Modeling and Simulation of PCB Cover Plate for Large Open Joints

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Abstract

An improved LS-DYNA® model of steel cover plate for accommodating variable gaps in roadside portable concrete barrier (PCB) installations has been developed. A two-piece cover plate model was evaluated using non-linear finite element analysis program LS-DYNA. Baseline model of F-shape PCB validated with full-scale crash testing is presented. Baseline modeling and simulation details are discussed, including the range of numerical problems and vehicle and evaluation parameters. Cover plates across the barrier joint were added using fully-integrated shell elements along with piecewise-linear plasticity material. Cover plate model was sufficiently calibrated with baseline model in order to evaluate the gap spanning hardware design. Computer simulations were conducted with a Chevrolet Silverado Version 2 (V2) model pickup truck impacting the PCB cover plate installation. Results show that cap thicknesses of less than 6 mm resulted in unacceptable buckling of cover plate. Good performance was obtained with a 6-mm thick cover plate with modified base plate and incremental stiffeners. Additional simulations and full-scale crash testing is required before guidelines can be recommended.

Introduction

Portable concrete barriers (PCB) are commonly used to protect workers in work zones and to shield motorists from hazards in construction areas. During setup or contractor operations in work zone areas, it is not uncommon to layout, construct, and connect free-standing PCB installations from different ends, which may result in a longitudinal gap between adjacent barrier segments. Longitudinal gaps can also be created due to tensioning issues following an impact event. These gaps can range from 152 mm to as long as a full barrier segment length, or 3.8 m, as shown in Figure 1. Gaps in the barrier system may pose a serious safety concern, and available guidance is challenging to accommodate this situation.

Overlapping two runs of barriers has been recommended in the past. For a more general solution to variable length gaps, the current guidance is to longitudinally overlap two adjacent barrier runs with a minimum of eight PCB segments and provide a minimum lateral offset of 0.6 m between adjacent barrier runs. However, the length of barrier overlap is relatively large and also requires significant lateral offset between the overlapped segments, which reduces available space in constricted work zones. While this solution is adequate in terms of crashworthiness, it is not always manageable in terms of available space in the work zone. Thus, a need exists to develop crashworthy and efficient methods for treating longitudinal gaps in adjacent runs of free-standing PCBs.

Gap-spanning hardware is the preferred treatment solution if it can be adjusted for a variable gap length, is easy to install and remove, and is crashworthy. In order to be crashworthy, a design solution would require development of continuity (shear, tensile, and flexural capacity) across the gap as well as the prevention of vehicle snag. The crashworthiness of the system is evaluated according to the criteria provided in the Manual for Assessing Safety Hardware (MASH), as published by the American Association of Safety Highway and Transportation Officials (AASHTO) [1]. The objective of this research effort is to develop a MASH TL-3 crashworthy system that accommodates variable gap lengths between adjacent runs of PCB segments. The research would focus on computer simulation aiding the design of the gap-spanning hardware for use with the MASH TL-3 crashworthy F-shape PCB currently used by the majority of the Midwest Pooled Fund States, gap lengths ranging from 152 mm to 3.8 m.

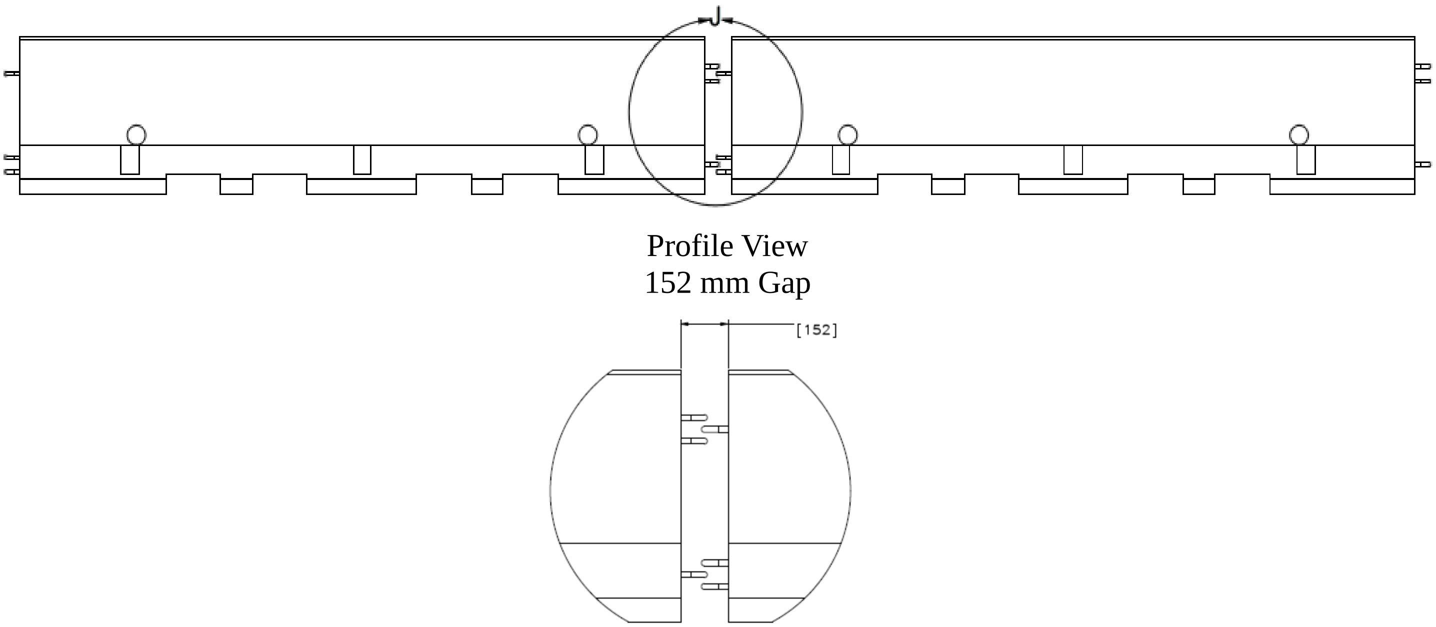


Figure 1. Example of Small Gap Formed between PCB Segments

Model of F-Shape PCB System

The model of the F-shape portable concrete barrier was based on models developed previously at Midwest Roadside Safety Facility (MwRSF) for simulation of portable concrete barriers [2-3]. The model consisted of the F-shape barrier, the end connection loops, and the connection pins, as shown in Figure 2. The geometry of the F-shape barrier model was created using shell elements with a rigid material defined with the proper mass and rotational inertias. The use of the shell elements improved the overall contact between the barrier and the vehicle. In addition, the use of shell elements made it easier to bevel the corners and edges of the barrier. By rounding off the barrier edges, the edge contacts and penetrations were reduced, thus further improving the contact interface.

The barrier-to-barrier connection consisted of two sets of three rebar loops. The connection loops were modeled with a rigid material as previous testing of the barrier in various configurations showed little to no deformation of the connection loops. The connection pin was modeled with MAT_PIECEWISE_LINEAR_PLASTICITY material in LS-DYNA [4] with the appropriate properties for ASTM A36 steel. The baseline barrier system model incorporated a total of sixteen barrier segments. A list of component used in the F-Shape barrier model and associated LS-DYNA modeling parameters is shown in Table 1.

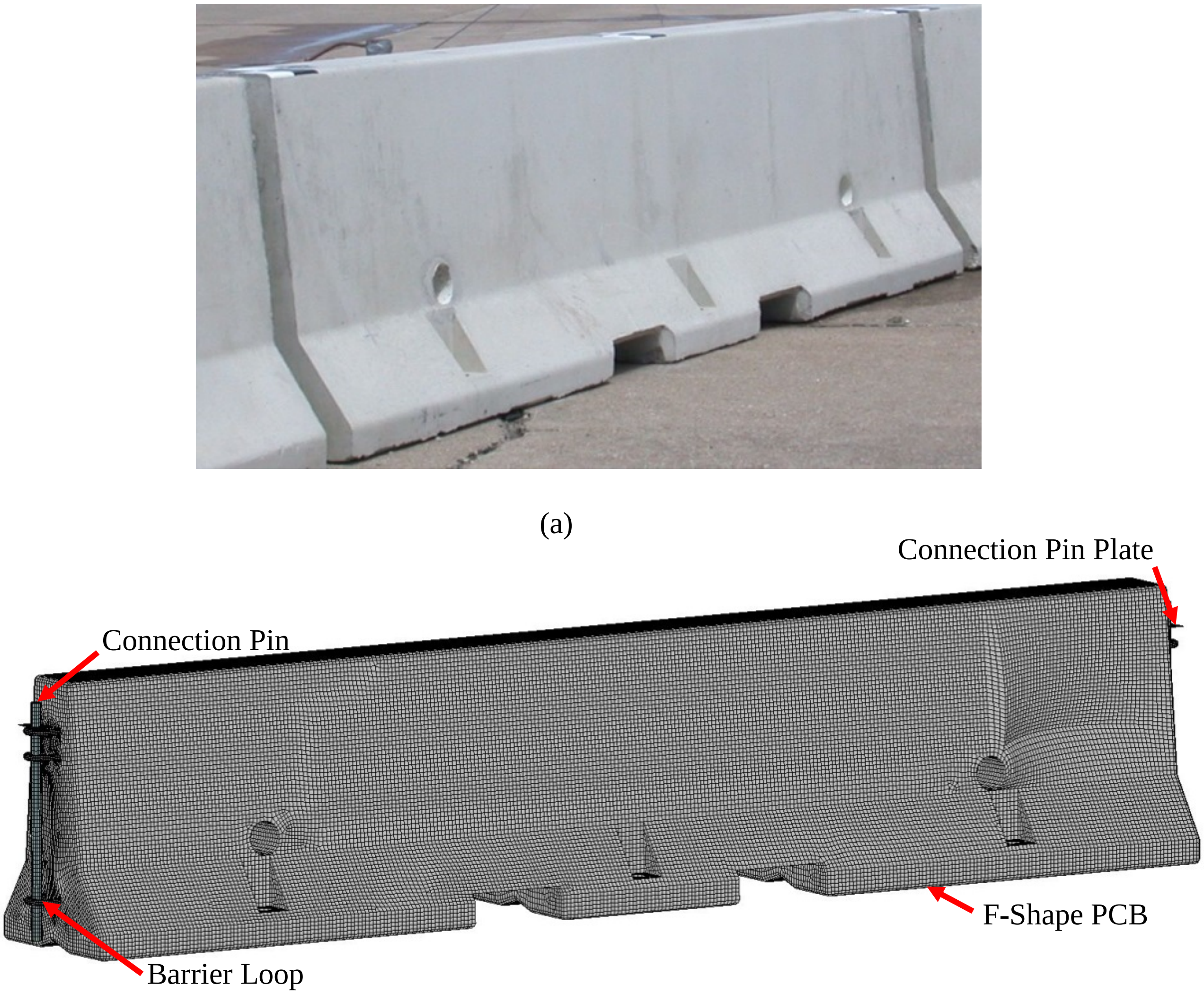


Figure 2. F-Shape PCB: (a) Actual and (b) Finite Element Model

Table 1. Summary of F- Shape PCB Parts and LS-DYNA Modeling Parameters

Part Description	Material Type	Material Formulation	Element Type	Element Formulation	Element Thickness mm
F-Shape PCB	Concrete	20 - Rigid	Shell	Belytschko-Tsay	2
Barrier Loops	ASTM A706	20 - Rigid	Solid	Constant Stress Solid Element	N/A
Connection Pin	ASTM A36	24 – Piecewise Linear Plastic	Solid	Fully Integrated, S/R Solid	N/A
Connection Pin Plate	ASTM A36	24 - Piecewise Linear Plastic	Shell	Belytschko-Tsay	12.7

NA = Not Applicable

A critical component of the baseline model of the free-standing, F-shape PCB was the definition of the barrier-to-ground friction. PCB systems use a combination of inertial resistance and longitudinal tension to redirect impacting vehicles. The longitudinal tension in the barrier system is largely developed by barrier-to-ground friction. Previous research at Texas Transportation Institute (TTI) and MwRSF measured the kinematic friction coefficient for a concrete PCB segment sliding on concrete surface to be between 0.40 and 0.44 [2, 5], and on an asphalt surface to be 0.51. The lower friction value of 0.40 was selected for use in the analysis in order to better correlate with the road surface used in the full-scale testing and to maximize potential deflections. This friction value was applied in the LS-DYNA baseline model between the barrier segments and the shell element ground.

In addition to providing appropriate friction coefficients, the barrier model needed to develop the correct normal forces on the ground. This behavior was accomplished by allowing the barriers in the simulation model to reach quasi-static equilibrium on the ground prior to being impacted. Damping was used to help the barriers reach a steady normal force on the ground and was turned off prior to vehicle impact. An example of the barrier weight forces on the ground in the model is shown in Figure 3.

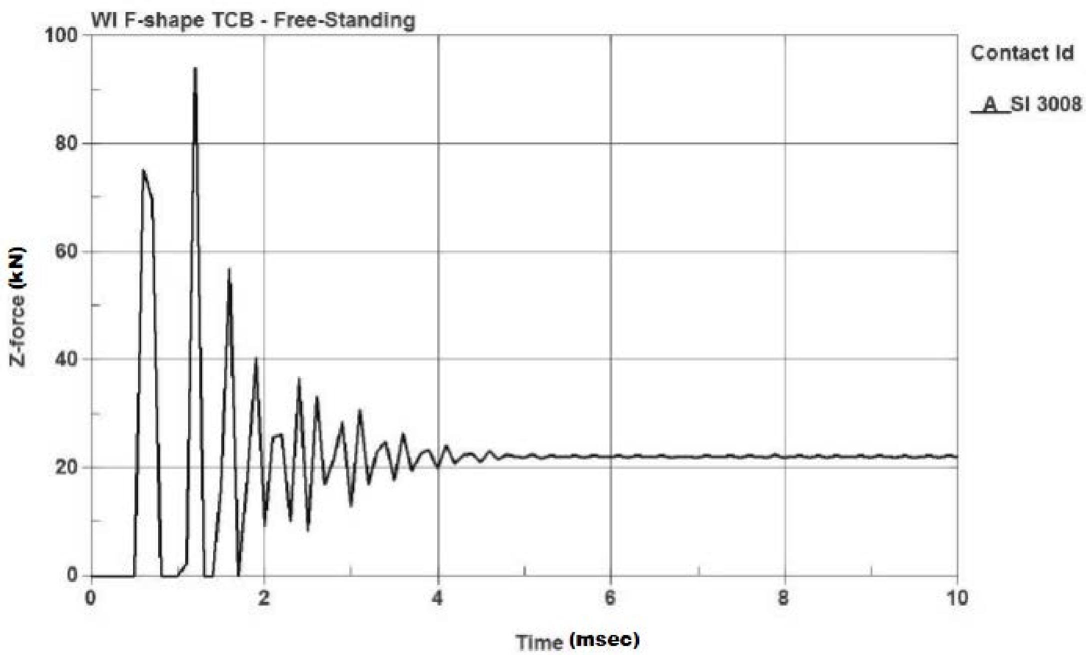


Figure 3. Barrier Segment-to-Ground Contact Forces Prior to Impact

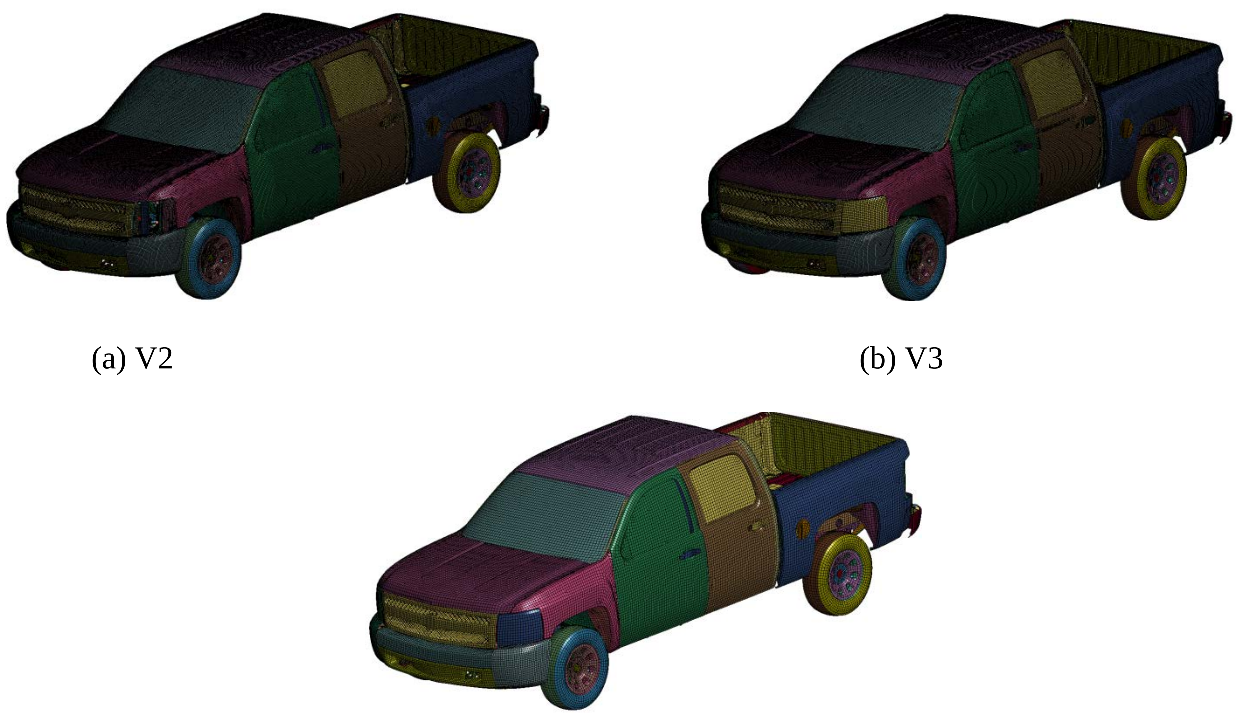
Vehicle Models

MASH denotes that a TL-3 longitudinal barrier such as the F-shape PCB utilized in this research, must be subjected to impacts with the 2270P pickup truck and the 1100C small car. However, the 2270P test vehicle was deemed more critical than the 1100C small car due to the likelihood of increased barrier deflections, impact loading, and barrier pocketing. Further, vehicle instabilities have been exhibited during full-scale crash tests involving 2270P pickup trucks with F-shape PCB systems due to vehicle climb.

The Chevrolet Silverado quad cab vehicle model was chosen for the research and simulation study. The Silverado vehicle model was originally created by the National Crash Analysis Center (NCAC) [6], and later modified by MwRSF personnel for use in roadside safety applications. Three versions of the Chevrolet

Silverado vehicle model were investigated as part of the analysis of the baseline model: Version 2 (V2); Version 3 (V3); and Version 3 – Reduced (V3r). All three versions of the vehicle model represented the same Chevrolet Silverado quad cab vehicle, but there were differences in the tires, steering capability, vehicle-to-ground friction, and mesh size, among other factors. These differences are summarized in Figure 4.

The V3 and V3r models of the truck incorporated steering of the front wheels, while the V2 model did not. The V2 model had a tire stiffness that correlated with the stiffness of actual truck tires, while the V3 and V3r models used significantly stiffer tire models. The meshes for all three versions of the truck model were different, with the main variation being the larger, coarser mesh of the reduced model. The coarser mesh of the V3r model improved its CPU efficiency, but it may have had other effects in terms of contacts and vehicle deformation. Finally, the V3 and V3r models used default tire-to-ground friction values that were over twice as high as the default value for the V2 model. It was believed that these differences in the vehicle models could contribute to the accuracy of the baseline model. Thus, all three vehicle models were used and compared when simulating the baseline model of the F-shape PCB system. Additional variations to the truck model that had been implemented by MwRSF over time were also investigated. These variations included the use of additional weld attachments between the truck box and frame in Version 3 that had previously been shown to improve stability and disengagement of the front wheels to represent suspension failure.



(a) V2

(b) V3

(c) V3r

Version No.	Tire	Steering Capability	Vehicle-to-Ground Friction	Mesh
V2	Softer	No	$\mu = 0.40$	Fine
V3	Harder	Yes	$\mu = 0.90$	Fine
V3r	Harder	Yes	$\mu = 0.90$	Coarse

Figure 4. Chevrolet Silverado 2270P Truck Model Variations

Baseline Model Simulations

The baseline model of the sixteen, free-standing, F-shape PCBs was simulated with a 2270P vehicle impacting the system at a speed of 62 mph (100 km/h) and at an angle of 25 degrees. The vehicle impacted the system 1.3 m upstream of the center of the joint between the eighth and ninth barrier segments. In order to evaluate the barrier model, a series of simulations were conducted with modified versions of the V2, V3, and V3r Chevrolet Silverado models, modifying tire-to-ground friction, exploring the use of front wheel disengagement, and the application of additional weld connections on the back end of the vehicle. The various models were compared to test no. 2214TB-2 [7] based on the high-speed video comparison, dynamic barrier deflection, and RSVVP comparison of transducer data.

Simulation of the F-shape PCB system with the Chevrolet Silverado V2 model demonstrated better correlation with the full-scale test results than the previous simulations with the V3 and V3r vehicles. The softer tires and lower tire-to-ground friction resulted in vehicle climb and roll and pitch motions that corresponded well with test no. 2214TB-2 as shown in Table 2. In addition, very little wheel turn was observed during test no. 2214TB-1, which was more similar to the V2 model than the V3 or V3r models. Similarly, vehicle yaw and lateral accelerations during tail slap were more similar with the V2 model as compared to the V3 and V3r models.

Table 2. Comparison Results of F-Shape PCB System Test and Simulation

Evaluation Parameters	Impact Speed (km/h)	Impact Angle deg.	Dynamic Deflection mm	Long. ORA (g's) < 20.49	Lateral ORA (g's) < 20.49	Long. OIV (m/s) < 12.2	Lateral OIV (m/s) < 12.2
Test No. 2214 TB-2	99.7	25.4	2,024	-7.17	-11.37	-5.18	-5.27
Simulation	99.7	25.0	2,059	-7.6	-12.7	-5.2	-5.4

The comparison of the results from the Chevrolet Silverado V2 model impacting the F-shape PCB system are shown in sequential images in Figures 5 through 6. The simulation of the PCB impact with the V2 model had a peak dynamic barrier displacement of 2,061 mm, which was nearly identical to the 2,022 mm displacement observed in test no. 2214TB-2 as shown in Table 2. Additional simulations were conducted with the Chevrolet Silverado V2 model impacting the F-shape PCB system that included disengagement of the front wheel on the impact side as was observed in the test. The overall response of the Chevrolet Silverado V2 model with front wheel disengagement was very similar to the original V2 simulation in terms of vehicle deceleration and barrier displacement. Disengagement of the front wheel increased vehicle roll and decreased vehicle climb of the barrier as compared to test no. 2214TB-2. Additionally, disengagement of the front wheel tended to produce instabilities in some impact configurations due to the interaction of the disengaged tire and wheel with the barrier and ground later in the impact event.

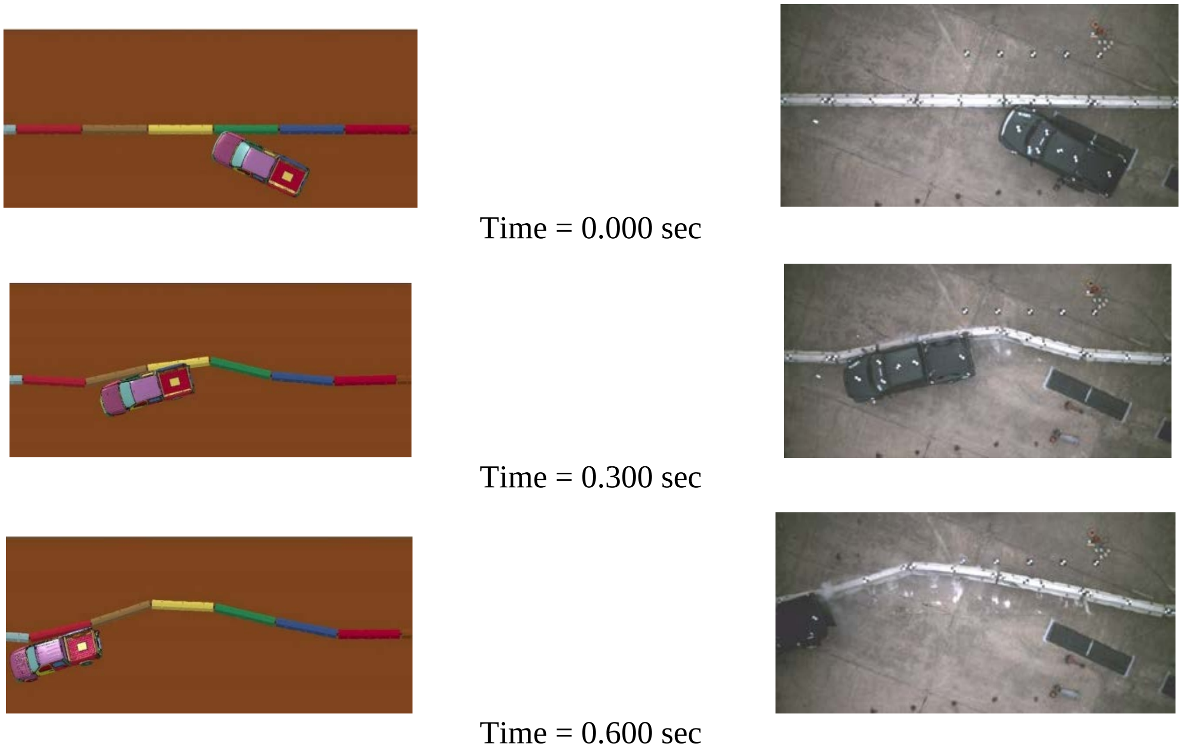


Figure 5. Overhead Sequential Views, Chevrolet Silverado V2 Model and Test No. 2214TB-2

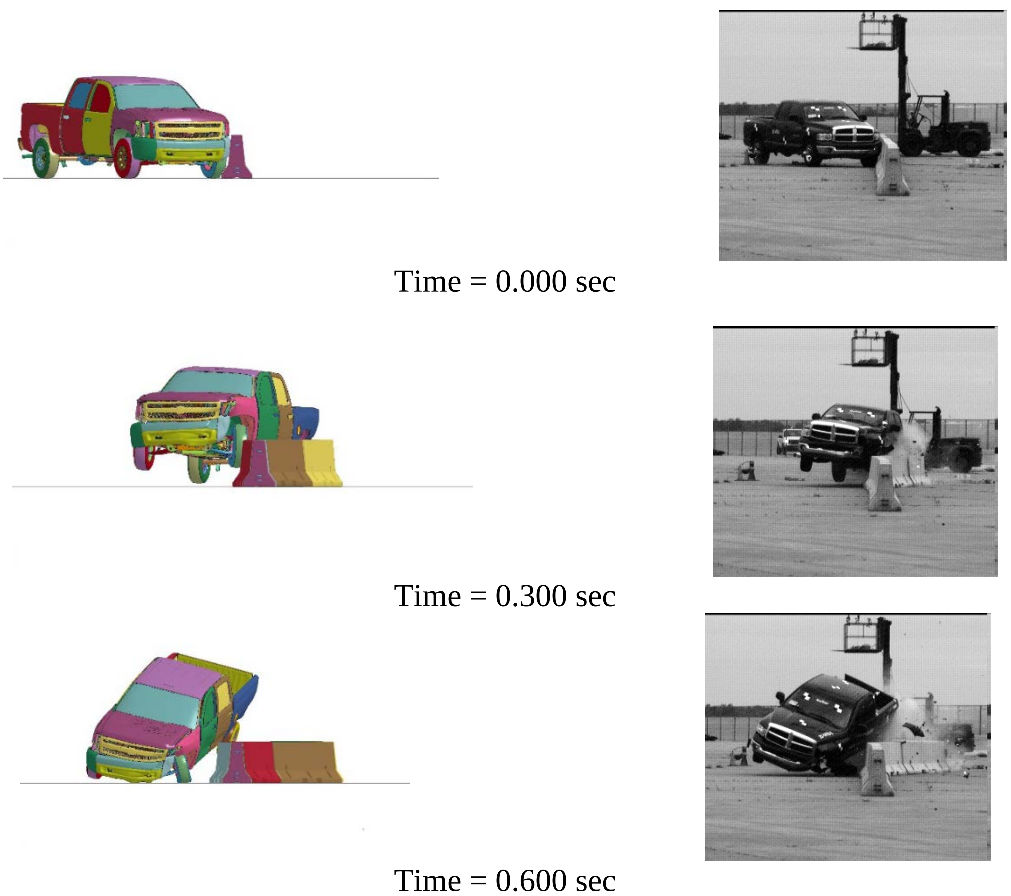
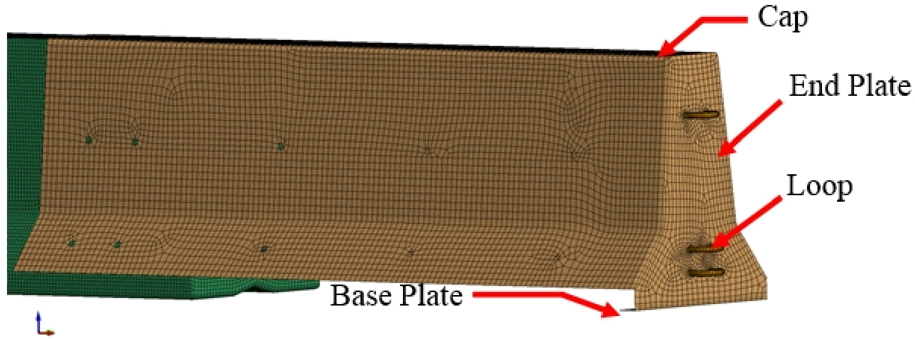


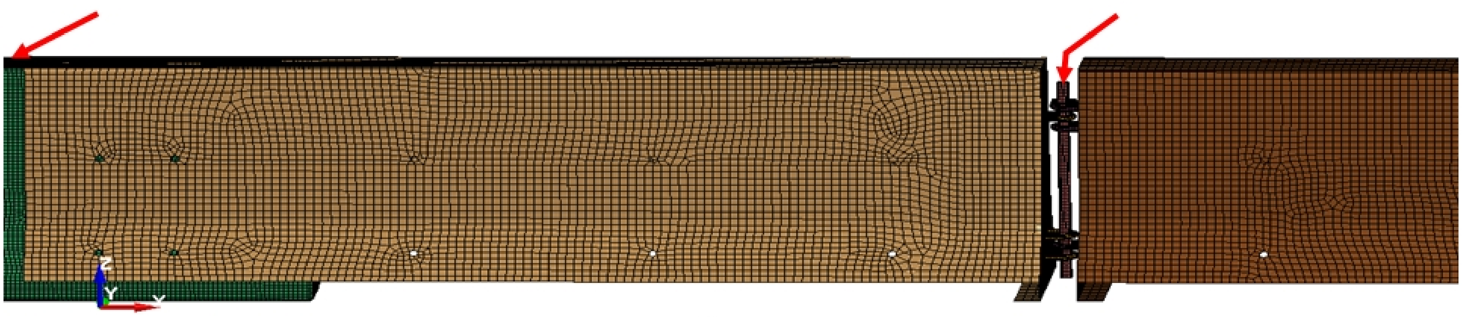
Figure 6. Downstream Sequential Views, Chevrolet Silverado V2 Model and Test No. 2214TB-2

Model of F-Shape PCB Cover Plate System

The baseline model of F-shape PCB was modified with the representations of cover plate design. The replacement one piece steel cover plate consists of a total length of 2,743 mm as shown in Figures 7 (a). If the gap is short, which is defined to be less than 1.8 m, only one cover plate is required, and the steel segment is connected to the downstream PCB segment using a standard pin-and-loop connection. If the gap is longer than 1.8 m, then two steel cover plates are required, anchored to PCBs on both sides of the gap and connected together using a pin-and-loop connection. In order to create a gap of 3.8 m, one barrier segment of the model was removed, and the two piece cover plates were added spanning the resulting gap. The cover plate geometry was modified to add multiple holes to accommodate variable gap length. Hence, the cover plate design configuration is capable of spanning gap lengths from 152 mm to 3.8 m. A 3D geometric model of cover plate was developed in Solidworks and was imported into Hypermesh for initial pre-processing and meshing of cover plate geometric model. Steel cover plate final meshed model and its one and two piece configuration is shown in Figures 7 (a) and 7(b).



(a)



(b)

Figure 7. PCB Gap Steel Cover Plate Model (a) 1-Piece Cover Plate (b) 2-Piece Cover Plate

Table 3. Summary of PCB Gap Parts and LS-DYNA Modeling Parameters

Part Description	Material Type	Material Formulation	Element Type	Element Formulation	Element Thickness mm
Cap	ASTM A1011 Grade 50	24 – Piecewise Linear Plastic	Shell	Fully integrated shell element	6
End Plate	ASTM A1011 Grade 50	24 – Piecewise Linear Plastic	Shell	Fully integrated shell element	13
Stiffeners	ASTM A1011 Grade 50	24 – Piecewise Linear Plastic	Shell	Fully integrated shell element	6

Cap across PCB segments was added using shell elements with MAT_24_PIECEWISE_LINEAR_PLASTICITY, to define the ASTM A1011 Grade 50 steel material properties for these components. The element equivalences is applied to cover plates at the anchored locations overlapped with barrier segments. The solid loops were added using rigid material properties and the meshes of the loops and surface of the end cap were merged together. Cylindrical steel pins were used to connect adjacent cover plates together using MAT-24 and A36 material. A list of PCB steel cover plate modelling parts and associated LS-DYNA modeling parameters is shown in Table 3.

PCB Gap Cover Plate Simulations

The LS-DYNA model of fifteen, free standing F shape PCBs and a two piece cover plate were simulated with 2270P vehicle impacting the system at a speed of 100 km/h and at an angle of 25 degrees. The vehicle impacted the system 1.3 m upstream from the center of the cover plate joint. For this initial study, the model was modified to conduct the simulation with five different cap thicknesses of cover plate in order to evaluate the suitable thickness for prototype design. End plate thickness was started with 13 mm, and the stiffener sections are included in simulations, as defined in Table 3.

It was necessary to determine evaluation criteria for which to properly analyze and rank the concepts as well as determine the likelihood of crash test success. The evaluation criteria included vehicle behavior, occupant risk, lateral barrier deflection, and damage to cover plates. Occupant risk measurements in MASH are used to evaluate the degree of hazard to the occupant in the impacting vehicle; they include the occupant impact velocity (OIV) and the occupant ride down acceleration (ORA) [1]. In addition, the barrier dynamic deflection was measured in each simulation. Cap lateral deformation were also considered to evaluate the damage to cover plates.

The results of the simulation of various cover plate configurations were collected, compared, and used to select the most desired concept for the development of a prototype system for full-scale crash testing. Simulations were conducted with non-stiffened caps with thickness of (13 mm, 10 mm, 6 mm, 5 mm, 3 mm). All the cases met the MASH criteria for ORA and OIV evaluations. A summary of the model runs is shown in Table 4. Sequential photographs with a cap thickness of 6 mm at impact point of 1,300 mm upstream of cover plate joint are shown in Figure 8. The performance of 13-mm and 10-mm non-stiffened thick caps were deemed acceptable, but plastic hinge was formed with 3-mm and 5-mm thin caps, as shown in Figure 9, which is a potential for vehicle snag and instability. Of the five simulation cases, only cap thickness with 10-mm and 13-mm passed the criteria due to excessive plastic hinge formation and excessive deformation (lateral deformation < 76 mm), as compared to the rest of cases.

Table 4. Summary of Simulation Results – Cap Thickness Varied with Impact Point 1.3 m Upstream from Cap Joint

Cap Thickness mm	Cap Lat. Deformation mm < 76	Lat. Barrier Deflection mm	Lat. OIV m/s	Long. OIV m/s	Lat. ORA g's	Long. ORA g's	Roll deg	Pitch deg
3	476.0	3,355	-3.8	-7.1	-13.2	-10.0	-20.5	9.0
5	328.3	2,961	-3.8	-6.0	-12.8	-7.5	-57.6	17.2
6	241.0	2,628	-4.2	-5.6	-12.4	6.6	-18.3	9.6
10	78.6	2,138	-4.4	-5.0	-16.8	-5.2	-19.9	15.0
13	13.5	1,989	-4.3	-4.6	-17.6	-4.9	-20.9	13.6
MASH Limits	N/A	N/A	12.2	12.2	≤ 20.49	≤ 20.49	< 75	< 75

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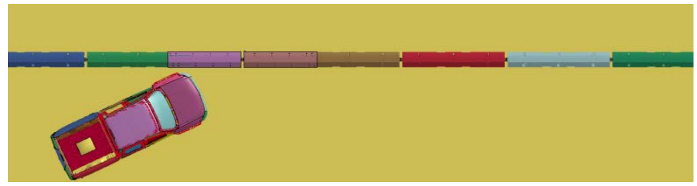

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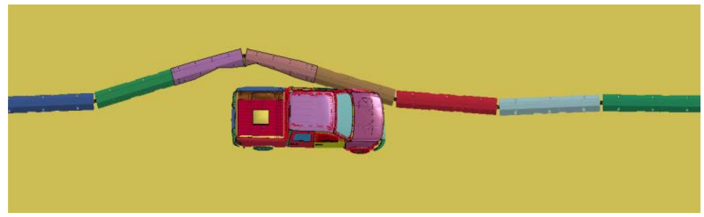

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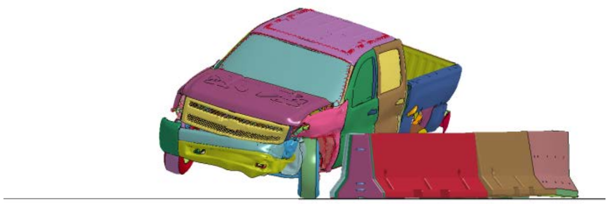

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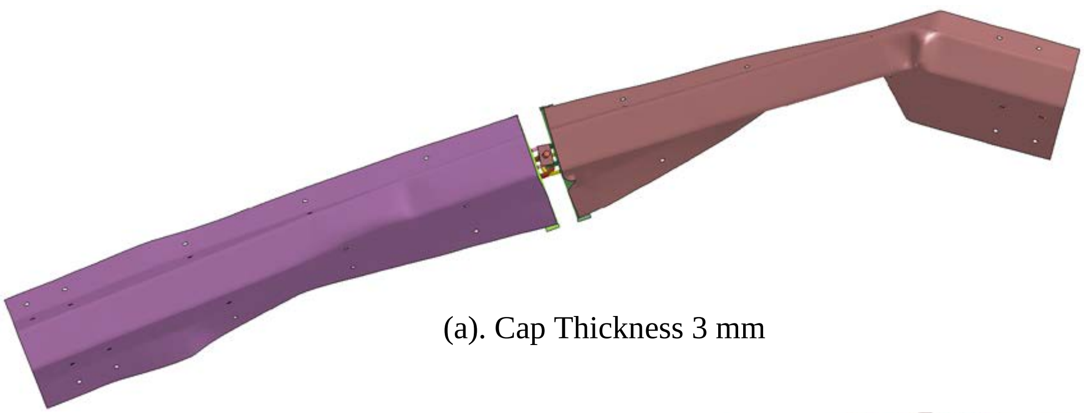
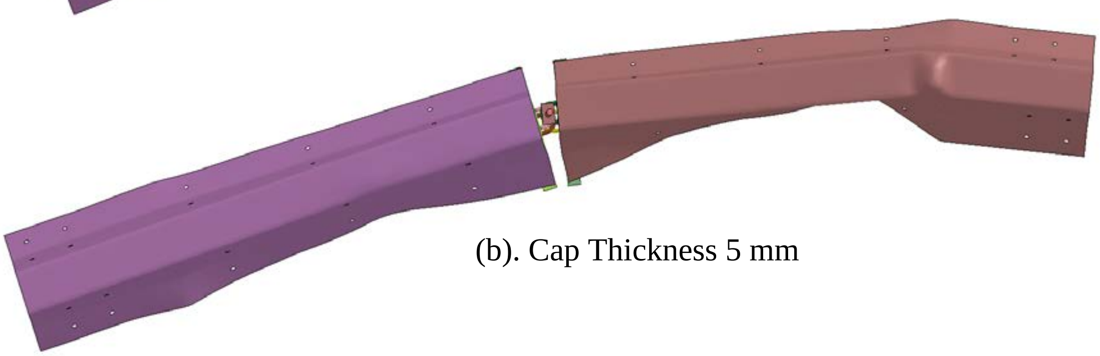
Figure 8. Sequential Photographs: Cap Thickness of 6 mm, Impact Point 1.3 m Upstream Cover Plate Joint



(a). Cap Thickness 3 mm



(b). Cap Thickness 5 mm

Figure 9. Plastic Hinge Formation (a) Cap Thickness 3 mm, (b) Cap Thickness 5 mm

In order to mitigate lateral crush concern and provide a smooth and safe gap spanning hardware between adjacent PCB segments, several design modifications were proposed including the modification in the cap thickness, a modified base plate and incremental stiffeners to optimize the cover plate design. Three and six stiffeners were modelled with various thicknesses and spacing. Three stiffeners configuration with modified box tube is shown in Figure 10. A summary of simulation results with varied cap and stiffeners thickness at an impact point 1.3 m upstream from cover plate joint is shown in Table 5. Three stiffeners at a spacing of 645 mm with an end plate sections of 16 mm resulted in an excellent improvement in lateral deformation of cap. Replacing the base plate with 76-mm x 76-mm x 16-mm box tube improved the overall lateral deformation behavior but the localized crush near the toe area was not resolved completely.

After evaluation of simulation results in Table 5, three 6-mm thick stiffeners showed good performance for 6 mm thick cap. Therefore, the selected thickness of cap and stiffeners sections was 6 mm. End plate sections with 76-mm x 76-mm x 16-mm box tube were fabricated with 16-mm thick plate with standard pin-and-loop connection as shown in Figure 11. The standard pin and loop connection consists of 32-mm diameter A36 steel connection pins and connection pin plates placed between 19-mm diameter, epoxy coated reinforcing bar loops. Standard dimensions were selected for connections of final prototype design of cover plates. Further, impacts upstream and downstream of the cover plates are required to evaluate the structural capacity and the potential for vehicle snag and stability. Thus, additional simulations and full scale crash testing is required before guidelines can be recommended.

Table 5. Summary of Simulation Results - Cap Thickness Varied along with Stiffeners – Impact Point 1.3 m Upstream of Cover Plate Joint

Cap Thickness mm	Stiffeners			Cap Lateral Deformation mm < 76	System Lateral Dynamic Deflection mm
	Quantity	Thickness mm	Spacing mm		
3	6	3	356	142.9	2,080[1]
5	3	6	645	99.1	2,443
	3	5	645	98.8	2,443
	6	5	356	16.9	2,280
6	3	6	645	72.2	2,268
	6	6	356	19.3	2,103
10	3	10	645	12	1,828

[1] Maximum value was not reached prior to conclusion of simulation

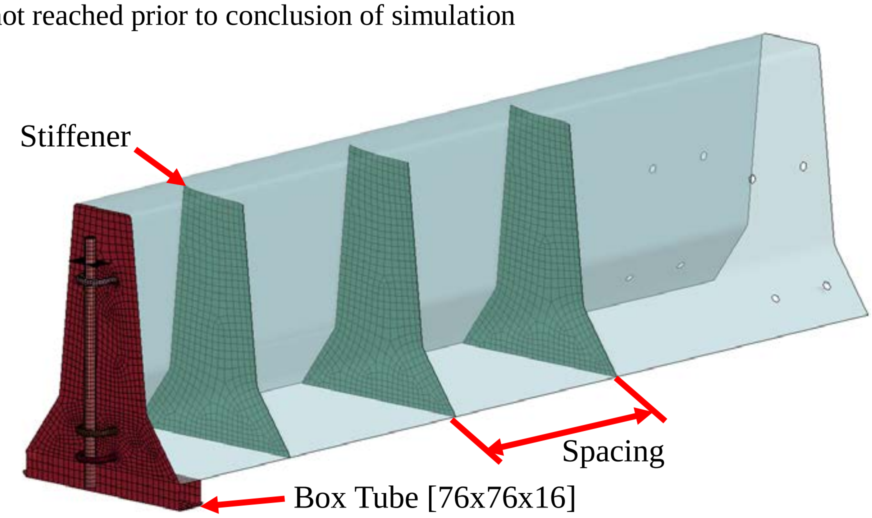


Figure 10. Cover Plate with 3 Stiffeners and Box Tube Added

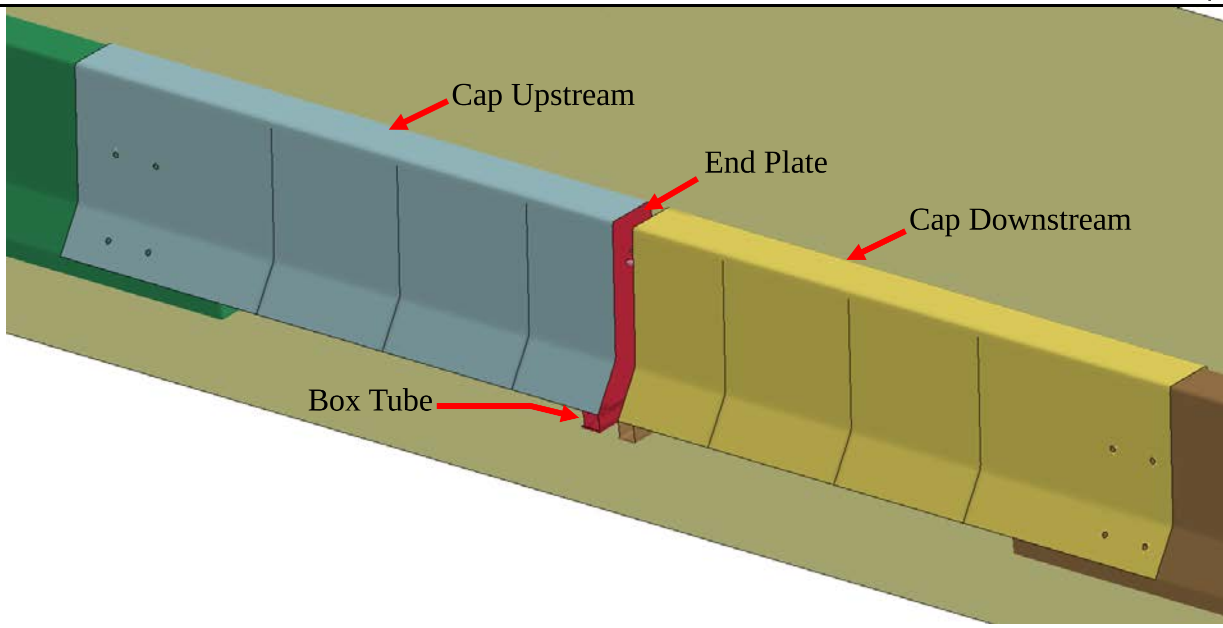


Figure 11. Cover Plate PCB Gap System - Final Prototype Design for 12.5 ft Gap

Summary and Conclusions

An improved LS-DYNA model of steel cover plate for accommodating variable gaps in roadside portable concrete barrier (PCB) installations has been developed. Two-piece cover plate with cap length of each 9 ft long was selected and evaluated using non-linear finite element analysis program LS-DYNA. Baseline model of F-shape PCB validated with full-scale crash testing is presented. Baseline modelling and simulation details are discussed including the range of numerical problems and vehicle and evaluation parameters. Cover plates across the barrier joint were added using fully integrated shell element along with piecewise linear plasticity material. The cover plates are connected through standard pin and loop connection with deformable ASTM A36 steel pins.

Computer simulations were conducted with a Chevrolet Silverado V2 model pickup truck impacting the PCB cover plate installation with varying cap thickness. Cover plate model was sufficiently calibrated with baseline model in order to evaluate the gap spanning hardware design. The evaluations were performed for gap spanning cover plates to investigate barrier loading, pocketing, and tension transfer. Results show that cap thickness of less than 6 mm may cause concern in regards to acceptable crash test performance for PCB gap spanning hardware system. Good performance was obtained with a 6-mm thick cover plate with modified base plate and incremental stiffeners. Thus, the selected thickness of cap and stiffeners sections was 6 mm, and end plate sections with 76-mm x 76-mm x 16-mm box tube were fabricated with 16-mm thick plate, including the standard dimensions of pin and loop connection for final prototype design of cover plate.

Future Work

The newly developed model significantly improved the performance of simulating impacts for PCB gap spanning harware installations between adjacent runs of PCB segments. The final design will be investigated further for gap analysis and subsequently for pickup truck critical impact analysis. Further evaluation with single cover plate design will be conducted, and the system should pass the MASH criteria. Additional simulation and full scale crash testing is required before guidelines can be recommended for full-scale crash testing.

Acknowledgement

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