend, that the EX configuration had the smallest and the WO the biggest overall displacement, is noticeable. This trend for the car to PDB crash test (Figure 3.9) was similar to the C2C cases (Figure 3.3).

The sub-frame interaction area in the beginning of the crash (from about 400 mm of vehicle displacement, in Figure 3.3 and Figure 3.9 marked by a circle) was not as distinguished as the C2C cases, but the overall trend was the same through the different sub-frame configurations. The longer sub-frame had earlier interaction with PDB.

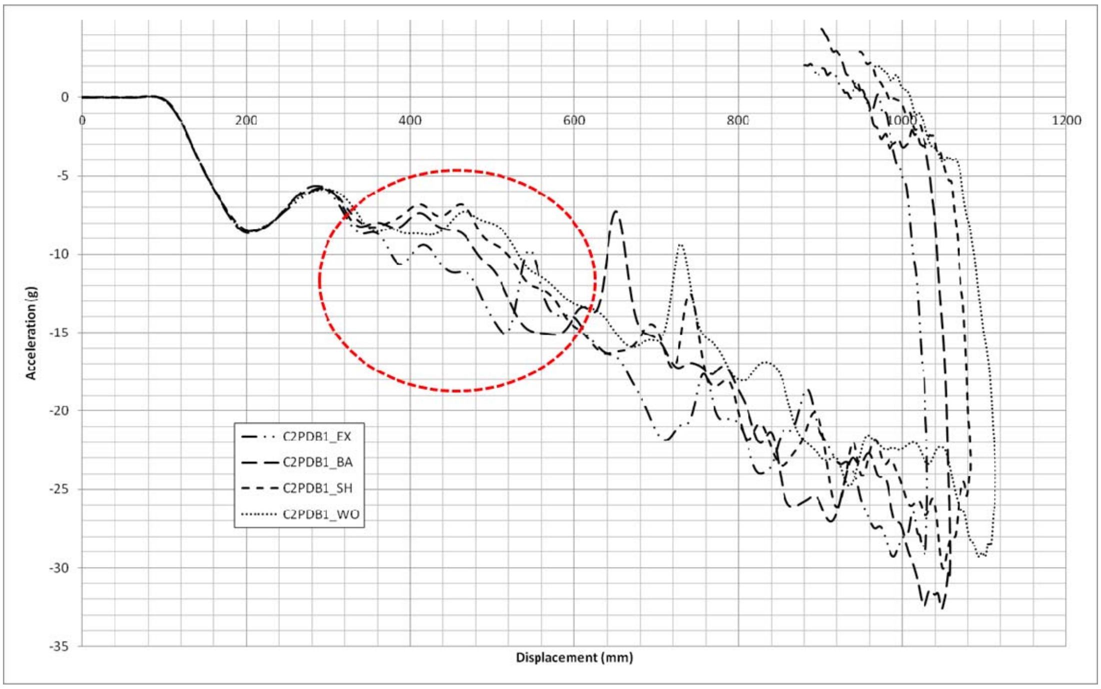

Figure 3.9 Acceleration comparison between of the car to standard PDB model crash simulations with different sub-frame configurations

Figure 3.10 represents the firewall intrusion of the vehicles with different sub-frame configurations after the collision to the PDB. The overall amount of the firewall intrusion is smaller compared to the C2C cases (Figure 3.4). The C2C cases show the clear trend of the intrusions by increasing the length of sub-frames, while the car to PDB impacts do not show the distinguished amount of the firewall intrusions.

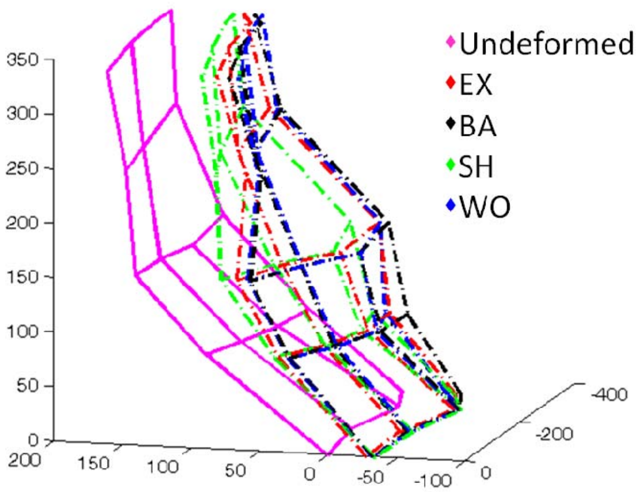

Figure 3.10 Car to PDB firewall intrusions

Discussion

In this section crash tests of the car to PDB were described. The PDB model had two issues. First, the interaction of the PDB and sub-frame parts was not proper. In the beginning of the crash the lower edge of the PDB was lifted up by the outer cladding sheet. For this reason, the sub-frame did not interact with the front honeycomb and slid under it. Also, the SH sub-frame configuration had the better interaction with the middle honeycomb layers than the EX model, because the lower honeycomb layers of the SH model were raised up less than in the EX case.

The thick outer cladding sheet and the contact plate prevented detection of the vehicle structural interactions properly. One of the purposes of using the PDB instead of the ODB barrier is to detect structural interaction. The covering surfaces of the current PDB distribute the forces over the honeycomb and local deformations are prevented. As a result, a few modifications will be applied to the current PDB model. These modifications would be trials to show, how the above described issues could be solved.

The firewall intrusions of the C2PDB were not similar to neither bullet neither target C2C case, because of the different structures of the colliding objects. The firewall intrusions of the C2C_WO (target vehicle) and C2PDB cases were similar, because the sub-frame was not loaded locally during these collisions cases.

3.3 Car to modified PDB model

The issues of the PDB model were described in the end of the previous chapter. A few modifications were applied to the current PDB model for trying to solve the described issues.

Modifications

1. **Removing the outer cladding sheet**

The thick outer cladding sheet was removed. The lower edge of the outer cladding sheet was pulling up the front honeycomb layer (Figure 3.11). For this reason it was preventing the proper interaction of the sub-frame cross beam and the front honeycomb layer. The sub-frame cross beam was sliding under the front honeycomb layer. The outer cladding sheet was removed to prevent the pulling up effect of the honeycomb.

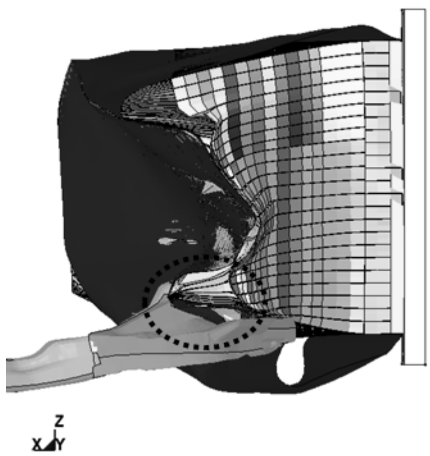

Figure 3.11 The outer cladding sheet pulling up effect

2. **Modifying the contact plate**

The contact plate and the outer cladding sheet were collaborating to distribute the forces of the impacting structures; the contact plate was useful for scanning the PDB deformation. For this reason, the mechanical properties of the contact plate were changed to represent a neutral plate. The Young's modulus and yield strength of the contact plate were decreased by 1000 times. As a result, the contact plate had no influence on the deformation behavior and just was used for scanning the PDB deformation.

3. **Modifying the epoxy resin**

Figure 3.12 shows the insufficient strength of epoxy resin. For this reason, the mechanical properties of the epoxy resin used between the plates and the honeycombs in the PDB model were investigated. Epoxy resin H9440 is recommended by the French proposal of PDB [4] and based on the datasheet from the Axson Company, the epoxy resin has 21 MPa of shear strength and 30 MPa of tensile strength. But in some areas of the PDB model and specially in the front layers the strength of 8 kPa was used for the epoxy resin (between contact plate and front deformable core and between intermediate plate and front deformable core), therefore the described epoxy strength used in the PDB model was changed from 8 kPa to 21 MPa.

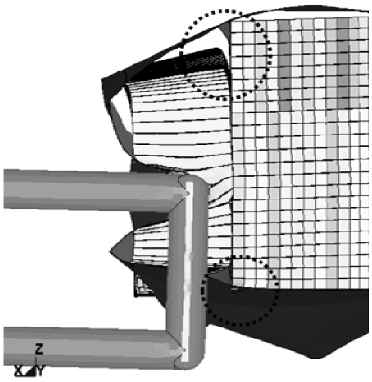

Figure 3.12 Epoxy resin failure

Results of the modified PDB model

Figure 3.13 represents the front structure interaction of the Taurus with different configurations to the modified PDB. The interaction of the sub-frame could be noticed in the bottom view shown in the upper row of the picture and interactions of the lower rails of the vehicle are presented in the lower row of the picture (PDB model is removed from view for better visualization).

The sub-frame cross beam interacted as expected with the front deformable core in all crash test configurations. The sub-frame cross beam did not slide under the PDB. The interaction of the sub-frame cross beam started from the front deformable core and not from the middle deformable core like the C2PDB1 cases (Figure 3.5).

Generally, the bumper cross beam had more significant fork effect than in the C2PDB1 cases.

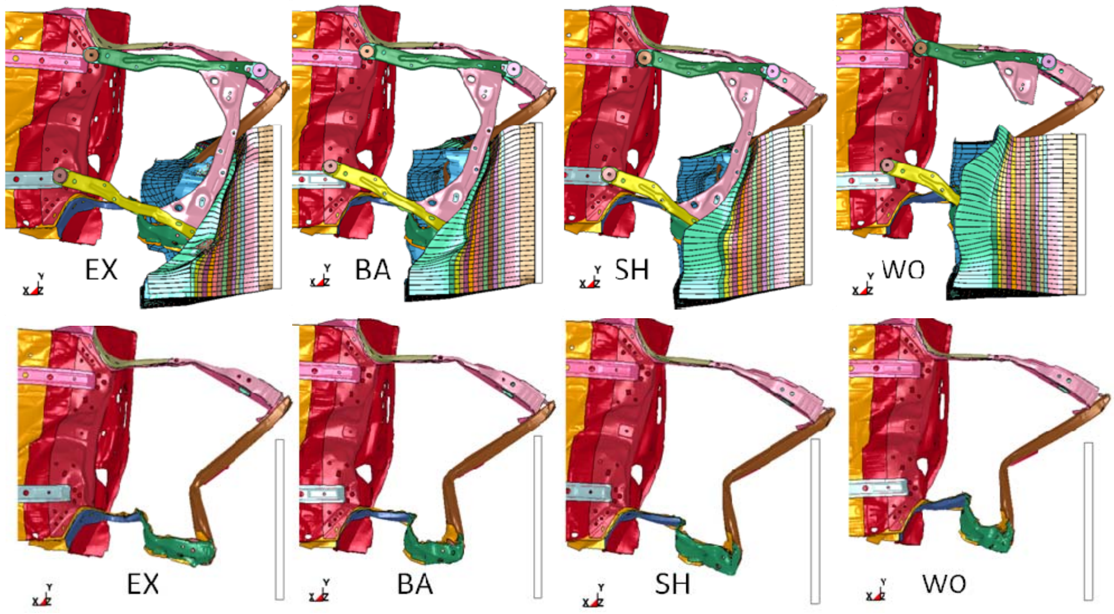

Figure 3.13 Front structure deformation during collision with modified PDB

Figure 3.14 shows the deformation of the modified PDB during the crash with different vehicle configurations. A comparison to Figure 3.6 shows that the modified PDB is able to detect more local structural interaction. The interaction of the sub-frame cross beam was better seen in the lower area of the PDB deformation. In the C2PDB1 and in the EX model (Figure 3.6), this interaction is not noticeable in the lower area and this problem is solved in the modified version of the PDB model.

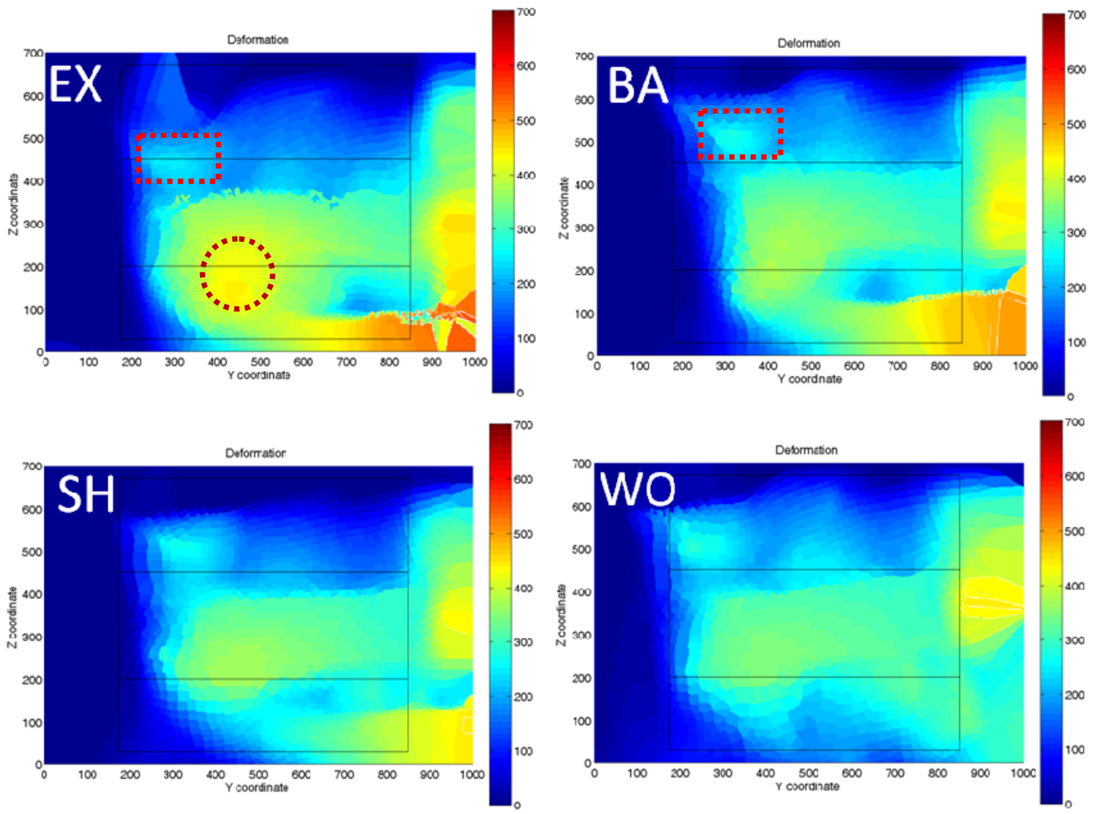

Figure 3.14 Modified PDB deformation comparison

Figure 3.15 shows the amount of 99^{th} percentile of deformation in PDB front surfaces. The deformation trend (longer sub-frame cause bigger deformation in the lower area and smaller deformation in the upper area) for the lower and the upper areas was similar to C2PDB1 cases (Figure 3.8). The EX model had around 370 mm in the standard PDB and around 510 mm of 99^{th} percentile in the lower area of the modified PDB. The 99^{th} percentile deformation increased in the lower area, because of the sufficient sub-frame and PDB interaction. As a result the modified PDB is able to detect the interaction of different sub-frame lengths in the lower area.

The 99^{th} percentile deformation increased in the middle area of the C2PDB2 EX case, because the EX lower rails were stiffened by the extended sub-frame arms and more local deformation was caused (Figure 3.14, marked by the circle). While in the C2PDB1 EX case local loads were distributed (Figure 3.6) by the cladding sheet and contact plate and stiffer structure was not detected by the standard PDB.

The 99^{th} percentile deformation increased by around 50 mm in the EX upper area compared to BA, because the modified PDB was less stable without the cladding sheet and upper outboard corner of the barrier moved down around 60 mm more in the EX than BA case. Thus, the area, marked by the square, (Figure 3.14 BA and EX) partly moved down to the middle area and 99^{th} percentile decreased in the upper area (Figure 3.15).

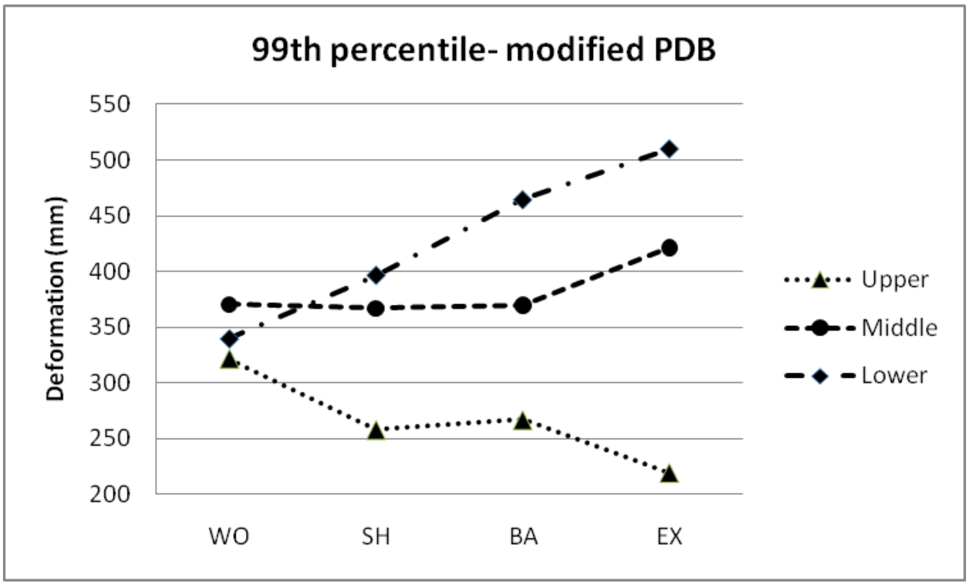

Figure 3.15 99th percentile deformation comparison of modified PDB areas

Figure 3.16 shows the acceleration pulse of the crash simulation of different vehicle configurations to the modified PDB. In this picture it could be noticed that the interaction area of the sub-frame (from about displacement of 400 mm) has more distinguished shape for the different sub-frame configurations. Generally, the vehicle with the longer sub-frame had higher acceleration at the beginning of the sub-frame interaction (from 400 mm displacement). The trend of the overall displacement was similar to the C2PDB1 (Figure 3.9) case, but more distinguished. However, the WO and SH models had the same overall displacement. The C2PDB2 acceleration trend was more distinguished and similar to the C2C (Figure 3.3) case than C2PDB1.The acceleration increases slower through C2PDB collisions compared to C2C, because the structure of PDB is more homogenous than the front of the vehicle.

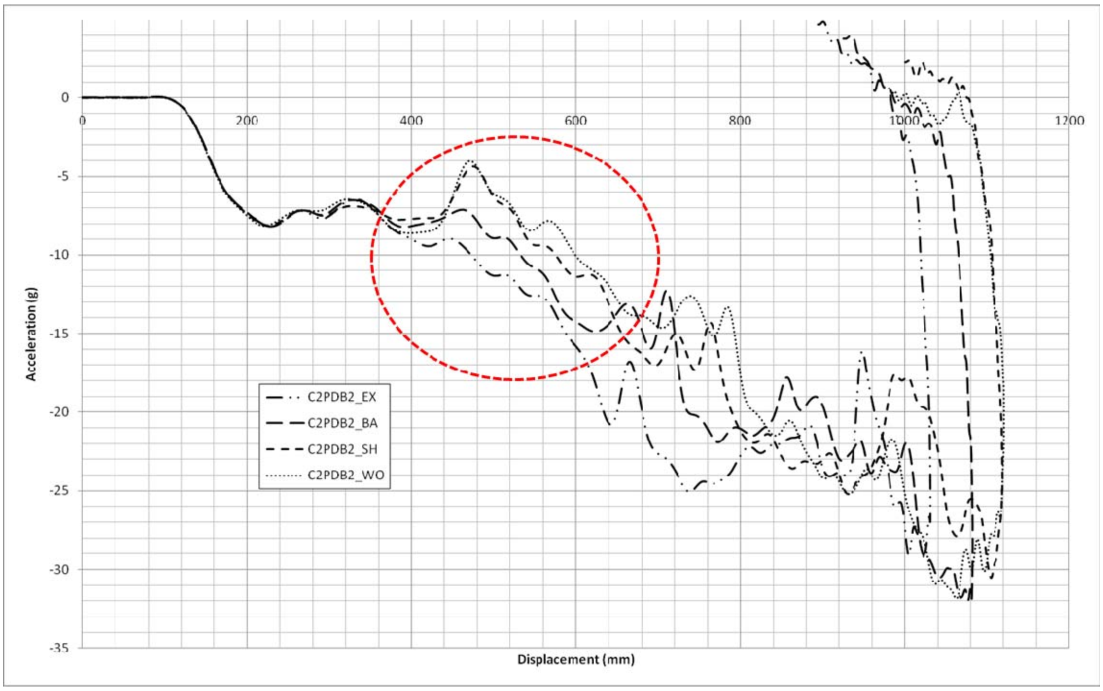

Figure 3.16 Acceleration comparison of the car to modified PDB model crash simulations with different subframe configurations

Figure 3.17 represents the firewall intrusions of the vehicle with different sub-frame configurations. The C2PDB2 firewall intrusions were more distinguished compared with the C2PDB1 case. Thus, the SH and WO sub-frame configuration were penalized more than the EX and BA models in the upper area. Though, the firewall intrusion does not have any specific trend in the lower area. Generally the overall amount of firewall intrusion increased in the C2PDB2 in comparison to C2PDB1 crash tests.

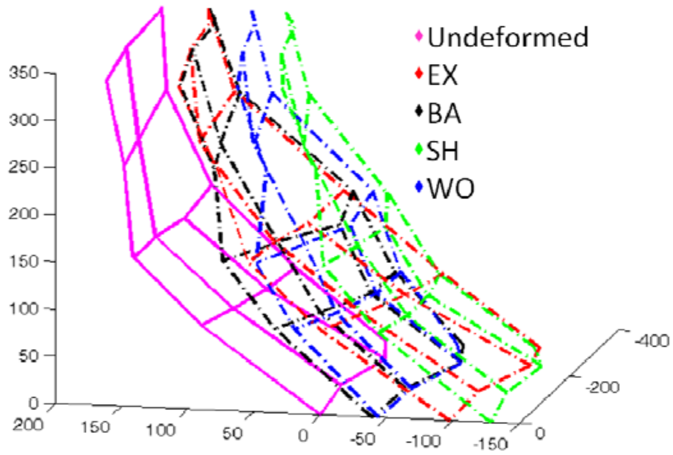

Figure 3.17 C2PDB2 firewall intrusions

Discussion

In the C2PDB1simulations the PDB had issues, described in the discussion of the section 3.2, and for this reason the FE PDB model was modified. The modifications of the PDB showed promising results. The sub-frame interaction issue was solved by

Generally, the amounts of the firewall intrusions of the C2PDB2 were bigger than the C2PDB1 and more similar to C2C cases. The trend between the different sub-frame configurations were not clear because the difference between structure interaction in the C2C and C2PDB. In the C2C cases, the front structures of the vehicles interacted locally with each other, while in the C2PDB cases, the vehicle front structure interacted to the homogenous honeycomb layers.

The acceleration pulses in C2PDB2 cases were generally similar to the C2PDB1, but the differences between the acceleration in the beginning of the crash for different sub-frame configurations were bigger for the C2PDB2 cases.

3.4 Crash test comparison

In this section the PDB ability to detect different vehicles structural interaction for crash compatibility evaluation will be compared.

PDB deformation comparison

Figure 3.18 shows the vehicle structural interaction to the PDB and modified PDB. The local structural interaction is more amplified in the modified PDB than standard PDB face. The lower structures were not detected by the standard PDB, because the front deformable core was pulled up by the outer cladding sheet. Thus, the modified PDB represented more data about the front end structure of the vehicle, for this reason the protection of the partner vehicle could be estimated better.

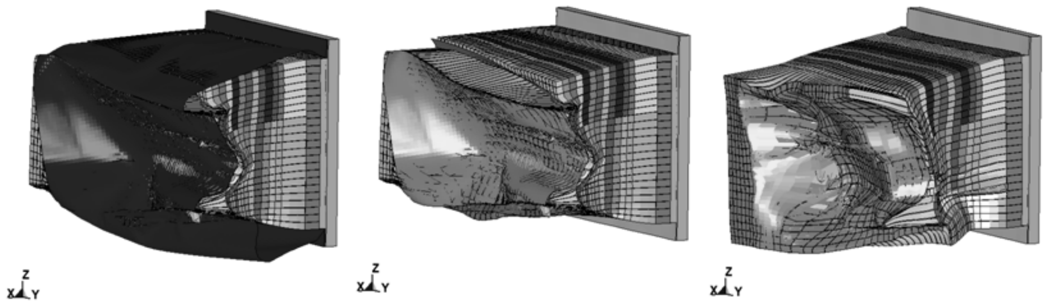

Figure 3.18 C2PDB1 and C2PDB2 deformation comparison (from the left: C2PDB1, C2PDB1 without outer cladding in the view, C2PDB2)

Figure 3.19 shows that the issue of interaction of the sub-frame cross-beam is solved in the modified PDB. The lower honeycomb layers are deformed by the sub-frame cross beam. Consequently the lower structures of the vehicle were detected properly by the modified PDB model.

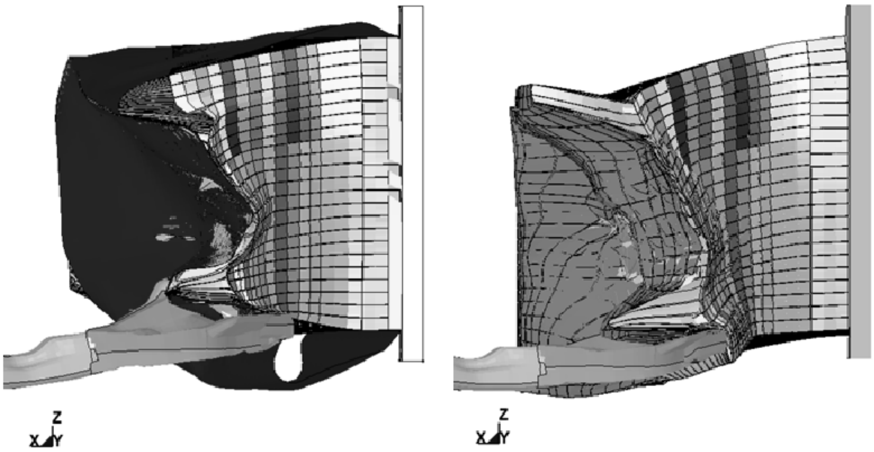

Figure 3.19 Sub-frame cross beam interaction to PDB comparison (from the left: C2PDB1, C2PDB2)

Figure 3.20 shows the shape of the front bumper beam after crash. The shape of the bumper beam deformation for all of the vehicle configurations in each case is similar. It could be noticed that the C2PDB2 cases have more similar fork effect to the C2C cases.

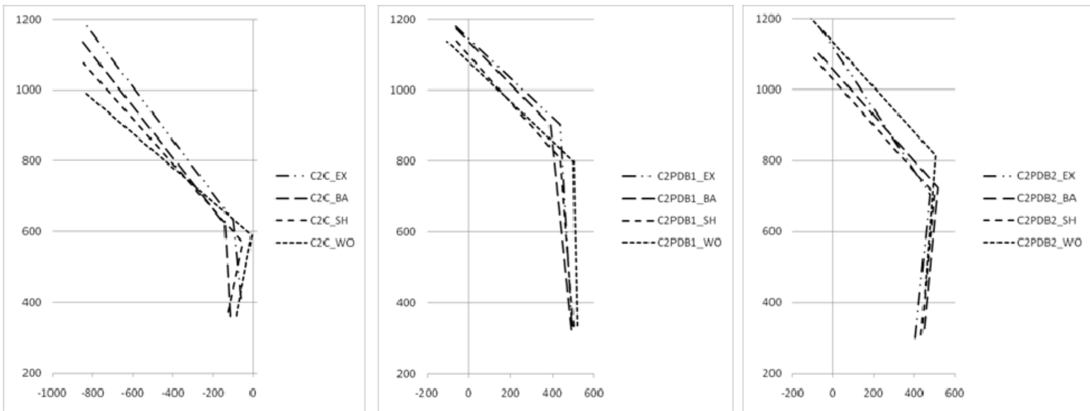

Figure 3.20 Deformation shape of the front bumper beam (from the left: C2C, C2PDB1, C2PDB2)

Acceleration pulse

The following 4 figures (Figure 3.21, Figure 3.22, Figure 3.23, Figure 3.24) show the acceleration pulse for each sub-frame configuration in each crash test scenario. The C2PDB have similar shapes of acceleration pulse during the crash and would start without any specific peak in the middle of the crash and would continue to the end of the crash to the maximum acceleration point by a constant slope.

The car to car cases with EX and BA models are starting with a high peak in the sub-frame interaction area (from about 35ms). The car to car cases with SH and WO models are starting to have higher acceleration later than EX and BA models (but without any specific acceleration peak).

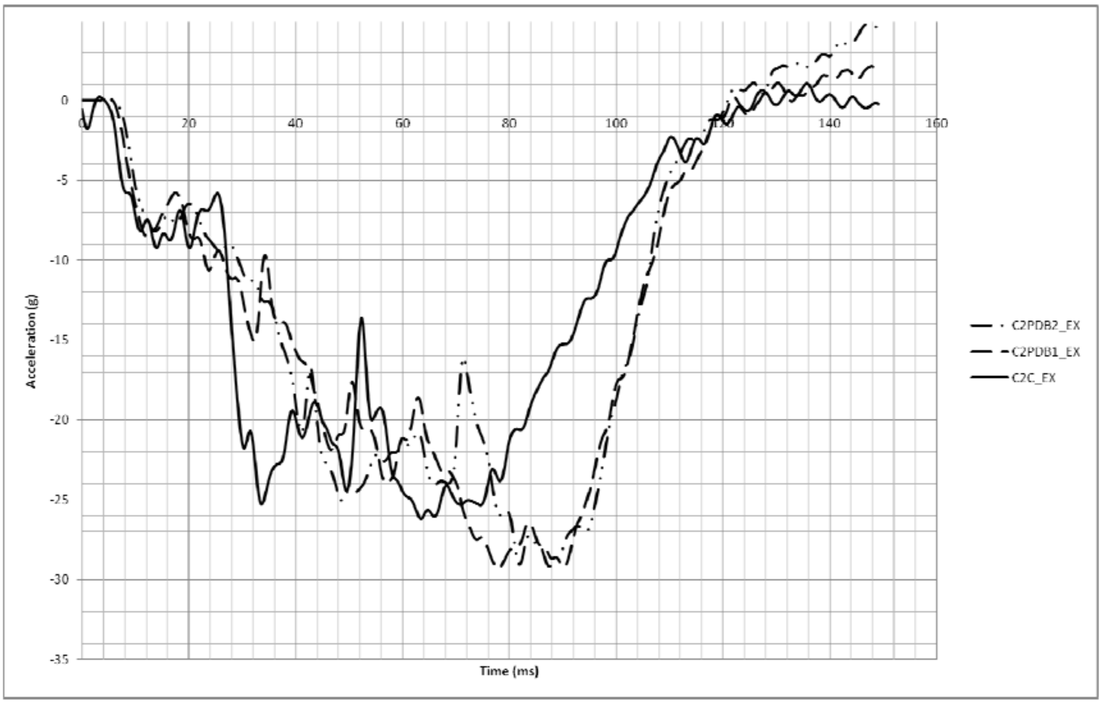

Figure 3.21 Acceleration comparison between car-to-car crash simulations and car to different PDB model configurations (Car with extended sub-frame)

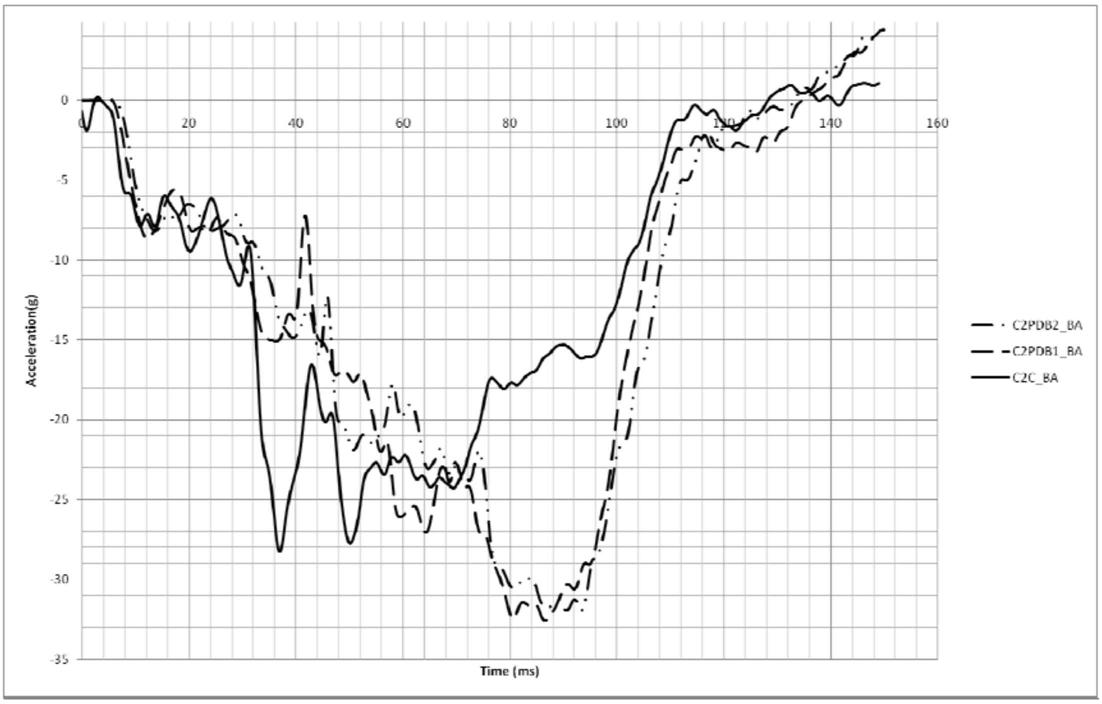

Figure 3.22 Acceleration comparison between car-to-car crash simulation and car to different PDB model configurations (Car with basic subframe)

The slope of acceleration in the C2C_SH and C2C_WO is more similar to the C2PDB cases, because of the less significant structural interaction.

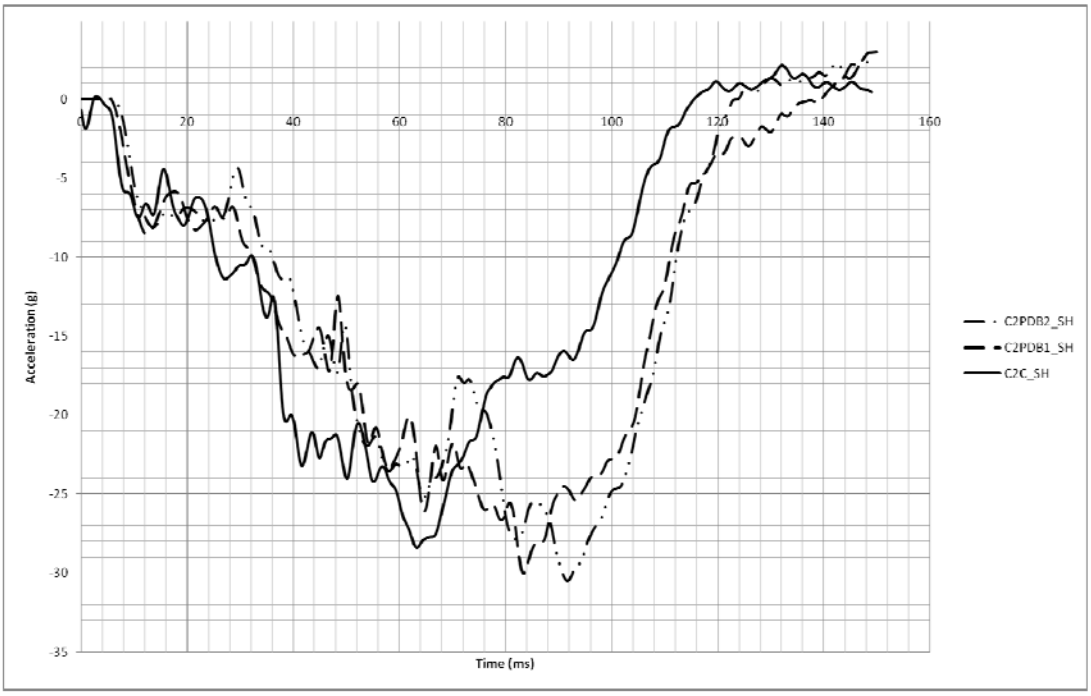

Figure 3.23 Acceleration comparison between car-to-car crash simulation and car to different PDB model configurations (Car with shortened subframe)

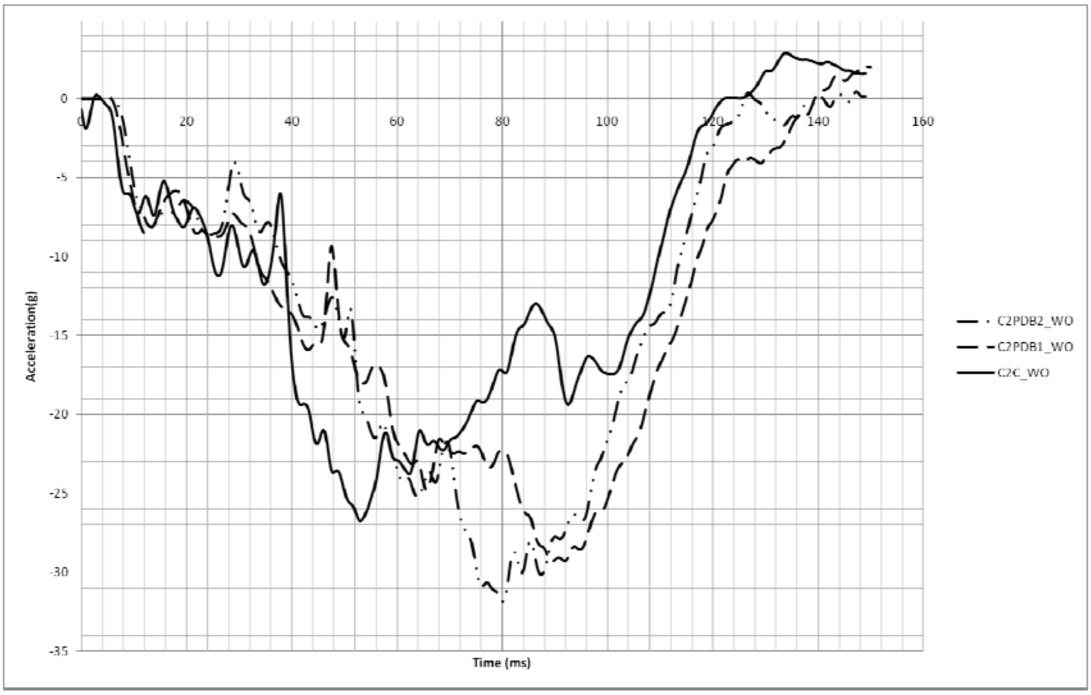

Figure 3.24 Acceleration comparison between car-to-car crash simulation and car to different PDB model configurations (Car without subframe)

The first acceleration peak in C2C cases is starting with sub-frame interactions (around 35ms) and the second peak is the interaction of wheels to the sub-frame of the partner vehicle (around 55ms). The sub-frame interaction acceleration peak is higher for EX and BA (around 35 ms) because they had longer sub-frames and the peak was lower for SH and WO (around 40 ms) because of less engagement of their sub-frame parts for absorbing energy. The acceleration peak in the C2PDB cases is observed around 90ms which is in the final moments of the crash and that means the overall collapsing and buckling of the crash energy absorbing structures are completed.

Energy calculation comparison

Figure 3.25 and Figure 3.26 show the amount of the absorbed energy by PDB. Three methods were used to extract this data: the PDB software developed by UTAC and Universite de Provence, the MATLAB script, provided by VTI and LS-PrePost. The MATLAB script and the PDB software estimates similar amount of absorbed energy. The estimation is based on the deformation of the PDB front plate scanned after deformation. The LS-PrePost data is based on the change of the PDB internal energy, thus the barrier volume and shape after a deformation. In this case the EES was not consistent with the other software. The main reason was the negative sliding energy caused by negative volume of solid elements. This energy was 3% of the total energy during the SH with C2PDB1 simulation. During the C2PDB2 simulations, the negative sliding energy varied between 5-8 %, except during the EX case – 49 %. For this reason, the EES trend based on the C2PDB2 LS-PrePost data is not reliable.

In Figure 3.25 the C2PDB1 data shows that the vehicle with longer sub-frame absorbed more energy, except the EX case. In this case the PDB was deformed from underneath, thus the MATLAB script and the PDB software estimated bigger energy absorption by the PDB, but the LS-PrePost (except SH) to C2PDB1 as well as C2PDB2 simulations data show more reasonable trend, because the PDB front was not lifted up from underneath during C2PDB2 simulations.

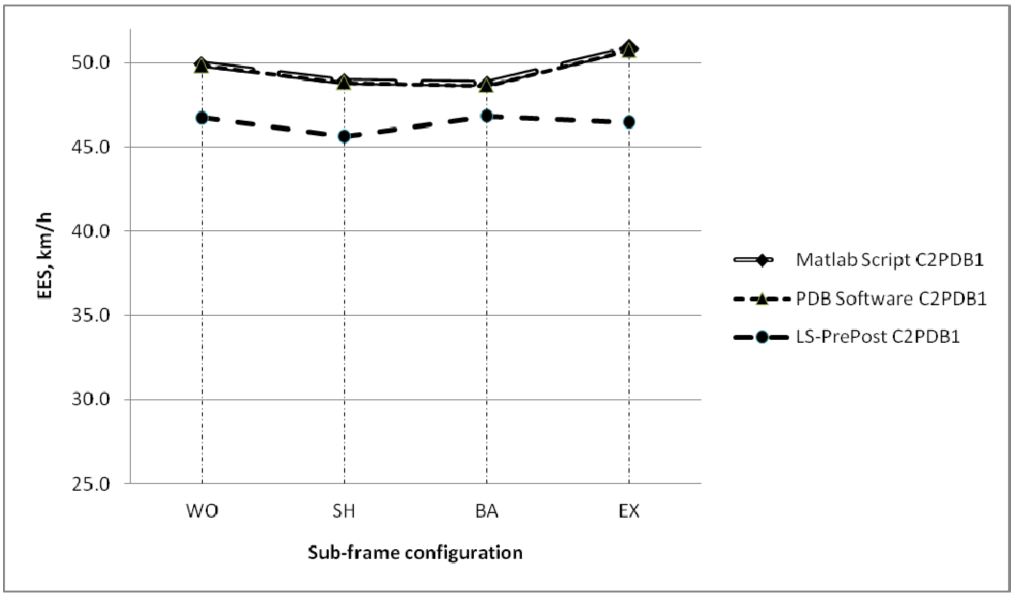

Figure 3.25 EES calculation by the different software for the C2PDB1 simulations

The C2PDB2 data shows that the more clear relation between sub-frame length and absorbed energy by the vehicle, Figure 3.26. The EES estimation by LS-PrePost failed due to the described sliding energy issue.

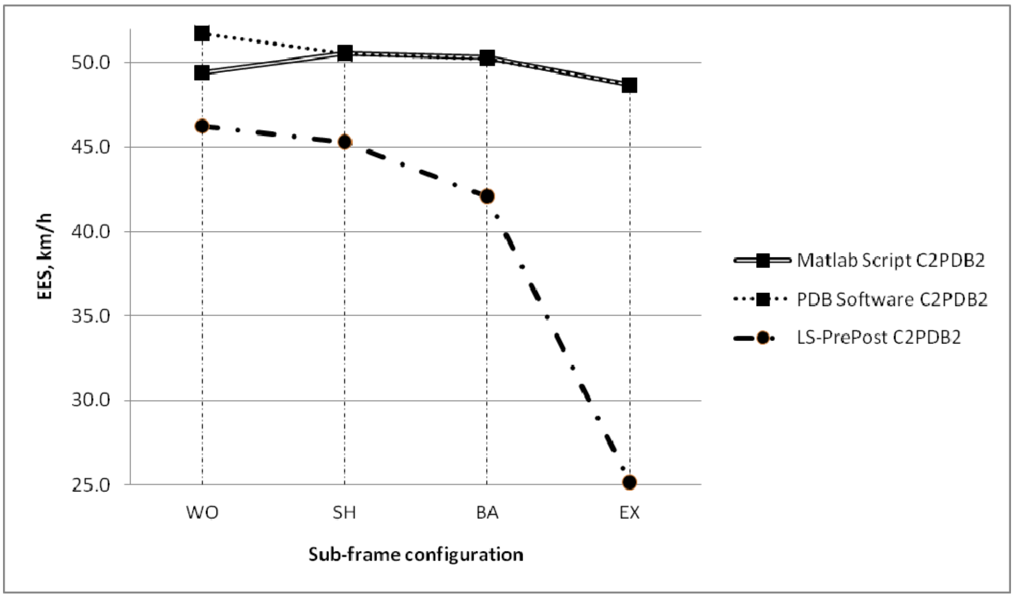

Figure 3.26 EES calculation by the different software for the C2PDB2 simulations

The data shows that longer sub-frames absorb more energy, the difference between WO and EX version was up to 8% of total energy. Hence, the longer sub-frame caused better structural interaction and more energy absorption.

The LS-Dyna absorbed energy data estimation for C2PDB2 EX case was affected by negative volume of deformed solid elements. This energy issue did not influence the deformation and acceleration data, because the C2PDB2 results were inline with the C2PDB1results in terms of trends in the acceleration and deformation values. Thus, we estimate that the sliding energy was affected only.

Discussion

In this section the results of all crash tests were compared. The modified PDB had better interactions with the lower vehicle structures and was more sensitive for the local loads, because of the removed cladding sheet and weakened contact plate. In the C2PDB2 more fork effect was observed in bumper cross beam in comparison to the C2PDB1 and was more similar to C2C cases in general shape of the bumper beam.

The EES estimation of C2PDB2 by LS-PrePost failed due to FE model behavior, but the deformation amount of the EX vehicle and PDB trend was as expected (based on C2C and C2PDB1 cases). Hence, the sliding energy became negative and increased total energy amount by 48%, but did not affect the deformation of the vehicle and the PDB. After overall analysis we could conclude that the more energy was absorbed by the PDB through the vehicle with longer sub-frame configuration collision to the barrier cases than through the vehicle with shorter sub-frame collision to PDB cases.

The PDB was not able to act like another vehicle and have structural interaction. Besides, the PDB detected the pressure of the vehicle structure through the collisions, thus the deformation amount of PDB was related to the interaction area and the load (loads are related to stiffness of the vehicle structure), while the deformation amount was related to the structure stiffness through the C2C cases. It absorbed the crash energy in a controlled way.

4 PDB criteria

The PDB barrier is candidate for assessing the crash compatibility of the vehicles in comparison to the current ODB barrier. Evaluation method of crash compatibility with the help of the PDB is very critical for the condition that the PDB would be used for the regulation of frontal collision

A crash compatibility criterion has been developed during this project. The assessment criterion was tested on the results of crash test of 36 vehicles to the PDB barrier, the crash data obtained from FIMCAR project and a few of them are published in the website of the FIMCAR. This method of crash compatibility evaluation is described in this chapter

Analysis of the different areas

The different areas of the PDB were described in Section 1.4. Figure 4.1 shows the PDB deformation of a sample vehicle. The middle area of the PDB shows a large hole that has more than 600 mm of deformation and means that the vehicle has very strong lower rails and had improper structural interaction with the PDB barrier in the middle area. From this picture it could be concluded that the partner vehicle in the front to front impact to this vehicle would have big intrusion in the same area, if the partner car does not have a strong structure in the same position. This conclusion is true only if all of the impact partners to this vehicle have homogenous front structure like the whole structure of the PDB barrier. However the structural interaction of the front to front impact of the vehicles is complicated and is specific to each case, the PDB barrier has promising abilities to evaluate it to some extent.

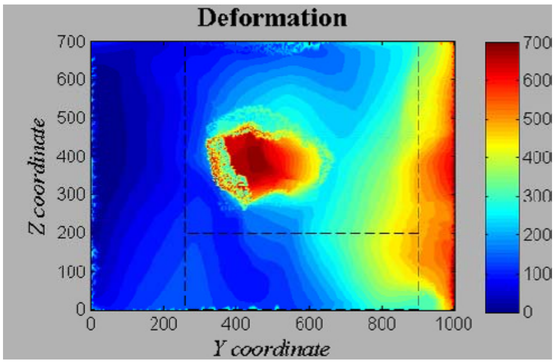

Figure 4.1 PDB deformation of a sample vehicle

The assessment of crash compatibility of the vehicles is wide and complicated, this assessment has been implemented by using a few parameters and a simple procedure.

Assessment introduction

The middle area of the PDB is considered as the main core of the evaluation. The interaction of the lower rails, which are handling the biggest energy absorption of the impact, because those are the main load paths in the front structures of the vehicles, of the vehicles would be detected in the middle area of the PDB. The evaluation of this area would build the main score of the vehicle in the criteria. The lower and upper areas of the PDB would be evaluated and in the case of improper structural interactions, the main score would be penalized.

The homogeneity of the deformation is important for just the lower and middle areas of the PDB because the main impact load carrying structures of the vehicles like lower rails and sub-frames would interact with those areas. The only important parameter for the upper area of the PDB is the amount of the deformation and not homogeneity of the deformation. If a structure of any vehicle interacts to the upper area of the PDB and make big deformations to that area, the vehicle would have higher risks of overriding the partner vehicle in the front to front impact (because there would be a risk of having lower rails in the high height), and direct interaction to upper part of the passenger body in the partner vehicle in side impact. Thus, the amount of deformation is crucial in the upper area of the PDB even with a homogenous surface of deformation.

The lower and middle areas of the PDB have been evaluated with the calculation of total variations of the PDB deformations which is representing the homogeneity of the deformed surface of the PDB and the amount of total deformation in each area. For balancing the effect of the main front structures, the relation between the amount of deformation in the lower and middle area of the PDB is considered.

Further explanation of special parameters for evaluating the PDB deformations is introduced and the assessment based on them as found in the following section.

Percentiles of the deformations

Percentiles of the deformations are used as a statistical value for checking different amounts of deformation in the PDB face. It is the statistical percentage of deformation is data that below its value. For example, if the value of the 50^{th} percentile of the deformations is 300mm, it means that, 50 percent of deformations are smaller than 300mm.

Reference depth of deformation

Detecting the holes in the PDB deformation and comparing the amount of the deformation of each area to the other area of the PDB needs a reference depth of PDB deformation. One method to find a proper reference depth is to use the most common range of deformation by calculating the distribution of deformation in each depth.

Figure 4.2 shows the distribution of the grid cells of the PDB middle area for the vehicle from the Figure 4.1. Different ranges of the depth of deformation have been tested in order to find the one that could represent the most common depth of deformation and not the holes and other improper features of the PDB deformation. This range of depth is a moving window that is assessed over the data in Figure 4.2.

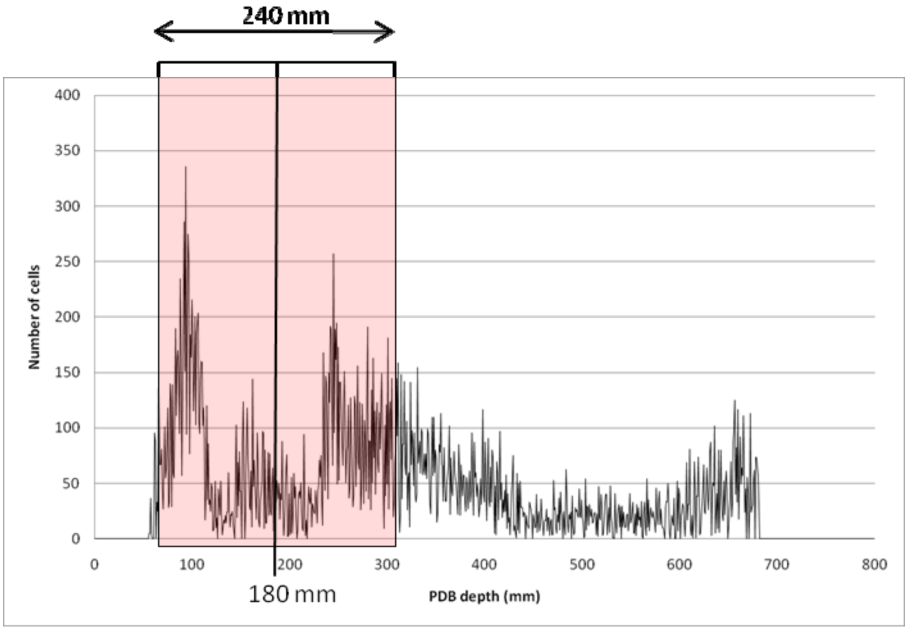

Figure 4.2 Distribution of cells through PDB depth for a sample vehicle

The best range of depth was 240 mm and it means for which 240 mm window of depth the maximum distribution of the PDB deformation occurred. The middle depth of the most common depth of range for the middle area of the sample PDB described above was 188 mm (obtained by analyzing the PDB). Figure 4.3 shows the most common range of depth for the middle PDB area of the sample vehicle. The range is starting from 68 until 308 mm of deformation. The depth that is indicating the middle depth of the mentioned range of depth is called the reference depth in this project. It could be noticed that the selected area didn't include the hole.

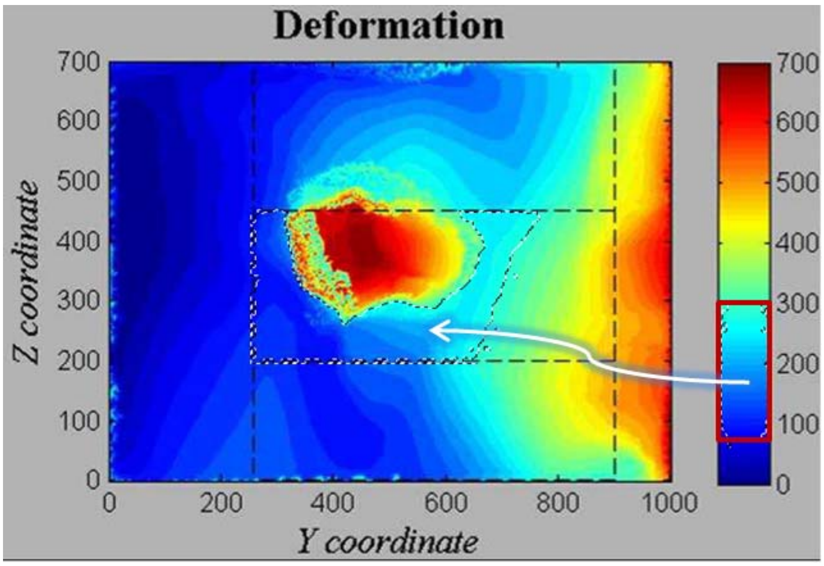

Figure 4.3 The most common range of depth for a sample car

Assessment procedure

The first step in the assessment is to evaluate the middle area of the PDB deformation for the main score and subtract the results of the other areas of deformation from this core score. The idea for evaluation of the middle area is to combine the total variation, 99th percentile of deformation and the reference depth for the middle area. Formula 3.1 is showing how the evaluation of the middle area has been done.

$$ScoreM = w \times \frac{1}{TV(M) \times \max(DM,\ DM - M99) \times M99 \times \sqrt{(DM - M5)}} \qquad (3.1)$$

$ScoreM$: $Score\ of\ the\ middle\ area$

w: $weigthing\ factor$

$TV(M)$: $total\ variation\ of\ the\ middle\ area$

DM: $reference\ depth\ for\ the\ middle\ area$

$M5$: $5th\ percentile\ of\ the\ deformations\ in\ the\ middle\ area$

$M99$: $99th\ percentile\ of\ the\ deformations\ in\ the\ middle\ area$

The term "$\max(DM,\ DM - M99)$" selects the maximum value between the deviations of biggest deformations from the reference depth and the reference depth itself and is sensitive to the holes in the surfaces. The reason for multiplying this term to "TV" is that "TV" increases with the number of holes and is not sensitive enough to small smooth holes. The terms containing the reference depth amplify the effect of the narrow deep holes. The term "$\sqrt{(DM - M5)}$" gives the differences between the reference depth and the small deformations and is sensitive to small overlap of the structures in the area. The score was increased to an objective value by weight factor, which is 1×10^6. The theoretical scale of the middle area $ScoreM \in (0; +\infty)$, where better performing vehicles have higher scores.

Figure 4.4 shows the PDB deformation of 8 sample vehicles from the FIMCAR and the results of the calculation of the formula above are represented in Figure 4.5. It could be noticed that the PDB faces with holes in the middle area received lower scores than the PDBs with homogenous deformation in the middle area.

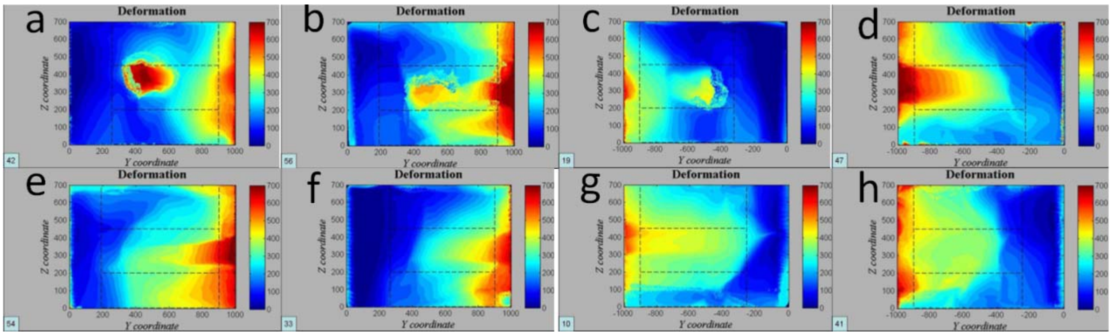

Figure 4.4 Deformation PDB samples from FIMCAR

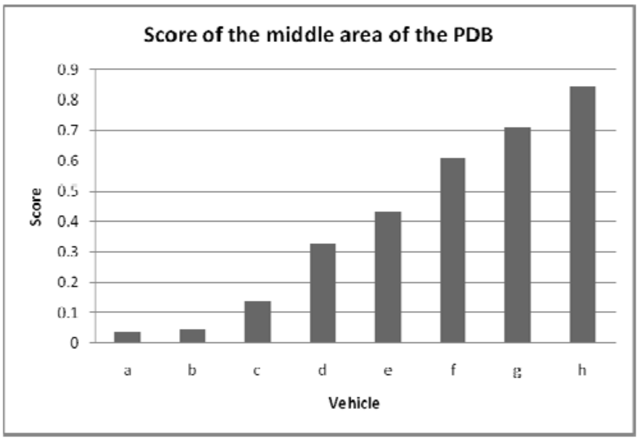

Figure 4.5 Score of the middle area of the PDB for the sample vehicles

The balance between the amounts of deformation of the lower and the upper area of the PDB is important for the assessment because the big difference should increase the risk of the structural interaction misalignment and under/overriding during the front to front impact. For investigating the mentioned balance, the relation between the reference depth of the middle and lower area is helpful. Figure 4.6 shows the ratio between the reference depth of the middle and lower area for the above eight PDB samples. It could be noticed that the models with ratios closer to one, have more similar amount of deformation for the lower and upper areas (without considering the holes).

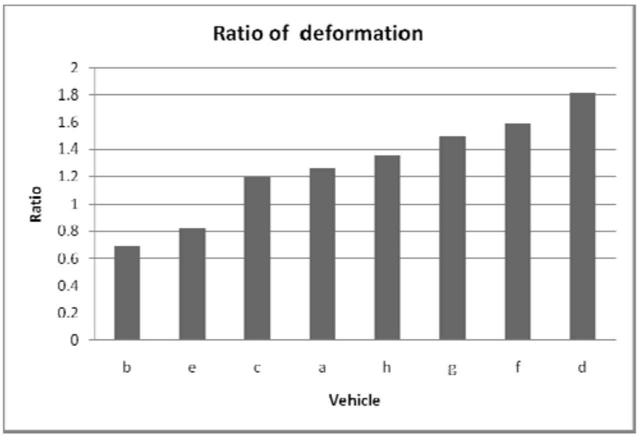

Figure 4.6 Ratio between the reference depth of the middle and lower area

If the ratios bigger than 1.5 between middle and lower area, the "TV" of the lower area are subtracted from the core score, the final score of the lower and middle area would be the result (3.2):

(3.2)

The theoretical scale of the lower and middle area score is difficult to define. Based on physical PDB data variation, expected values for this scoring system are . The maximum score represents the best performance of a frontal vehicle structure.

The calculation results of the above formula could be seen in the Figure 4.7. It could be noticed that the vehicle “d” has the lowest score because it has big structural interaction in the middle area and almost no interaction in the lower area. The vehicle “e” went higher in the ranking because it had good balance of interaction between the lower and middle area.

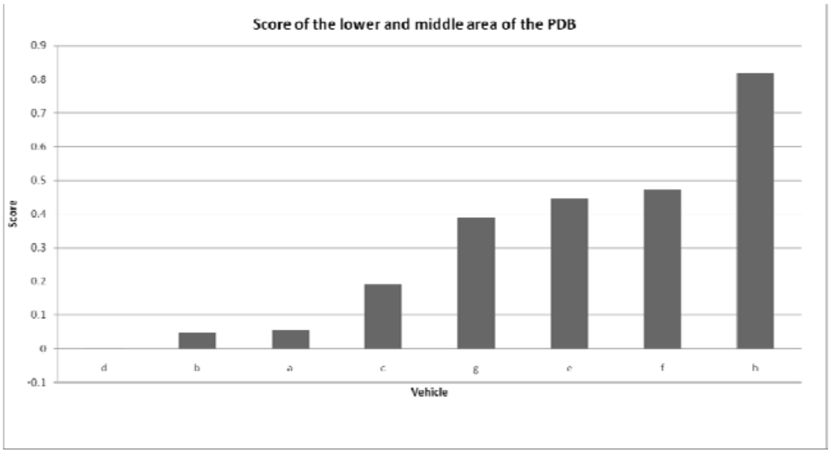

Figure 4.7 Score of the lower and middle area of the PDB for the sample vehicles

More evaluation of the PDB deformation could be performed specially for the upper area. The upper area of the PDB has strange deformations in the upper edge of the barrier (ex. Vehicle b, e and f) because the upper part of the PDB is pulled down. Thus, the evaluation of the upper part of PDB is uncertain in the provided sample PDBs. The procedure of evaluation could be a combination of amount deformation to prevent large deformations in the upper area (regardless of homogeneity).

Evaluation of the results

The Figure 4.8 shows the score for the lower and middle area of the PDB deformation for C2PDB1 and C2PDB2 crash scenarios. In the standard PDB deformations, The BA has the lowest score because it had the best interaction of the sub-frame to the lower area of the PDB. The exterior, like the front bumper cover were excluded from the vehicle model, thus the frontal structures have an aggressive interaction to the PDB. This is the reason for having lower scores for more interaction of the sub-frame cross beam to the PDB. The EX model has similar score to the WO and BA because the sub-frame in EX did not have proper interaction (Figure 3.6).

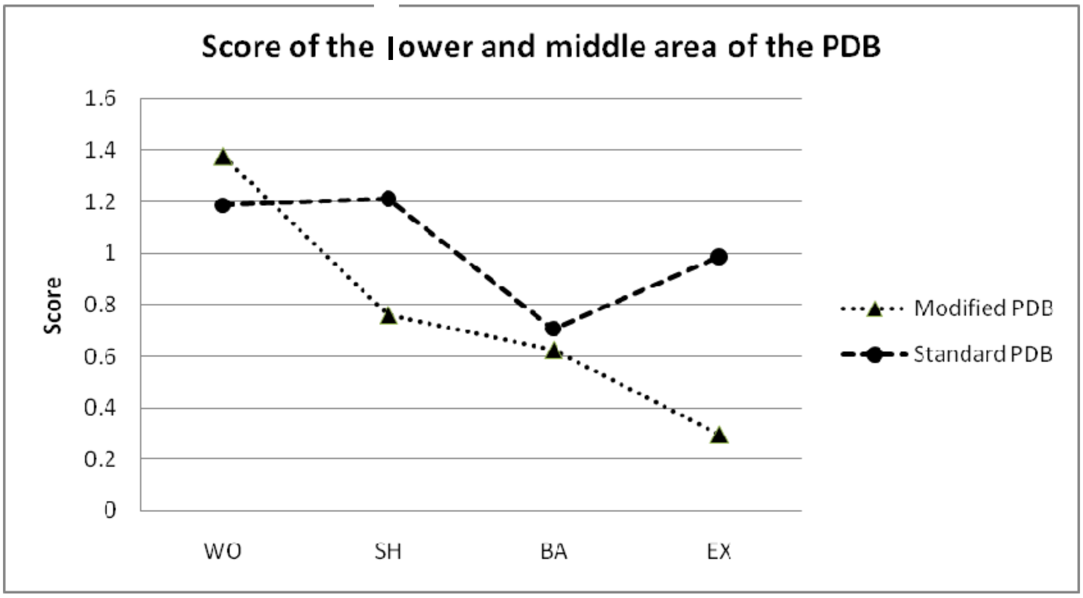

Figure 4.8 Score of the PDB deformations from results

In the modified PDB configuration scores, increasing the length of a sub-frame decreased the evaluation score. The sub-frame cross beam had proper interaction to the lower area of the PDB and elongation of the sub-frame caused deeper deformations and bigger total variation of the deformation in the lower area, for this reason score of the lower and middle area decreased. It could be noticed that the WO model has the highest score in comparison to other models with sub-frame cross beam.

Discussion

The PDB barrier was capable of evaluating the crash compatibility of vehicles, the assessment of the evaluation is more important than the PDB itself.

The criteria explained in this chapter were based on the following factors:

- Over/under running effect, detected by term.
- Fork effect, detected by term.
- Small and not enough overlap, detected by ratio between the reference depth of the middle and lower area (*ratio ML*).

The formulas and methods were examined on 36 PDB samples from the FIMCAR project and explained based on 8 selected models of those models. The criteria were applied on the PDB deformations from the results of the project also.

By extending the subframe parts, lower scores were achieved for the PDB assessment on the simulation results of C2PDB2 despite longer sub-frame showed better self protection in C2C simulations. The vehicle models had aggressive front ends with locally stiff structure and excluded exterior parts and the PDB has uniform strength in its honeycomb structure which is sensitive to pressure. Thus each of load paths interacted to PDB individually and sub-frame cross beam had smaller area and caused more local pressure to the lower area and as a consequence the total variation of the lower area increased. The longer sub-frame intruded more into the lower part of the PDB locally and increased the total variation more, thus the score for the extended subframe was the lowest. In C2C cases, the front structures were in perfect match in the vertical direction and longer sub-frames showed better performance.

Investigation of the research of Park [13] showed that misalignment of the interacting front structures would cause more intrusion to the firewalls of the colliding cars with all different sub-frame configurations. As a result, the PDB should give information about the worse case for interaction of the front structures of the examined vehicle, rather than in the case of matching front structures of the colliding vehicles.

The current criteria has good abilities to compare different PDB models in the factors described above, but some thresholds should be defined for the failure of the cars in the examination and some for maximum scores.

5 Summary and conclusions

Crash test based legal requirements for vehicle compatibility do not exist. The French proposal is to change Regulation No. 94 [4] using the PDB (progressive deformable barrier) for frontal collisions. This study reviews the ability of the PDB to assess the collision compatibility between vehicles. For this purpose, the simulations of car-to-car crash with different sub-frame configurations were done as well as car to the PDB cases. The simulation results were compared and the correlation between car to PDB and car to car crashes was found.

The study revealed the PDB's ability to detect lower structural changes in the front end. The deformed PDB provides useful data to investigate the aggressivity of vehicles, but the PDB barrier does not have a validated system for the evaluation of the partner vehicle protection. Thus, the PDB criterion was developed.

The car to car simulation results showed that the longer sub-frame configuration decreased fork effect and firewall intrusions and the frontal structures of the vehicles started interacting earlier during C2C simulation. While the C2PDB1 with EX crash test signified improper interaction of the PDB and the sub-frame. The interaction of the PDB and the EX sub-frame encountered issues during the C2PDB1 simulations. The front lower edge of the PDB front deformable core was lifted up by the cladding sheet and the contact between the sub-frame and PDB did not occur. Furthermore, the local forces of the structural interaction was distributed by the thick cladding sheet and contact plate. For this reason, the PDB was modified.

After modifications to the PDB model, the C2PDB2 simulations showed that the sub-frame interaction issue was solved and the PDB front deformable core deformations were more local. Also, the vehicle firewall intrusions were bigger and more similar to C2C compared to C2PDB1 results.

During the C2C, C2PDB1 and C2PDB2 result comparison, it was observed that the PDB did not behave like a vehicle because the structural design of the front of a vehicle is inhomogeneous while the PDB structure is uniform. Deformation shape of the PDB front is caused by the pressure applied through the front end structures of the vehicle. Hence, the PDB structure was deformed locally by the vehicle structure. For this reason the deformed front surface of the PDB was used for crash compatibility criteria. The PDB criteria took into account under running, overrunning, fork effect and small overlap aspects.

The longer sub-frame configurations caused a better self protection during C2C crash tests. The standard FE PDB version was not able to detect some configurations of the lower vehicle structures, this issue was solved by modifying the barrier. After the modifications, the PDB detects lower structures. Because of higher sensitivity of the modified PDB to the local deformations and aggressive front structures of the vehicle model, the longer sub-frame configurations earned lower scores in the PDB criteria.

The physical car to PDB crash tests deformation results of the front PDB surface showed that the barrier is able to detect different vehicle structures. The aggressiveness of a car can be evaluated by the compatibility criteria. The developed criteria assessed PDB deformations in a reasonable order and proved that the compatibility of a car can be evaluated by the analysis of the deformed PDB and the vehicle. Thus the PDB has ability to detect the structural interaction, but the procedure that the PDB deformation would be evaluated is crucial.

6 Recommendations

During the crash test simulations of the original Taurus vehicle model to PDB, the deformations of the barrier were more distributed. The local deformations of the PDB were more concentrated during the C2PDB1 simulation. This trend happened because the exterior parts of the original model distributed forces more than the simplified model. For this reason the simplified vehicle model presented more severe PDB model deformation than the standard vehicle. The EX to PDB simulation revealed the structural interaction issue in the lower area. Therefore the PDB should be validated in ultimate cases as well, even if the case does not represent existent vehicle configuration.

The standard FE PDB was not able to detect the lower structural interaction and had a negative sliding energy issue during the EX to C2PDB1 simulation. The modified FE PDB model has detected the lower structures, but the negative sliding energy issue was magnified. Thus, the FE PDB model should be developed further. One of the approaches could be the development of PDB model based on shell elements instead of the solid elements to present aluminium honeycomb crushable foam specifications. Another solution could be to develop the FE PDB model with the shell elements in the front deformable core, while other cores would remain with solid elements. The hybrid configuration requires less simulations time than FE PDB model with all shell elements, in this case the front PDB face and the sub-frame structural interaction issue also could be solved.

The final FE PDB version should be validated by the rigid tubular impactor and a detailed car to the PDB simulation case. These results should be compared and validated with corresponding physical tests.

The proposed PDB criterion evaluates aggressiveness of a vehicle. Thus, the criteria would be used in the new regulation and should be well defined, because the evaluation results will be compared and vehicles would be rated based on it. Therefore, the rating should be robust, otherwise there is a risk of unreasonable scores for some vehicles. Hence, the proposed criteria should be verified by more of PDB crash tests. As a result the implementation of a faulty criterion would be prevented.

The PDB barrier is sensitive to pressure which means, structures with smaller front surface would make big intrusions in the PDB surface compared to structures with bigger front surface (with the same stiffness). Thus the front structure of the vehicle should have the responsibility of distributing crash forces among the different load paths of vehicle front structure. This could be achieved by increasing the number of load paths in the front structure and joining them together for more force distributing effect in the interacting height of the lower and middle area of the PDB, because side collision scenarios also should be considered.

7 References

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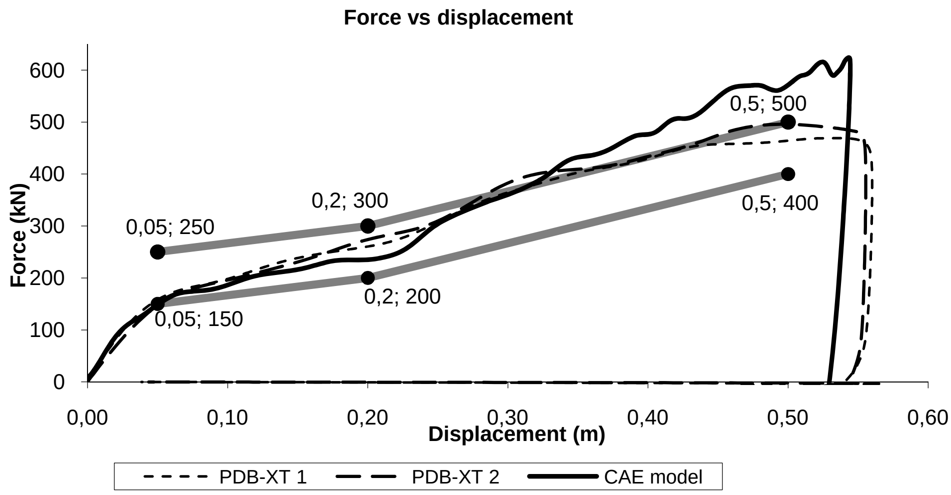
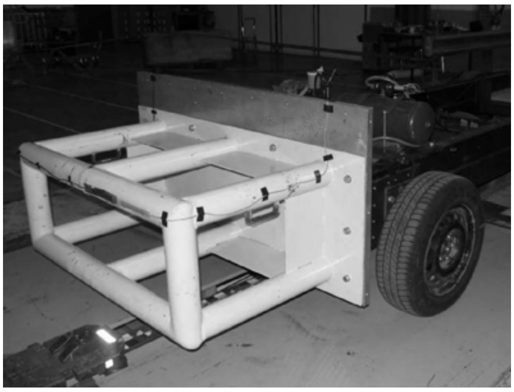
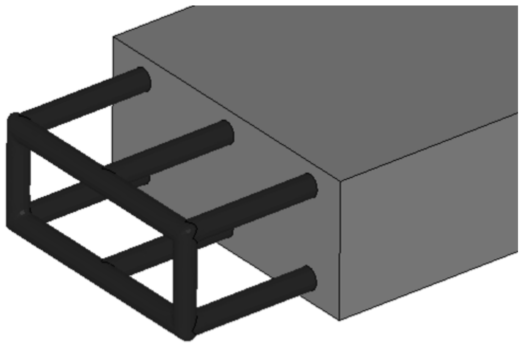
Appendices

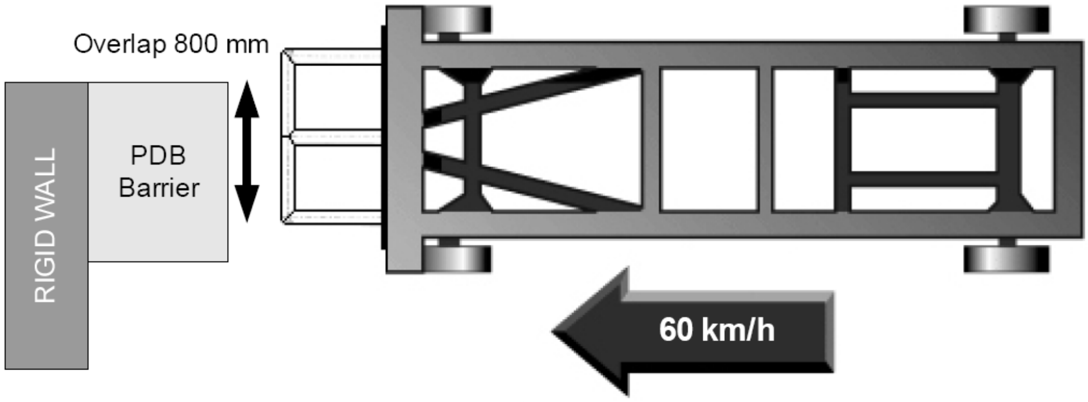
Appendix A. PDB Model Validation

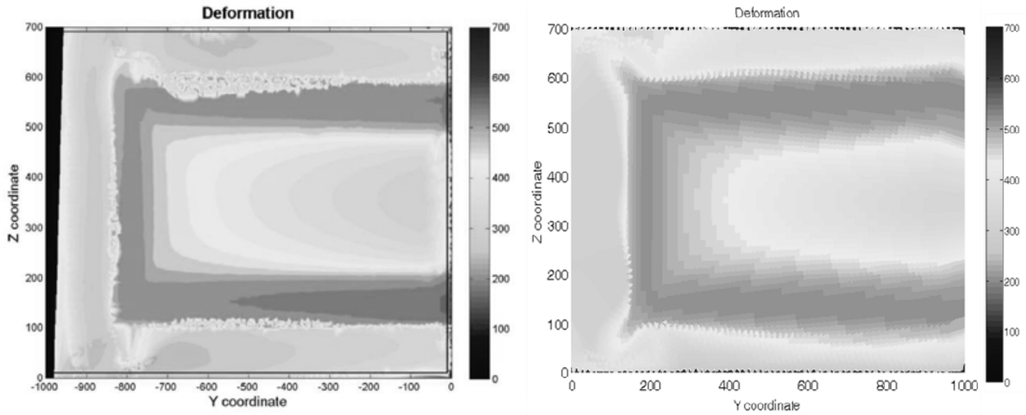
Tubular impactor crash to PDB for the conformity of the PDB model and its data and comparison of that with the physical tests. The test procedure is described in the proposal for the Regulation No.94 [4].











Appendix B. MATLAB Codes

1. Homogeneity calculation code

```
%% Compute homogeneity of lower, middle and upper area

% Calculates the homogeneity for lower area
Lower=deformation(start_index_z:low_end_index,start_index_y:end_index_y);

HL = 0;
for i = 1:length(Lower(:,1))-1
    for j = 1:length(Lower(1,:))-1
        a = abs(Lower(i,j+1)-Lower(i,j)) + abs(Lower(i+1,j)-Lower(i,j));
        HL = HL + a;
    end
end

HL = HL / ( 2 * (length(Lower(:,1))-1) * (length(Lower(1,:))-1) );
HL = 1 / HL;

% Calculates the homogeneity for Middle area
Middle=deformation(low_end_index+1:mid_end_index,start_index_y:end_index_y);

HM = 0;
for i = 1:length(Middle(:,1))-1
    for j = 1:length(Middle(1,:))-1
        a = abs(Middle(i,j+1)-Middle(i,j)) + abs(Middle(i+1,j)-Middle(i,j));
        HM = HM + a;
    end
end

HM = HM / ( 2 * (length(Middle(:,1))-1) * (length(Middle(1,:))-1) );
HM = 1 / HM;

% Calculates the homogeneity for Upper area
```

```
Upper=deformation(mid_end_index+1:end_index_z,start_index_y:end_index_y);

HU = 0;
for i = 1:length(Upper(:,1))-1
    for j = 1:length(Upper(1,:))-1
        a = abs(Upper(i,j+1)-Upper(i,j)) + abs(Upper(i+1,j)-Upper(i,j));
        HU = HU + a;
    end
end

HU = HU / ( 2 * (length(Upper(:,1))-1) * (length(Upper(1,:))-1) );
HU = 1 / HU;
```

2. Reference depth calculation code

```
%% Hole detection of lower, middle and upper area

%% Counts the number of grids in each depth div in lower area
Lower=deformation(start_index_z:low_end_index,start_index_y:end_index_y);

CountLow = zeros(1,n);
for i = 1:length(Lower(:,1))
    for j = 1:length(Lower(1,:))
          k = ceil( Lower(i,j) / DivSize);
          CountLow(k) = CountLow(k) + 1;
    end
end

% figure(20)
% t = DivSize:DivSize:PDBdepth;
% plot(t,CountLow)

% Finds the most common depth of deformation for lower area

for i = 1:n-m+1
    CountLow2(i) = sum(CountLow(i:i+m-1));
end

[d f] = max(CountLow2);

DL = 0;
for i = 1:m
    DL = DL + (f+i-1)*DivSize *(CountLow(f+i-1) / CountLow2(f));
end
% DL

HL = 0;
for i = 1:length(Lower(:,1))
    for j = 1:length(Lower(1,:))
        a = abs(DL-Lower(i,j))^p;
        HL = HL + a;
    end
end

HL = HL / (length(Lower(:,1)) * length(Lower(1,:)));

HL = 100/((HL)^(1/p));


%% Counts the number of grids in each depth div in middle area
Middle=deformation(low_end_index+1:mid_end_index,start_index_y:end_index_y);

CountMiddle = zeros(1,n);
for i = 1:length(Middle(:,1))
    for j = 1:length(Middle(1,:))
```

```
        k = ceil( Middle(i,j) / DivSize);
          CountMiddle(k) = CountMiddle(k) + 1;
    end
end

% Finds the most common depth of deformation for Middle area

for i = 1:n-m+1
    CountMiddle2(i) = sum(CountMiddle(i:i+m-1));
end

[d f] = max(CountMiddle2);


% figure(21)
% t = DivSize:DivSize:PDBdepth;
% plot(t,CountMiddle)


DM = 0;
for i = 1:m
    DM = DM + (f+i-1)*DivSize *(CountMiddle(f+i-1) / CountMiddle2(f));
end
% DM

HM = 0;
for i = 1:length(Middle(:,1))
    for j = 1:length(Middle(1,:))
        a = abs(DM-Middle(i,j))^p;
        HM = HM + a;
    end
end

HM = HM / (length(Middle(:,1)) * length(Middle(1,:)));

HM = 100/((HM)^(1/p));

%% Counts the number of grids in each depth div in upper area
Upper=deformation(mid_end_index+1:end_index_z,start_index_y:end_index_y);

CountUpper = zeros(1,n);
for i = 1:length(Upper(:,1))
    for j = 1:length(Upper(1,:))
        if Upper(i,j) <= 0
            Upper(i,j) = 0.1;
        end
        if Upper(i,j) >= PDBdepth
            Upper(i,j) = PDBdepth-0.1;
        end
        k = ceil( Upper(i,j) / DivSize);
        CountUpper(k) = CountUpper(k) + 1;
    end
end

% Finds the most common depth of deformation for upper area

for i = 1:n-m+1
    CountUpper2(i) = sum(CountUpper(i:i+m-1));
end

[d f] = max(CountUpper2);

DU = 0;
for i = 1:m
    DU = DU + (f+i-1)*DivSize *(CountUpper(f+i-1) / CountUpper2(f));
end
DU
```

```
HU = 0;
for i = 1:length(Upper(:,1))
    for j = 1:length(Upper(1,:))
        a = abs(DU-Upper(i,j))^p;
        HU = HU + a;
    end
end

HU = HU / (length(Upper(:,1)) * length(Upper(1,:)));

HU = 100/((HU)^(1/p));
```

3. Firewall nodes data extractor from the nodout file (Based on the idea from Krusper, A.)

```
function Firewall_graph(filename,Time,ShiftNodeID,LineShape,Thickness)

M = textread(filename,'%s');

NodeDatabase=NodeDB;
NodeDatabase(:,1)=NodeDatabase(:,1)+ShiftNodeID;
Nodes = NodeDatabase(:,1);


%% finding desired time's row in the file
i = 2;
    while ~(strcmp(M(i), Time) && strcmp(M(i-1), 'time') )
        i = i + 1;
    end
    d = i;

%% Shifting Nodes related to node number 3183940

NodeDatabase(:,2) = NodeDatabase(:,2) - NodeDatabase(4,2);
NodeDatabase(:,3) = NodeDatabase(:,3) - NodeDatabase(4,3);
NodeDatabase(:,4) = NodeDatabase(:,4) - NodeDatabase(4,4);


%% Extracting displacements from the desired time
for i= 1:length(Nodes)
    k = 1;
    while  ~(strcmp( M(d+k), num2str(Nodes(i)) ))
        k = k + 1;
    end
    NodeDisplacemant(i,1) = Nodes(i);
    NodeDisplacemant(i,2) = str2double(M(d+k+1));
    NodeDisplacemant(i,3) = str2double(M(d+k+2));
    NodeDisplacemant(i,4) = str2double(M(d+k+3));

    NodeCoorAfterDeform(i,1) = NodeDatabase (i,1);
    NodeCoorAfterDeform(i,2) = NodeDatabase (i,2) + NodeDisplacemant(i,2);
    NodeCoorAfterDeform(i,3) = NodeDatabase (i,3);
    NodeCoorAfterDeform(i,4) = NodeDatabase (i,4);
end
```