

Evaluation of the Safety Performance and Weight Reduction Using CFRP Modified Automotive Structures in NHTSA's Frontal Oblique Impact Test

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ABSTRACT

In a project conducted for NHTSA during 2016-2017, finite element analysis simulations were conducted representing NHTSA's right and left oblique impact configurations being developed for possible use in the agency's New Car Assessment Program. For the study using this test procedure, simulations were conducted representing an offset moving deformable barrier impacting a stationary 2015 Toyota Camry with a 35 percent overlap and an angle of 15 degrees (from collinear) at a speed of 90 km/h. In the NHTSA project, the model was successfully used to develop structural countermeasures in order to reduce occupant compartment intrusion for the new oblique impact configuration. Higher strength steel materials and modification of component thicknesses allowed the reduction of occupant compartment intrusion by more than 50%. As part of this effort, George Mason University (GMU) calculated mass and relative material expense comparisons to traditional materials. As a result, three optimized models using traditional materials were created. The accomplished reduction of occupant compartment intrusion ranged from 52% to 69% and the associated added mass ranged from 7.3 kg to 17.3 kg. The significant reduction in intrusion was achieved without unintended consequences, i.e., no considerable increases in the vehicle pulse severity for oblique and co-linear crash configurations were observed.

Following these results, the American Chemistry Council (ACC) commissioned this subsequent study to determine if the vehicle could be lightweighted and provide a similar reduction of occupant compartment intrusion for NHTSA's right and left oblique impact configurations using carbon fiber reinforced plastic (CFRP) composite materials. Different thicknesses for relevant components were evaluated and associated reductions in intrusion, associated changes in mass, and associated critical areas with material failure were determined. As a result of using selected components made out of a composite material, a similar reduction in occupant compartment intrusion was achieved in NHTSA's right and left oblique impact configuration as realized for the best high strength steel model. In using the CFRP composite material, the associated change in mass was a reduction of 7 kg of the baseline vehicle as compared to an increase of 17 kg in the baseline vehicle mass when using more traditional countermeasures--higher component thicknesses and use of high strength steel materials.

The developed and incorporated countermeasures using composite materials were also evaluated to determine if they produced unintended consequences in other impact configurations. The developed FE models, which showed reduced occupant compartment intrusion due to components made out of the CFRP composite material in NHTSA's oblique crash configuration, were also evaluated in NHTSA's NCAP full overlap and in the Insurance Institute for Highway Safety (IIHS) partial overlap crash configurations. No unintended consequences were observed when the results were analyzed with respect to vehicle pulse and intrusion when compared to the results using the baseline simulation model.

In addition to the above technical achievements, in partnership with Honda R&D Americas and LSTC; other efforts are underway. These include the development of a material constitutive model of the composite material for use in modeling and subsequent simulation in automotive crash applications. Also, validation efforts using CFRP components will be undertaken.

INTRODUCTION

In fiscal year 2006, Congress directed the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation (DOT) to begin the development of a program to examine the possible safety benefits of lightweight Plastics- and Composite-Intensive Vehicles (PCIVs). NHTSA tasked the Volpe National Transportation Systems Center to conduct focused research in cooperation with industry partners from the American Plastics Council (APC), now the American Chemistry Council Plastics Division (ACC-PD).

NHTSA concentrated on the safety-related research issues affecting the deployment of PCIVs in 2020. In 2007, the Volpe Center developed a safety roadmap for future PCIVs and described the approach, activities, and results of an evaluation of potential safety benefits of PCIVs [1,2]. Barnes et al. identified outstanding safety issues and research needs for PCIVs to facilitate their safety deployment by 2020, and recommended three topics pertinent to crashworthiness of PCIVs: (1) material database, (2) crashworthiness test method development, and (3) crash modeling [3].

In 2001, the APC (now the ACC-PD) outlined a Vision and Technology Roadmap for the automotive and plastics industries [4]. In the technology integration workshop in 2005, the ACC-PD provided an expansive safety road mapping effort, examining PCIVs [5]. In 2009, the ACC-PD updated the vision and technology roadmap to outline the industry's action priorities for achieving the technology and manufacturing innovations required to realize PCIVs [6]. In addition, the ACC-PD recommended three research activities: (1) improvement of the understanding of composite component response in vehicle crashes, (2) development of a database of relevant parameters for composite materials, and (3) enhancement of predictive models to avoid costly overdesign [7].

There is an increasing need to investigate opportunities for weight reduction of the vehicle fleet to improve fuel economy and compatibility. However, this should be achieved without sacrificing the current self-protection. Innovative plastics and fiber-reinforced composite materials offer a means to lightweight vehicle structures. The main advantages of composites over the more conventional isotropic materials are the lower density, very high specific strength, and specific stiffness that can be achieved.

In 2014, the ACC-PD updated the Plastics and Polymer Composites Technology Roadmap for Automotive Markets [8] in response to the U.S. Corporate Average Fuel Economy (CAFE) standards in order to develop an effective industry-wide strategy that will extend to 2030 and beyond. The roadmap addresses current barriers and key initiatives to recognize plastics and polymer composites as preferred material solutions that meet automotive performance and sustainability requirements.

As part of implementing the ACC roadmap, the ACC partnered with the George Mason University's Center for Collision and Safety Analysis (GMU/CCSA) to conduct research to evaluate the application of plastics and composites using Computer-Aided Engineering (CAE) simulations. In a previous study, the GMU Team developed a lightweight vehicle by replacing existing steel components with plastics or composite components in a reverse-engineered computer model. To support realistic development, industry partners participated in the project by providing available plastics/composite materials and their application and design. The crashworthiness of the lightweighted components was investigated through impact simulations, both at a component level and at a full vehicle level. The results were documented in Reference [9].

A more specific research task was adopted in this current project. Using computer simulation, an evaluation was conducted to determine if countermeasures using CFRP modified automotive structures in NHTSA's newly developed frontal oblique impact test procedure could achieve a similar reduction in occupant compartment intrusion as countermeasures using high-strength steel materials.

Consumer information crash tests, such as NHTSA's New Car Assessment Program's (NCAP's) full overlap frontal impact and the Insurance Institute for Highway Safety's (IIHS's) small and moderate overlap frontal impacts, have contributed to advance vehicle safety and reduce injury risk in the past. Recent studies have indicated that oblique crashes represent common real-world accident patterns related to belted occupant fatalities [10]. When comparing the number of injuries by body region for oblique and co-linear frontal impacts, it was observed that drivers in left oblique impacts experienced more Maximum Abbreviated Injury Scale (MAIS) 3+ injuries in almost every body region than drivers in co-linear crashes [11].

The Center for Collision Safety and Analysis (CCSA) at George Mason University (GMU) has analyzed sixteen left oblique tests conducted by NHTSA regarding intrusion patterns and related injury risk [12]. Furthermore, 65 oblique and 265 NCAP full overlap tests were analyzed regarding vehicle pulse, intrusion, and injury metrics. While there was no clear trend linking higher intrusion to higher tibia loads, it was found that occupant compartment intrusion, pulse severity, and local effects could contribute to lower extremity injuries. It can be concluded that risk of injury can increase as the maximum intrusion from the occupant compartment increases.

IIHS compared the performance of 25 vehicles in NHTSA's frontal oblique condition and the IIHS small overlap configuration. The selected cars represented a wide range of vehicle sizes. With respect to lower extremity injuries, it was found that 36% (9 cars) of the vehicles exceeded preliminary Injury Assessment Reference Values (IARVs) in the oblique impact, while only 8% (2 cars) exceeded the IARVs for the small overlap configuration [13]. Differences in vehicle pulse and occupant compartment intrusion are considered possible reasons.

The oblique impact test captures the deformations of a significant number of real-world accidents that occur today, and the development of additional countermeasures for restraints and vehicle structure may have the potential to further improve vehicle safety and reduce injury risk in the future. Consequently, NHTSA is considering adopting a frontal oblique impact configuration into its NCAP rating protocol [11].

The developed laboratory test procedure is conducted in combination with a more biofidelic dummy, the Test device for Human Occupant Restraints (THOR) [11]. An Oblique Moving Deformable Barrier (OMDB) was developed to produce target vehicle crush patterns similar to real-world cases [14]. It has a weight of 2,500 kilograms (kg) and impacts a stationary vehicle at a speed of 90 kilometers per hour (km/h). The vehicle is placed at a 15-degree angle and a 35-percent overlap occurs between the OMDB and the front end of the struck vehicle, as shown in Figure 1.

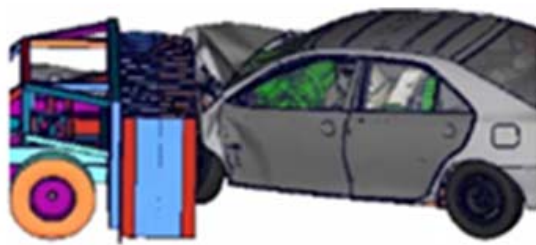


Figure 1 - Frontal Oblique Test Configuration

Crash test results have shown that vehicles may require structural modifications for good performance in NHTSA's frontal oblique test procedure. In a previous project that was funded by NHTSA, the GMU team determined incremental vehicle structural change requirements using steel materials and their associated mass to significantly reduce occupant compartment intrusion.

An available FE model of a 2012 Toyota Camry mid-size sedan was updated and validated using data to represent a 2015 Toyota Camry. The newly generated baseline model correlated well with the New Car Assessment Program (NCAP) full overlap test, NHTSA's left and right oblique impact tests, and with the IIHS small and moderate overlap crash configurations. An iterative process was used to develop countermeasures to significantly reduce occupant compartment intrusion for the left and right oblique impact configuration. No un-intended consequences (i.e., no considerable increase in the vehicle pulses for the oblique and co-linear crash configurations) were observed. The associated added mass was +17 kg using high-strength steel materials [15].

The aforementioned developed FE model and tools were used to determine if similar results (i.e., a similar reduction in occupant compartment intrusion, and no un-intended consequences, such as significantly more severe vehicle crash pulses) could be achieved using composite materials for select components.

OBJECTIVE

The objective of this research was to develop changes using CFRP composite materials to modify a passenger vehicle's structure to provide equivalent performance as the vehicle modified with high strength steel modifications in order to reduce occupant compartment intrusion in NHTSA's oblique frontal crash test condition. Structural countermeasures for both the driver's and passenger's sides of the vehicle for left- and right-side oblique impacts were to be developed.

VEHICLE SELECTION

The vehicle selected for this study was the baseline selected for the NHTSA study using the high strength steels for improving the crash performance in the frontal oblique offset test. Several criteria were used to determine an appropriate vehicle on which to conduct that research. This included evaluation of the number of vehicle sales as a measure of how well it represents mid-size sedans in the United States (US), performance in existing consumer information tests, and availability of an adequate FE simulation baseline model. The vehicle also was required to meet the structural intrusion requirements for a "GOOD" or "ACCEPTABLE" structural rating in the IIHS small overlap crash test, "GOOD" rating in the IIHS moderate overlap crash test, and a 5-Star rating in the NCAP full frontal crash test.

Satisfying the aforementioned criteria, a FE model of a 2012 Toyota Camry, which had been developed by the GMU Team, was used as a starting point. Toyota introduced structural design changes in January 2014. The MY 2012 mid-size sedan FE model was updated accordingly. Figure 2a illustrates the relevant structural differences between MY 2012 and MY 2015. Figure 2b shows (from right to left) a bottom view of the finite element model with an enlarged view of the added bumper reinforcement extension and "spacer" for the simulation model and the physical vehicle.

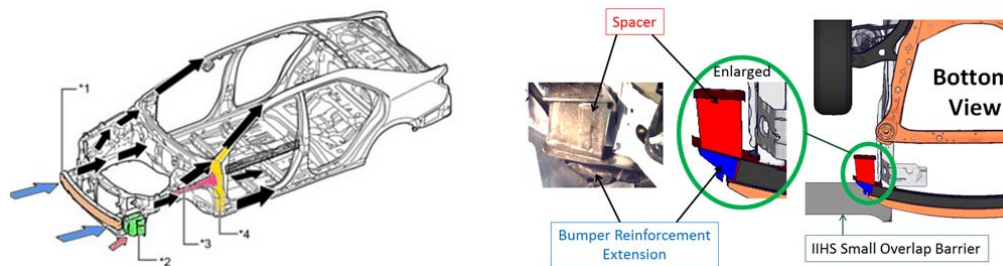


Figure 2 – Design Changes (a) Schematic, (b) “Spacer”

Advanced modeling techniques for the wheel connection were implemented into the FE model to better represent the failure mechanisms and wheel kinematics seen in the IIHS small overlap impact. The added bumper reinforcement extension and spacer interacts with the IIHS small overlap barrier and activates the frontal rail on the driver side. The deformation of the longitudinal rail contributes to the structural crash energy absorption. Full-scale test results showed that the design changes mainly affected performance in the IIHS small overlap impact, while other crash configurations, such as NCAP full overlap and NHTSA left oblique impact, showed similar results for the MY 2012 and MY 2015 vehicles.

All updates were implemented to the driver and passenger side of the FE model. The associated added vehicle mass was equivalent to 9.7 kg and is like the difference in vehicle mass from NHTSA's left oblique test of a MY 2015 vehicle (test #8790, 1450 kg as delivered, 1734 kg as tested) and a MY 2012 vehicle (test #9124, 1443 kg as delivered, 1759 kg as tested).

Test data from the MY 2015 vehicle was used to evaluate the updated FE model. Full-scale crash tests with vehicles that included these changes are called “2015 Toyota Camry” tests in the remainder of this paper. Even though complete information for all the detailed design changes from MY 2012 to MY 2015 was not available, it was determined that the updated FE model does a good job of simulating the performance of the MY 2015 mid-size sedan in the respective crash configurations.

Shown in Figures 3 and 4 are the vehicle's longitudinal (X-axis) acceleration time histories for the left oblique and right oblique simulations versus the test results. Also shown in each figure is the CORA rating value. The CORA values of 0.94 and 0.93 respectively represent a good correlation between the test and simulation results.

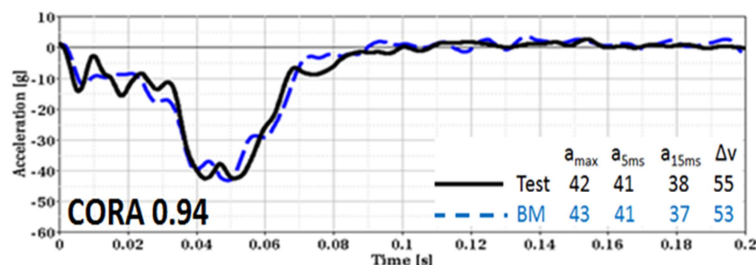


Figure 3 - 2015 Left Oblique Test vs Sim. - Vehicle Pulse

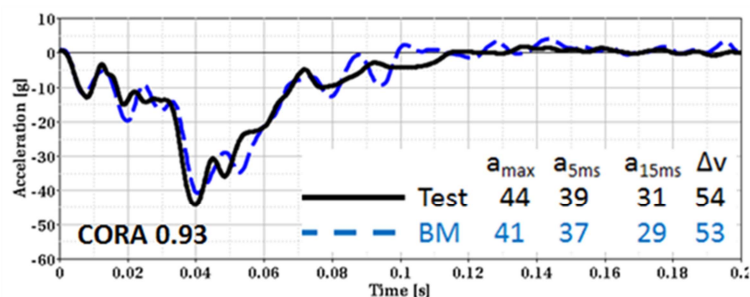


Figure 4 - Right Oblique Test vs Sim. - Vehicle Pulse

All baseline simulations were conducted using this model. It will be called the “2015 Toyota Camry Baseline Model (TCBM)” in the remainder of this paper. For this study looking at CFRP composite structural modifications, the developed structural countermeasures to significantly reduce occupant compartment intrusion were evaluated with respect to the TCBM and to the TCBM with the high strength steel modifications.

CFRP COMPOSITE MATERIAL SELECTED FOR STUDY

In a previous study [16], a braided carbon-fiber thermoset composite material was selected as the steel substitute in the vehicle structures. Many material tests and numerical simulations were conducted to identify its material characteristics for a Carbon Fiber Reinforced Plastic (CFRP). Their results are described in the project report [16]. A brief summary of these is described in this section. The developed and validated material card was used for select components when developing structural countermeasures to reduce occupant compartment intrusion in NHTSA’s oblique impact configuration.

Tri-axial braided composites can offer an isotropic design by using axial and angled fiber bundles in a single plan. Braided composites also offer better damage resistance, torsional stability, and bending strength compared to unidirectional or weaved composites. Tri-axial braided composites have been used in the commercial aerospace and automotive industry for over 20 years. They are well suited for components that are of simple geometry and need to provide off-axis as well as unidirectional strength. In addition, various studies using braided composites have been conducted and published.

The selected braided CFRP composite used for the material tests is described as follows. The carbon fiber was Torayca T700S C 12000, manufactured by Toray Carbon Fibers America, Inc. The braid architecture is $0^\circ/\pm 60^\circ$ 2D triaxial (2D3A), as shown in Figure 5. The axial fiber tows contained 24K fibers. The bias tows contained 12K fibers. The resin was Epon 862 epoxy with an Epikure W curing agent, both manufactured by Momenive.

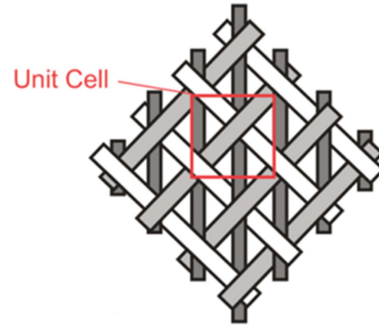
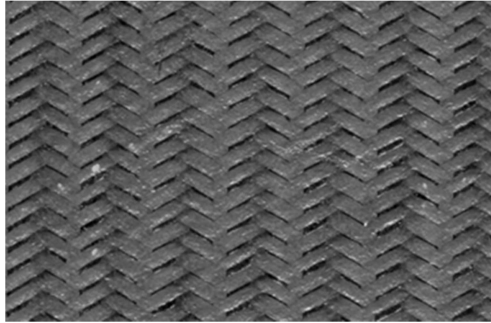


Figure 5 - 2D3A braided composite: (a) panel, (b) unit cell.

Tension, compression and shear coupon tests were performed in two different directions (axial and transverse) and at four different loading rates. The tension test used two different types of specimens; a standard specimen and a bowtie specimen. A total of 72 coupon tests were conducted. Tube compression tests were performed with three different loading rates. Reference 16 provides a summary of the test data and the material properties used for LSDYNA's MAT58 material cards.

STRUCTURAL COUNTERMEASURES

Three sets of countermeasures using high-strength steel materials were developed to meet the defined design goals in the previous project, funded by NHTSA. The countermeasure model ("CM-Steel") that showed the highest amount of occupant compartment intrusion reduction is discussed in this paper. It serves as reference for the countermeasure model using composite material ("CM-Composite"). Occupant compartment intrusion was reduced by more than 60% compared to the baseline model (BM). Figure 6 presents an overview of the implemented modifications for CM-Steel.

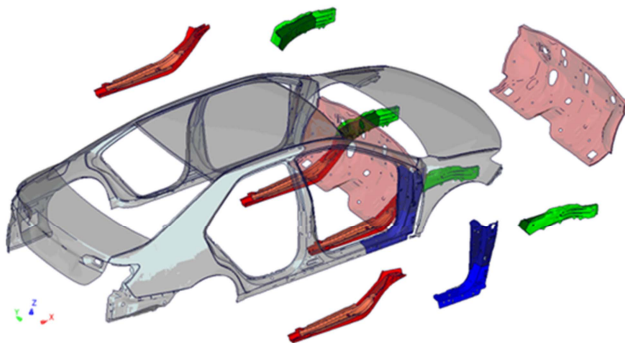


Figure 6 – CM Steel - Structural Countermeasures

The firewall, three components of the right hinge pillar, two parts of the left and right frontal rails, and three parts of the left and right mid-rails were modified.

In order to reduce maximum toe-pan intrusion and local buckling, the material thickness and material strength were increased for the firewall, shown in pink. Material thickness was also increased for three components of the right hinge pillar, shown in blue. For the inner hinge pillar (a) and the middle hinge pillar (b) material strength was also increased. The material strength for the outer hinge pillar (c) was not changed in order to allow the same manufacturing stamping process used for the BM. Changes to the right hinge pillar contributed to reduced intrusion and reduced local buckling, specifically in the right oblique impact. The parking brake on the driver side acts as a reinforcement of the hinge pillar area on the driver side. Therefore, the left hinge pillar components were not changed.

In order to reduce the load induced into the firewall, material thickness for two parts of the left and right frontal rails, shown in green, were marginally reduced. This contributed to reduction in maximum toe-pan intrusion and local buckling.

For this study, the use of CFRP composite material for the development of structural countermeasures to significantly reduce occupant compartment intrusion in NHTSA's oblique impact condition required having a thorough understanding of the crash mechanisms. The baseline vehicle model crash simulations were analyzed with respect to crash mechanisms that specifically contribute to the observed intrusion in left and right oblique impacts.

Local buckling of the firewall was found to be a major factor. Highest intrusion values were observed for toe-pan measurement points in row 1, which represent the most forward and upward locations. It was found that the load transferred through the longitudinal rail contributed to the maximum intrusion values. It can be noted that the load introduced through the frontal rails is being leveraged through the difference in height between the frontal rail and the bottom of the mid-rails. The load introduced through the frontal rail contributes to the maximum intrusion values and local buckling of the toe-pan.

Local buckling of the mid-rails also contributed to the observed occupant compartment intrusion. It was found that there was a significant amount of deformation occurring in the right mid-rail. The parking brake on the driver side is connected to the rocker pillar and the toe-pan area. It acts as a reinforcement of the rocker pillar area on the driver side. Since there is no equivalent component on the passenger side, a significant amount of deformation of the right rocker pillar components was observed in the right oblique impact configuration. Deformation of the rocker pillar components on the passenger side contributed to the maximum occupant compartment intrusion in the right oblique impact.

A firewall support component around the steering column exists on the driver side. The absence of an equivalent firewall support component on the passenger side contributed to the maximum occupant compartment intrusion in the right oblique impact.

As a result of the above analysis, an evaluation was undertaken to determine if a similar reduction of occupant compartment intrusion could be achieved by using the CFRP composite for the firewall component. Three different thicknesses, i.e., 1.2 mm (2 layers), 2.4 mm (4 layers), and 3.6 mm (6 layers) were evaluated. The associated change in vehicle mass for the CM-Composite vehicles compared to the TCBM was -15 kg, -11 kg, and -7 kg, respectively.

RESULTS

Left Oblique Impact

CM-Steel simulation results were compared against the respective BM simulation in NHTSA's left oblique impact configuration. The maximum toe-pan intrusion was reduced by more than 60%. Figure 7 shows a cross-section view of the left passenger compartment. The black line represents the un-deformed "pre-crash" vehicle. The red line represents the deformed shape of the baseline model with high occupant compartment intrusion. The green line shows the deformed shape of the CM-Steel vehicle with a significant reduction of intrusion compared to the BM. The associated change in mass when using countermeasures made out of steel, was +17 kg compared to the BM.

The dark red line represents the CM-Composite 1 vehicle, where a composite material made out of two layers was used for the firewall. Intrusion was as high as for the BM and the associated change in mass was -15 kg. The yellow line shows the CM-Composite 2 vehicle with 4 layers of composite and an associated change in mass of -11 kg. Intrusion was reduced compared to the BM but was still significantly higher than for the CM-Steel vehicle. The blue line represents the CM-Composite 3 vehicle with 6 layers of composite. The respective thickness was 3.6 mm and the associated reduction in mass compared to the BM was -7 kg. Similar reduction of occupant compartment intrusion was achieved with the CM-Composite 3 model compared to the CM-Steel vehicle. However, instead of adding 17 kg to the total vehicle mass when using steel countermeasures, a reduction of 7 kg was achieved when using composite countermeasures. The CM-Composite 3 vehicle will also be called "CM-Composite" in the remainder of this paper.



Figure 7 – Left Oblique Intrusion- Baseline vs. CM-Steel and CM-Composite

Figure 8 shows the vehicle pulse, measured at the rear of the vehicle and processed using a SAE 60 filter. An overall similar vehicle pulse was observed for the CM-Steel vehicle, shown in green, and the CM-Composite vehicle, shown in blue. The maximum peak of both vehicles was only marginally higher than measured for the BM, shown in red. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM-Steel and CM-Composite was therefore predicted.

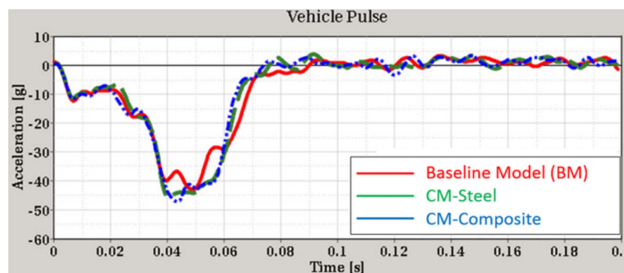


Figure 8 – Left Oblique Vehicle Pulse - BM vs. CM-Steel and CM-Composite

Right Oblique Impact

CM-Steel simulation results were compared against the respective BM simulation in NHTSA's right oblique impact configuration. The maximum toe-pan intrusion was reduced by more than 60%. Figure 9 shows a cross-section view of the left passenger compartment. The black line represents the un-deformed "pre-crash" vehicle. The red line represents the deformed shape of the baseline model with high occupant compartment intrusion. The green line shows the deformed shape of the CM-Steel vehicle with a significant reduction of intrusion compared to the BM. The associated change in mass when using countermeasures made out of steel, was +17 kg compared to the BM. The dark red line represents the CM-Composite 1 vehicle, where 2 layers of composite material were used for the firewall. Intrusion was as high as for the BM and the associated change in mass was -15 kg. The yellow line shows the CM-Composite 2 vehicle with 4 layers of composite and an associated change in mass of -11 kg. Intrusion was reduced compared to the BM but was still significantly higher than for the CM-Steel vehicle. The blue line represents the CM-Composite 3 vehicle with 3 layers of composite. The respective thickness was 3.6 mm and the associated reduction in mass compared to the BM was -7 kg. Similar reduction of occupant compartment intrusion was achieved with the CM-Composite 3 model compared to the CM-Steel vehicle. However, instead of adding 17 kg to the total vehicle mass when using steel countermeasures, a reduction of 7 kg was achieved when using composite countermeasures.



Figure 9 – Right Oblique Intrusion- Baseline vs. CM-Steel and CM-Composite

Figure 10 shows the vehicle pulse, measured at the rear of the vehicle and processed using a SAE 60 filter. An overall similar vehicle pulse was observed for the CM-Steel vehicle, shown in green, and the CM-Composite vehicle, shown in blue. The maximum peak of both vehicles was only marginally higher than measured for the BM, shown in red. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM-Steel and CM-Composite was therefore predicted.



Figure 10 – Right Oblique Vehicle Pulse - BM vs. CM-Steel and CM-Composite

NHTSA NCAP Full Overlap

In the NCAP full frontal configuration, the tested vehicle travels at a speed of 56 km/h with full overlap co-linear into a rigid wall. In the full-scale test, the vehicle is equipped with a 50th percentile male Hybrid III dummy in the driver seat and with a 5th percentile female Hybrid III dummy in the passenger seat. The current NCAP rating is based on injury risk assessment rather than occupant compartment intrusion.

The effect of structural countermeasures developed for NHTSA's oblique impact was evaluated for the NCAP full overlap load case. The CM-Steel vehicle with countermeasures using high-strength steel (+17 kg) and the CM-Composite vehicle with 6 layers (-7 kg) were evaluated with respect to the baseline model.

Figure 11 shows a cross-section view on the driver side. The geometrical shape of the vehicle “pre-crash” is shown in black. The deformed shape of the BM after the vehicle has impacted a rigid wall at 56 km/h is shown in red. The occupant compartment intrusion is smaller than for the oblique impact configurations. The vehicle with countermeasures out of high-strength steel (CM-Steel) is shown in green and the CM-Composite vehicle is depicted in blue. No significant occupant compartment intrusion was observed for either countermeasure models. CM-Steel and CM-Composite resulted in a reduction of occupant compartment intrusion compared to the BM in NHTSA's NCAP full overlap load case.

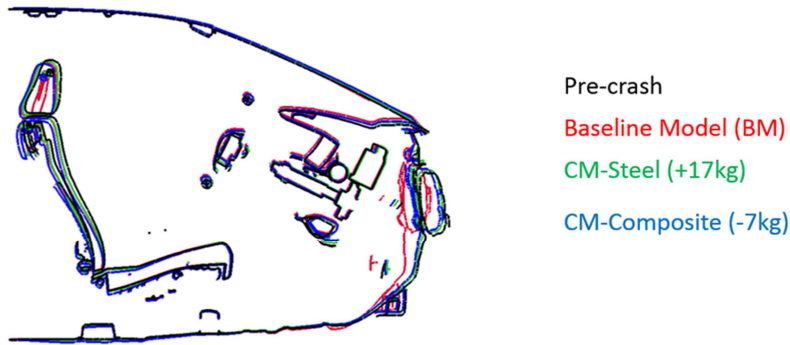


Figure 11 – NCAP Full Overlap – BM vs. CM-Steel and CM-Composite

Figure 12 shows the vehicle pulse, measured at the rear of the vehicle and processed using a SAE 60 filter. An overall similar vehicle pulse was observed for the CM-Steel vehicle, shown in green, and the CM-Composite vehicle, shown in blue. The maximum peak of both vehicles was similar to the BM, shown in red. While the first peak, caused by initial contact of the rigid barrier with the engine, was the same for the BM and CM-Steel, the initial peak was marginally lower for the CM-Composite vehicle. The second peak at about 50ms showed the opposite trend. The CM-Composite vehicle showed a marginally higher peak compared to the BM and CM-Steel. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM-Steel and CM-Composite was therefore predicted.

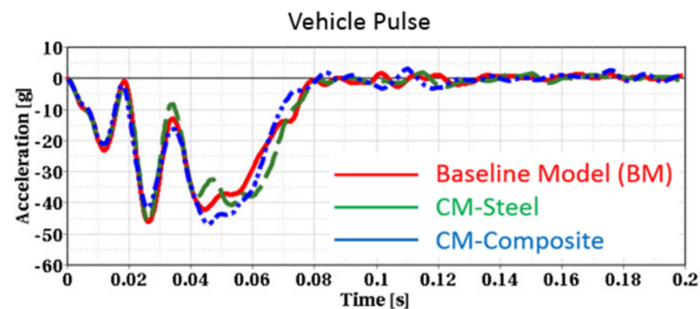


Figure 12 – NCAP Vehicle Pulse – BM vs. CM-Steel and CM-Composite

IIHS Moderate Overlap (40%)

In the IIHS moderate overlap configuration, the tested vehicle travels at a speed of 64 km/h with a 40 percent overlap co-linear into a fixed deformable barrier. In the full-scale test, the vehicle is equipped with a 50th percentile male Hybrid III dummy in the driver seat. The structural rating is based on comparison of intrusion measurements with rating guidelines for the upper and lower occupant compartment.

The effect of structural countermeasures developed for NHTSA's oblique impact was evaluated for the IIHS moderate overlap load case. The CM-Steel vehicle with countermeasures using high-strength steel (+17 kg) and the CM-Composite vehicle with six layers (-7 kg) were evaluated with respect to the baseline model.

Figure 13 shows a cross-section view on the driver side. The geometrical shape of the vehicle "pre-crash" is shown in black. The deformed shape of the BM after the vehicle impact is shown in red. A significant amount of occupant compartment intrusion can be observed for the BM. The vehicle with countermeasures out of high-strength steel (CM-Steel) is shown in green and the CM-Composite vehicle is depicted in blue. No significant occupant compartment intrusion was observed for either countermeasure models. CM-Steel and CM-Composite resulted in a reduction of occupant compartment intrusion compared to the BM in the IIHS moderate overlap load case.

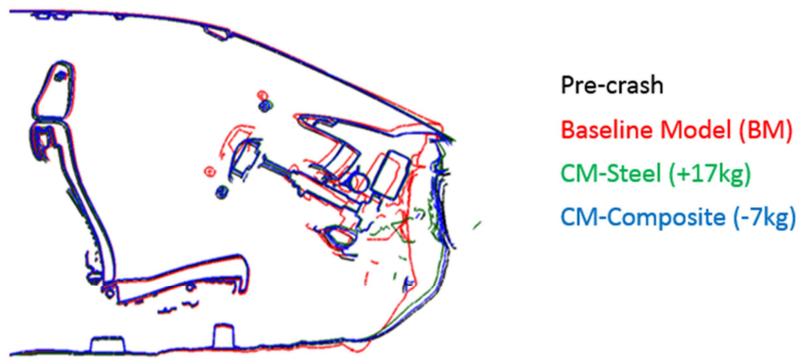


Figure 13 – IIHS Moderate Overlap – BM vs. CM-Steel and CM-Composite

Figure 14 shows the vehicle pulse, measured at the rear of the vehicle. An overall similar vehicle pulse was observed for the CM-Steel vehicle, shown in green, and the CM-Composite vehicle, shown in blue. The maximum peak of both vehicles was similar to the BM, shown in red. The maximum peak of the CM-Steel vehicle was slightly lower than the BM. The peak of the CM-Composite vehicle occurred marginally earlier than the BM. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM-Steel and CM-Composite was therefore predicted.

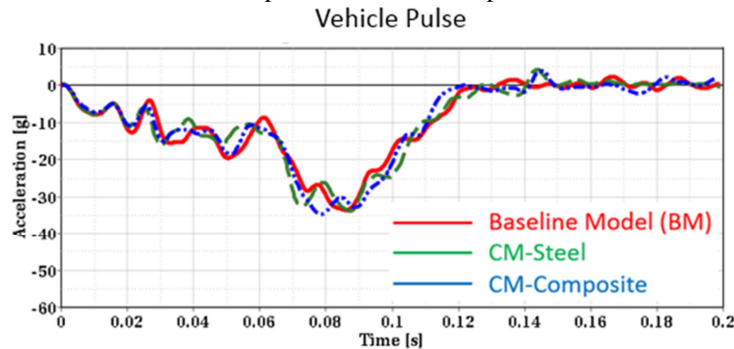


Figure 14 – IIHS MO Vehicle Pulse – BM vs. CM-Steel and CM-Composite

IIHS Small Overlap (25%)

In the IIHS small overlap configuration, the tested vehicle travels at a speed of 64 km/h with a 25 percent overlap co-linear into a fixed rigid barrier. In the full-scale test, the vehicle is equipped with a 50th percentile male Hybrid III dummy in the driver seat.

The effect of structural countermeasures developed for NHTSA's oblique impact was evaluated for the IIHS small overlap load case. The CM-Steel vehicle with countermeasures using high-strength steel (+17 kg) and the CM-Composite vehicle with six layers (-7 kg) were evaluated with respect to the baseline model.

Figure 15 shows a cross-section view on the driver side in the IIHS small (25%) overlap configuration. The geometrical shape of the vehicle "pre-crash" is shown in black. The deformed shape of the BM after the vehicle impact is shown in red. A similar amount of occupant compartment intrusion can be observed for the BM, the vehicle with countermeasures out of high-strength steel (CM-Steel), shown in green, and the CM-Composite vehicle, depicted in blue.

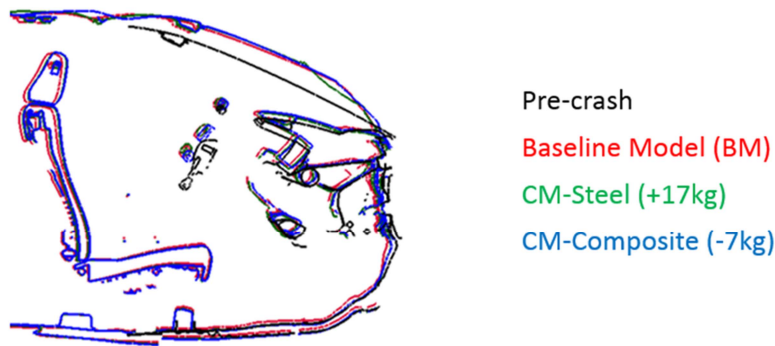


Figure 15 – IIHS Small Overlap – BM vs. CM-Steel and CM-Composite

Figure 16 shows the vehicle pulse, measured at the rear of the vehicle. An overall similar vehicle pulse was observed for the CM-Steel vehicle, shown in green, and the CM-Composite vehicle, shown in blue. The maximum peak of both vehicles was similar to the BM, shown in red. The maximum peak of the BM, CM-Steel vehicle, and CM-Composite vehicle was smaller than for other co-linear impact configurations. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM-Steel and CM-Composite was therefore predicted.

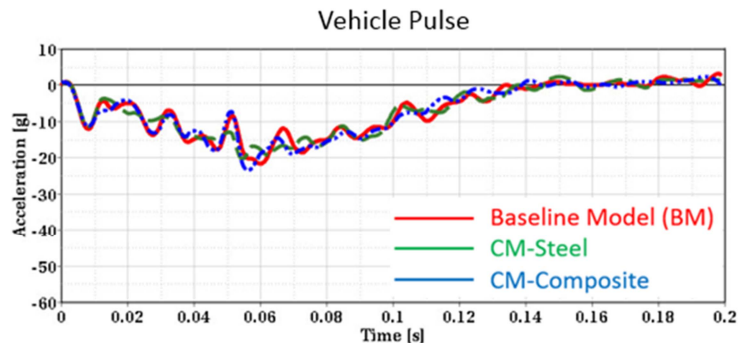


Figure 16 – IIHS SO Vehicle Pulse – BM vs. CM-Steel and CM-Composite

MATERIAL MODEL DEVELOPMENT

In an ongoing effort in cooperation with Honda R&D, a shell element version of Material Model MAT_213 in LS-DYNA for simulation of composites is being developed and validated. Between 2015 and 2018, the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), the Arizona State University (ASU), the George Mason University (GMU), and the Ohio State University's (OSU) composite material modeling consortium has sponsored the development of a material law (MAT_213) in the commercial LS-DYNA code for the simulation of composite materials under ballistic loads.

The MAT_213 has some features, such as (1) a deformation model involving elastic and plastic deformations, (2) dependency of strain-rate and temperature, (3) a damage model, (4) a failure model, and (5) a stochastic variation model. The model is driven by tabular data that is generated either using laboratory tests or via virtual testing. However, this material law was implemented for solid elements only.

In cooperation with Honda, GMU is implementing this material law for plane stress conditions so that it can be used by shell elements based on thin shell theory. This will allow for applying the material law to the simulation of thin panels undergoing loads occurring in automotive crash applications.

Current activities includes code development and verification, characterization of a material law for a composite material based on coupon testing, comparison of different discretization techniques when used in conjunction with MAT_213 for solids and/or shells, and validation of the material model based on component testing.

Many coupon tests are required to develop the material parameters of the material model for a particular composite. The developed material model will be validated by component test simulations, such as head form impact test and static/dynamic crush tests.

The material development and validation efforts within the formed consortium is of significant relevance for the research conducted by GMU for ACC. Honda is planning to share this work with plastic and composite material suppliers to allow them to develop material models of their composite products. That way, OEMs can directly use the material models provided from suppliers to be used in crash simulations for component designs and other analyses.

It is anticipated that this new material model will allow for better simulating and predicting the crash performance of components made out of composites in the future. Plastic and composite material suppliers can use methods and tools developed by the GMU Team in previous projects to evaluate their components in relevant crash loading conditions.

CONCLUSIONS

This research project helped to further understand the numerical polymer/composite material models and their CAE applications.

NHTSA found that oblique crashes represent common real-world accident patterns. The risk of injury in oblique impact configurations is often higher than in co-linear crashes. IIHS found that the risk of lower extremity injury was higher in the oblique impact tests compared to small overlap co-linear impact tests. The development of countermeasures for both restraints and vehicle structure for oblique configurations will therefore potentially improve vehicle safety and reduce injury risk in the future. Consequently, NHTSA is considering adopting a frontal oblique impact configuration into its NCAP rating protocol. NHTSA has contracted GMU in a previous project to evaluate structural countermeasures using high-strength steel materials, including associated mass, to reduce occupant compartment intrusion in the oblique impact condition.

A FE model of an appropriate mid-sized passenger vehicle was developed and validated to match the acceleration and intrusion measurements available from full-scale crash tests. Crash mechanisms that specifically contributed to high intrusion in the oblique impact condition were analyzed. Local deformation and buckling of the toe-pan, was found to be mainly responsible for producing high intrusions for both left-side and right-side oblique configurations.

A 60% reduction of the maximum intrusion was defined as the main design goal. Another design goal was to maintain moderate vehicle pulses in all impact configurations as a prerequisite for good restraint system performance and low injury risk in current and future rating tests. A model with a possible set of countermeasures using high-strength steel materials (CM-Steel) was developed. The associated increase in vehicle mass for the CM-Steel vehicle compared to the BM was +17 kg.

In the current project, countermeasures using composite material, i.e., Carbon Fiber Reinforced Plastic (CFRP), were developed to achieve a similar reduction in occupant compartment intrusion ("CM-Composite"). The associated reduction in mass for the CM-Composite was -7 kg compared to the BM and -24kg compared to the CM-Steel vehicle.

The change in vehicle pulse due to the developed countermeasures was not significant for oblique and co-linear impacts. Therefore, no unintended consequences were predicted.

In a parallel effort in cooperation with Honda R&D, a shell element version of Material Model MAT_213 in LS-DYNA for simulation of composites is being developed and validated. This will allow for better simulating and predicting the crash performance of components made out of composites in the future.

REFERENCES

- [1] Brecher, A., November 2007, "A Safety Roadmap for Future Plastics and Composites Intensive Vehicles, Report No. DOT HS 810 863, Washington, DC: National Highway Traffic Safety Administration.
- [2] Brecher, A., Brewer, J., Summers, S., & Patel S, 2009, "Characterizing and Enhancing the Safety of Future Plastic and Composite Intensive Vehicles," 21st International Conference on the Enhanced Safety of Vehicles, Stuttgart, Germany.
- [3] Barnes, G., Coles, I., Roberts, R., Adams, S. O., Garner, D. M., 2010, "Crash Safety Assurance Strategies for Future Plastic and Composite Intensive Vehicles (PCIVs)," Report No. DOT-VNTSC-NHTSA-10-01, Cambridge, MA: Volpe National Transportation Systems Center.
- [4] Fisher, M., & Cundiff, B., 2002, "APC Vision and Technology Roadmap for the Automotive Market - Defining Priority Research for Plastics in 21st Century Vehicles," SAE Technical Paper 2002-01-1890, Warrendale, PA: Society of Automotive Engineers.
- [5] Fisher, M., Kolb, J., & Cole, S., 2007, "Enhancing Future Automotive Safety with Plastics." Paper No. 07-0451, 20th International Conference on the Enhanced Safety of Vehicles, Lyon, France.
- [6] ACC Plastics Division, 2009, Retrieved from "Plastic in Automotive Markets Technology Roadmap – A New Vision for the Road Ahead," Available at www.plasticscar.com/roadmap_fullversion.
- [7] ACC Plastics Division. 2009, Plastic and Composite Intensive Vehicles: An Innovation Platform for Achieving National Priorities," Available at www.plastics-car.com/pcivs.
- [8] ACC Plastics Division, 2014, "Plastics and Polymer Composites Technology Roadmap for Automotive Markets," Available at <http://www.plastics-car.com/Tomorrows-Automobiles/Plastics-and-Polymer-Composites-Technology-Roadmap>.
- [9] Park, C-K., Achstetter, T., Kan, C-D., Hollowell, W., 2017, "Understanding of Numerical Polymer/Composite Material Models and Their CAE applications," George Mason University Final Report.
- [10] Bean, J., Kahane, C., Mynatt, M., Rudd, R., Rush, C., Wiacek, C., 2009, National Highway Traffic Safety Administration, "Fatalities in Frontal Crashes Despite Seat Belts and Air Bags", Report No. DOT HS 811 202.
- [11] DOT / NHTSA, December 2015, "New Car Assessment Program (NCAP), Request for Comments," Federal Register Vol. 80 No. 241.
- [12] Zhang, R., Reichert, R., Kan, C.-D. and Cao, L., 2015, "Evaluation of driver lower extremity injuries in 16 oblique crashes with THOR", International Journal of Crashworthiness, doi: 10.1080/13588265.2015.1120983.
- [13] Mueller, R., 2017, "Comparison of Frontal Crash Modes: IIHS Small Overlap and NHTSA Oblique", Insurance Institute for Highway Safety, SAE Government/Industry Meeting, Washington, DC.
- [14] Saunders, J., Craig, M.J., Suway, J., 2011, "NHTSA's Test Procedure Evaluations for Small Overlap/Oblique Crashes," The 22nd International Technical Conference for the Enhanced Safety of Vehicles, Paper No. 11-0343.
- [15] Reichert, Rudolf and Kan, Steve, TBD, "Structural Countermeasure Research Program," NHTSA Contract DTNH2215D00005/0001, Final Report to be published.
- [16] Park, C-K., Kan, C-D., Hollowell, W., & Hill, S.I. December 2012, Investigation of Opportunities for Lightweight Vehicles Using Advanced Plastics and Composites, Report No. DOT HS 811 692, Washington,

DC: National Highway Traffic Safety Administration. Available at
www.nhtsa.gov/DOT/NHTSA/NVS/Crashworthiness/Plastics/811692.pdf