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Research Article

Modeling and Comparative Analysis of Different Generic Cross Section B-Pillar Design in Roof Crush Impact

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Abstract: When a vehicle tips over onto its roof or side due to internal or external force on a vehicle is called Rollover impact. Rollover is a very critical impact compared to another mode of vehicle impacts. B-pillar and its cross-section design are very critical in the rollover impacts by reducing the cabin intrusion of vehicle. B-pillar absorbs most of the energy at the time of rollover and reduces the fatality rate of the passenger. In this work, a B-pillar finite element (FE) model is modeled to analyze as per FMVSS216a standard protocol to check the critical performance. Two generic cross-sections of the B-pillar are considered for preliminary assessment. This B-pillar designs FE model (cut model) are modeled and analyzed for FMVSS216a using LS-DYNA explicit code. The FMVS216a lab test is a quasi-static test and LS-DYNA is the well-accepted FEA tool to simulate the quasi-static test. LS-DYNA software is widely accepted as a multi-purpose finite element analysis (FEA), capable of solving complex problems in the field of Automobile, Aerospace, etc. So LS-DYNA is considered for the study of the B-Pillar simulations. Both the B-pillar designs are accessed and compared with respect to energy absorption, crush resistance characteristics with respect to the full vehicle rollover test. With the detailed performance study of both cross-section designs under rollover impact, the best performing B-pillar design in terms of high energy absorption and high vehicle resistance is selected for further optimization study to meet the Roof crush standard requirements.

***Keywords*:** Federal Motor Vehicle Safety Standards (FMVSS), Insurance Institute for Highway Safety (IIHS), design optimization, rollover

1. Introduction

Many people are injured and killed every year in rollover accidents. Rollover crashes are critical safety problems for light weight cars. The ultimate solution to minimize fatal injuries and deaths is to stop the cars from rolling over by some active or passive safety arrangement but that is not possible in all cases. Nowadays, electronic stability control or program (ESC/P) is playing a vital role in reducing rollovers. Also, Side curtain airbags and safety seat belts help in protecting the occupants inside. But for all the electronic control programs, airbags, seat belts, and safety measures to perform efficiently, the vehicle passenger compartment should keep sufficient survival space at the time of roof crush impact. For the less risk of injury and minimum fatal of the occupant, less intrusion is expected in the occupant

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compartment which can be achieved by the stronger B-pillar and roof in terms of rollover impact. The stronger B-pillar and roof also save the un-belted occupants from ejection through broken doors, windows, or windshields that have opened or broken due to high deformation of the B pillar and roof [1], [2].

There are mainly two types of rollover tests popular in the world of passenger car design. The first one is a government regulatory (FMVSS216a) and the second one is an Insurance Institute for Highway Safety (IIHS) test which is also derived from government regulatory (FMVSS216a) as well with some stringent target value. FMVSS216a and IIHS tests are USA market-driven but similar tests are also available in other regions of the world including India as well [3], [4].

This test is applicable for all the vehicle with a gross vehicle weight rating (GVWR) less than and equal to 4536 kg. In this test, the roof and B-Pillar strength are determined by applying force or displacement using an angled metal plate (platen-762 mm × 1829 mm) down on both sides of the roof (only one side in IIHS). The platen speed should have a constant speed and less than or equal to 13 mm/s. The roof and B pillar crushing force is measured during the motion of platen [3], [4].

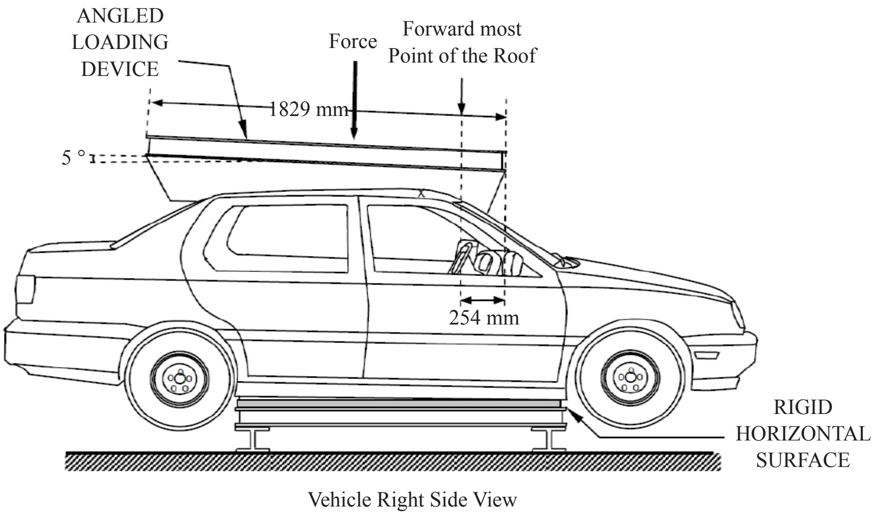

Figure 1. FMVSS216a-test setup [3], [4]

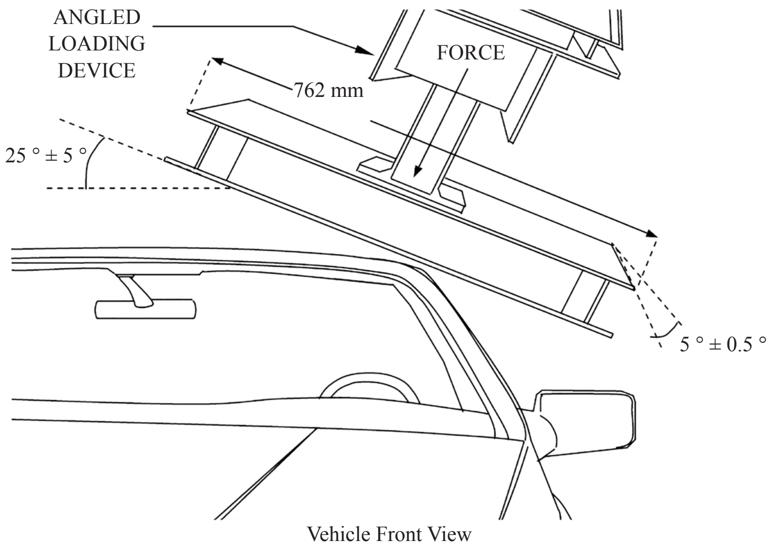

Figure 2. FMVSS216a-test setup [3], [4]

The vehicle sill or frame body is placed on a horizontal surface and fixed rigidly. The platen is positioned considering vehicle rolling and pitch angle in the rollover impact scenario as per the standard regulatory requirement as shown in Figure 1 and Figure 2 [3], [4].

The applied force (Input) for FMVSS216a is vehicle weight dependent. If the GVWR of a vehicle is less than and equal to 2722 kg, then the maximum force applied by the platen is 3 mg and if the GVWR of a vehicle is greater than 2722 kg then the maximum force applied by the platen is 1.5 mg, where 'm' is the unloaded vehicle weight (UVW) in kg and 'g' is the gravitational acceleration (9.8 m/s^2) [3], [4].

The test vehicle will pass the FMVSS216a regulation targets (outputs) if

1. The vehicle roof structure sustains the maximum applied force prior to the platen displacement reaches more than 127 mm, tested separately on each side of the vehicle [3].

2. Load on the head form located at the head position of the 50% male dummy should be less than or equal to 222 N [3].

In the insurance test, the input and output are slightly tweaked but the concept is the same. In the IIHS test, the platen is moved by 127 mm (5 mm/s) and the vehicle resistance force is monitored. The vehicle resistance force divided by the vehicle weight is called the strength to weight ratio (SWR). The SWR of 4 or more is a good rating followed by 3.25 or more for an acceptable rating and 2.5 or more for a marginal rating. A good rating is required for the Top Safety Pick Award [4].

Several optimization works are done by many authors with some constrained. Satope et al. [1] simulated and Optimized the structural capacity of a B-pillar design used in automobiles to meets the European New Car Assessment Programme (Euro-NCAP) Side Impact requirements. The study was limited to a given B pillar design and Reinforcement was added to meet the target. Nassef et al. [2] optimized the B-pillar inner and reinforcement thickness (reinforcement height as well) for a given Nissan B-pillar design under an assumed load. The study was limited to an available B-pillar design. Only B-pillar and Reinforcement thickness were optimized to meet the target. Steinhauser et al. [5] redesigned the Ford F-150 crew cab B-pillar reinforcement design to meet FMVSS216 rollover requirements. Lee et al. [6] optimized the 2012 Toyota Camry Body-in-White (BIW) Weight & Process (joints) for rollover test. The study was limited to a given BIW design. BIW weight and process were optimized to meet the target, not the design. Kulkarni et al. [7] improved the roof crush performance by adding shock-absorbing materials as an insert in the roof body and pillars. Kulkarni et al [8] studied the rollover performance study, improved technique, upgraded the B Pillar materials, and added shock-absorbing materials in the roof body and pillars to improve rollover performance. All the study was done on the already available B pillar design and selective optimization was done to meet the FMVSS216a rollover performance.

2. Objective

Many studies have been done to optimize the B-pillar design to meet the standard FMVSS216a Roof Crush resistance requirements for a given B-pillar design by many authors with the help of different Original Equipment Manufacturers (OEMs). But all these optimizations were done with some constraints from OEMs. No one tried to start with the generic design of B-pillar. The current work focus is on selecting the best performing B-pillar generic cross-section design and optimization of generic B-pillar thickness to meet the FMVSS216a rollover regulatory requirements for the highest applicable vehicle weight. So we started looking into the optimization of the generic B pillar design.

The prime objective of this paper is to select and optimize the best performing B-pillar cross-section design for maximum energy absorption in rollover (roof crush) impact. With maximum energy absorption and higher resistance force with high levels of safety, our target is to keep the structural mass and production cost minimal as well. So the overall objectives of this ongoing project are to optimize the B-Pillar intrusion and weight without compromising its impact energy absorption, resistant force properties.

Figure 3 shows a standard B pillar design of a car.

The B-pillar is a prime load-carrying member in any automotive vehicle. The B-pillar is manufactured or stamped of high strength steel thin sheet and it is seam-welded to make the closed-sectioned structure. The B-pillar cross-section has approximately a box section and beads are added to increase the stiffness. The B-pillar is the supporting structure for the roof. It supports both rear and front doors, also it is used for latching of the front doors and installing hinges for the rear doors. It supports the floor pan at the bottom end of the rocker panel. The B-pillar position in a vehicle makes it very critical in crash events that involve rollover, side-impact, and other modes of impact as well. So Vehicle B-Pillar design has a significant and very important role in all the impact modes including rollover (Roof Crush Resistance) Impact as well.

Figure 3. Standard vehicle-B Pillar design [2]

The generic B pillar design has a straight tube with a constant cross-section starting from bottom to some height (assumed 'h' for this project). Then, it curves and tapers into a similar or smaller cross-section till total height (assumed 'H' for this project) as shown in Figure 4. Now a day, some types of reinforcement are also placed inside the B-pillar to increase the stiffness for multi-purpose requirements.

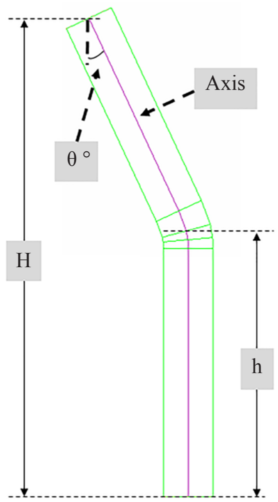

Figure 4. Generic B Pillar

3. Problem definition

In the two generic B-pillar cross-sections (circular and rectangular)' design, the thickness is optimized to maximize the energy absorption in the FMVSS216a rollover (roof crush resistance) standard impact environment. The below

(Figure 5) shape, size, height, and thickness of B-pillar are selected after checking many available vehicle B pillar designs. FE models are created for all cross-sections and simulated using LS-DYNA quasi-static explicit code.

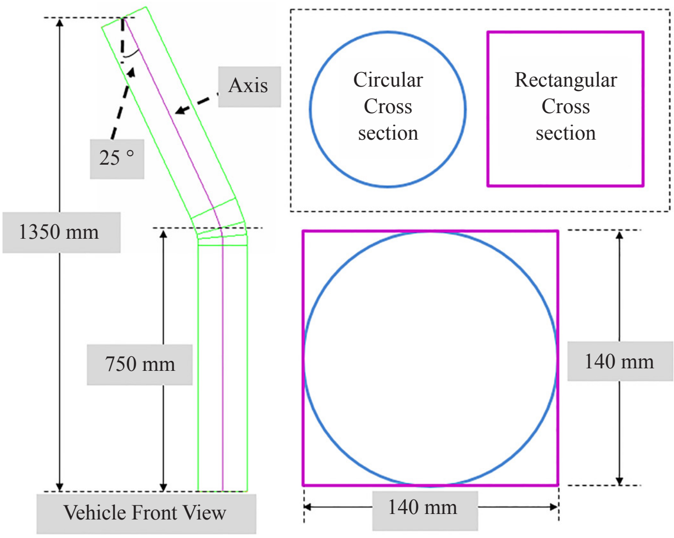

Figure 5. B-pillar design and cross-section

For this study, the FMVSS216a full vehicle quasi-static impact test is getting replicated with a B-pillar cut model to minimize the simulation time. The bottom of the B-pillar is constrained in all degrees of freedom and the top is getting loaded by platen similar to FMVSS216a standard as shown in Figure 6. The platen is positioned on the top of B-pillar and the platen angle is kept as per standard regulation with respect to the vehicle. The platen is moved perpendicular to its plane for 127 mm displacement and the B pillar crush resistance is monitored through the simulation.

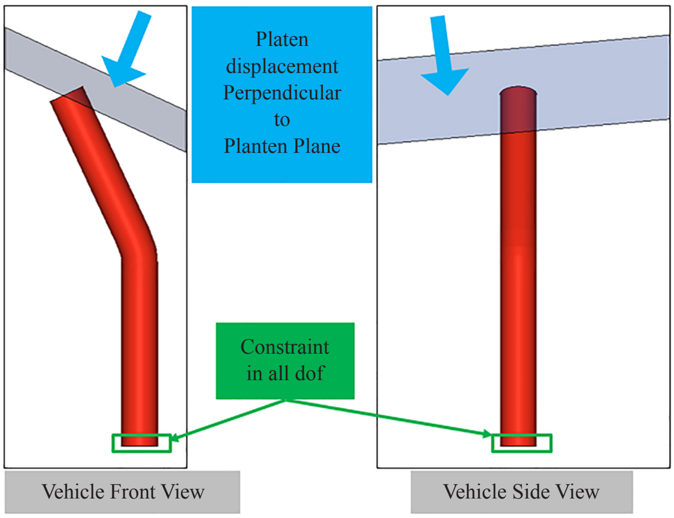

Figure 6. Model setup

Considered the highest GVWR of 4536 kg applicable for FMVSS216a regulation and assumed a total of 536 kg cargo or occupant mass specified by the vehicle manufacturer. The total applied force by the platen or the expected vehicle resistance as per FMVSS216a is

$$\begin{aligned} F &= 1.5 \times UVW \times 9.8\ N \\ &= 1.5 \times 4000 \times 9.8\ N \\ &= 58800\ N \\ &= 58.8\ kN \end{aligned}$$

The above circular and rectangular cross-section B Pillar design is simulated using finite element LS-DYNA explicit code as per the above model setup.

4. Results

The circular and rectangular cross-section B-pillar design FEA results are accessed and compared with respect to internal energy, kinetic energy, total energy, external work, and resistance force characteristics. Figure 7 shows the energy balance of circular and rectangular cross-section B-pillar design roof crush analysis.

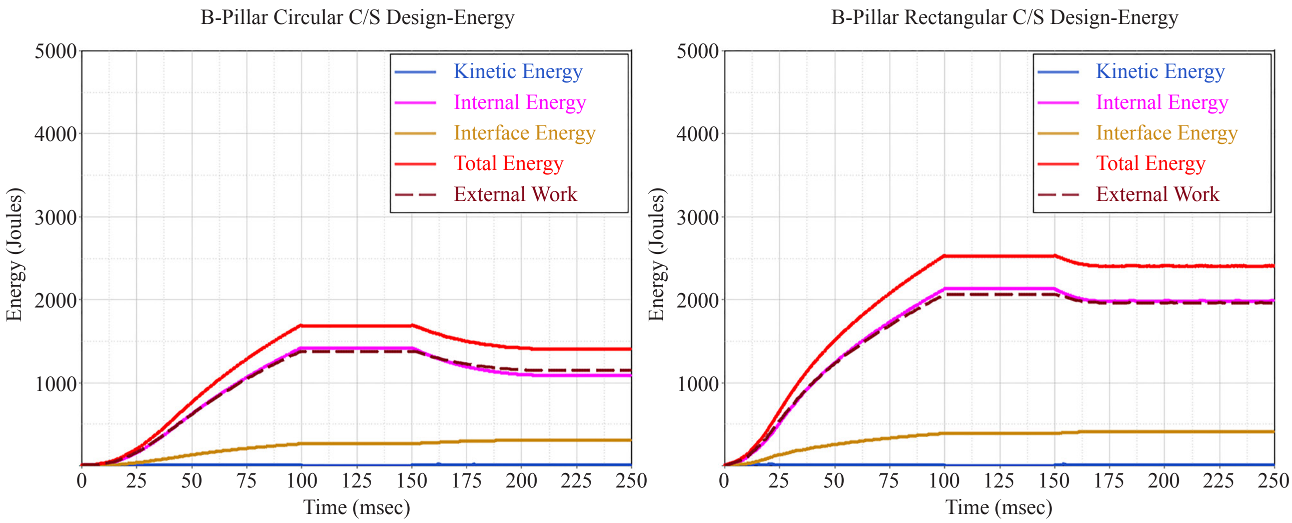

Figure 7. Energy balance of roof crush analysis

As this is quasi-static analysis, the kinetic energy should be zero or negligible compared to total energy. Also, external work and internal energy absorbed by the system should be approximately similar. Looking at the above curves of internal energy and external work, it is getting overlapped for both the cross-section analysis and kinetic energy is also almost zero. So our FE simulation setup and loading condition is full filling the mandatory criteria of quasi-static analysis. After comparing all the energies of circular and rectangular cross-section B-pillar design, the rectangular cross-section shows more promising rollover performance in terms of energy absorption of the design. Out of all the energies shown above, internal energy absorbed by the B-pillar is critical and will drive the crush resistance force of B-pillar. So going further, we will be only comparing the internal energy for all the simulations.

Figure 8 shows the platen displacement and resistance force generated by B-pillar. A higher force of 36.5 kN by rectangular cross-section compared to 21.3 kN by circular cross-section B-pillar. Early peak force (as shown in Figure 9) of rectangular cross-section B-pillar compared to circular cross-section B-pillar is also a positive point in terms of cabin intrusions.

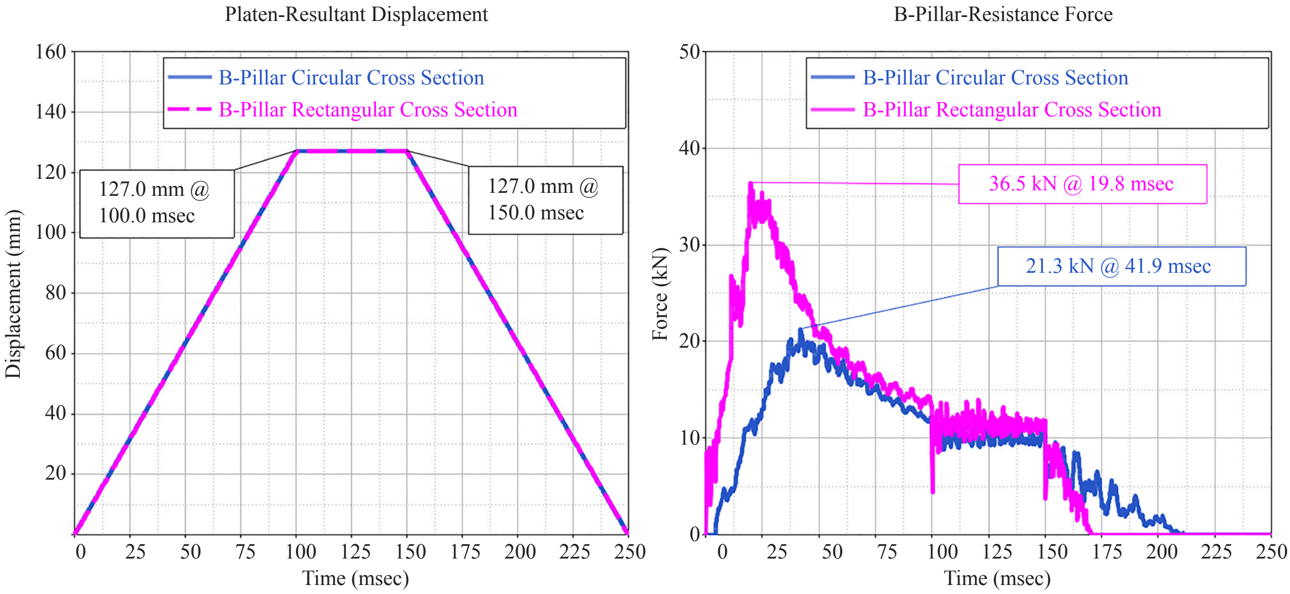

Figure 8. Platen displacement and B Pillar resistance force

Figure 9. Force v/s displacement curve

Higher energy absorption of 2131.6 joules by rectangular compared to 1421.9 joules by circular cross-section B-pillar as shown in Figure 10.

High plastic strain observed in rectangular compared to circular cross-section B-pillar as shown in Figure 11 and Figure 12.

After studying the above comparison of critical B-pillar parameters in rollover performance, the rectangular cross-section is performing better compared to circular cross-section B-pillar as summarized in Table 1.

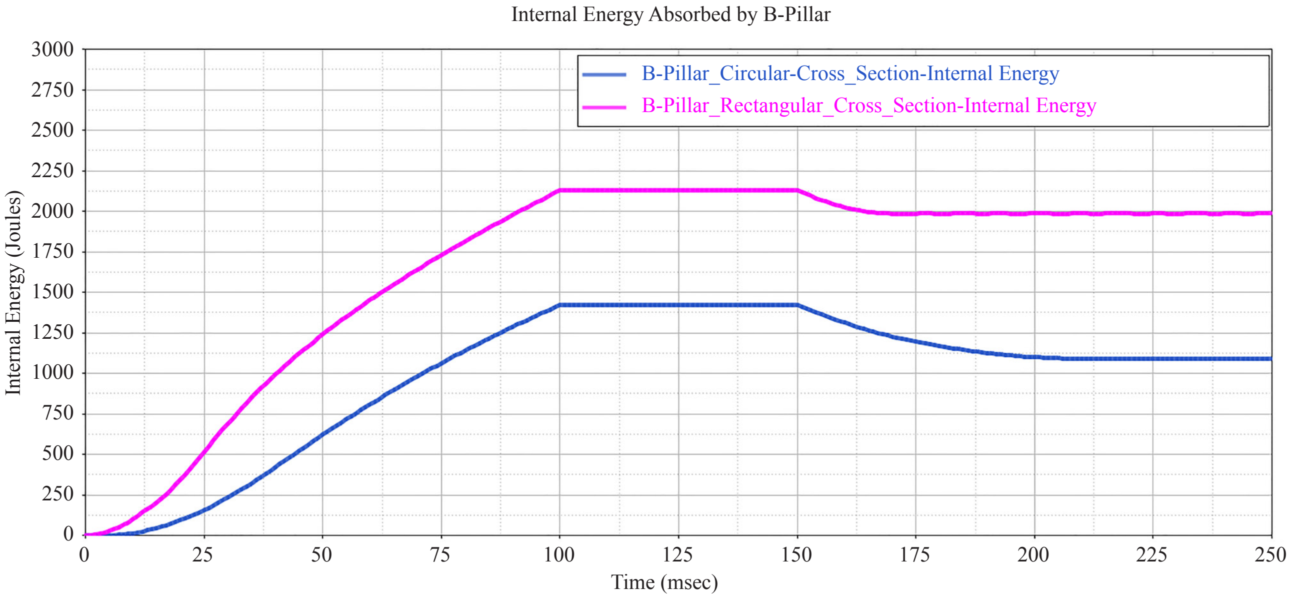

Figure 10. B Pillar internal energy

Table 1. B Pillar resistance force and internal energy

B-Pillar Cross Section	Maximum Internal Energy (Joules)	Maximum Crush Resistance Force (kN)
Circular	1421.9	21.3
Rectangular	2131.6	36.5

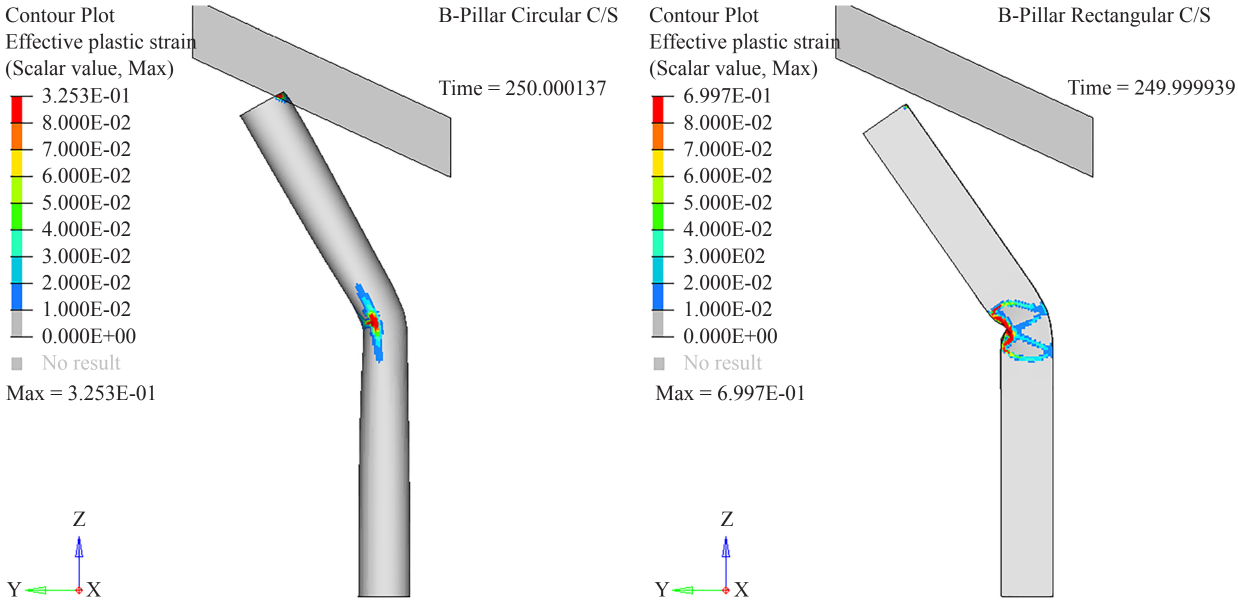

Figure 11. B Pillar bend and plastic strain

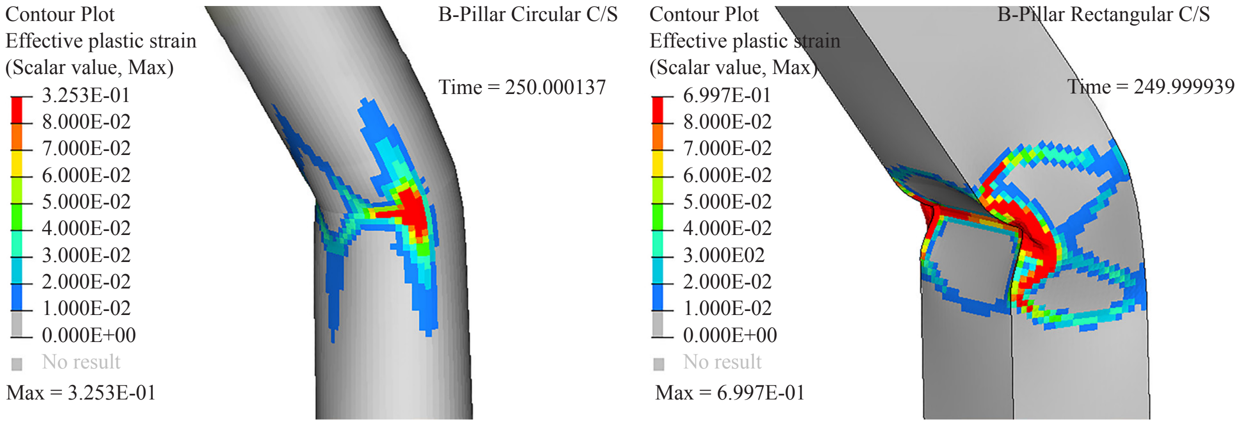

Figure 12. B Pillar bend and plastic strain (partial magnification of Figure 11)

Looking at the rectangular cross-section B-pillar performance. Rectangular cross-section B-pillar design is the better option to proceed further for optimization study. Before starting the optimization study, we validated both cross-section results with different mesh sizes. We selected 3 mm, 6 mm, and 9 mm nominal mesh sizes for both the cross-section and compared the variation in internal energy and crush resistance force as shown in Table 2.

Table 2. B Pillar mesh sensitivity study

B-Pillar Cross Section	Mesh Size (mm)	Internal Energy(Joules)	% Change in Internal Energy	Crush Resistance Force (kN)	% Change in Crush Resistance Force
Circular	3	1384.2		20.4417	
Circular	6	1421.9	2.72	21.2508	3.96
Circular	9	1441.4	4.13	21.2513	3.96
Rectangular	3	2186.4		37.9387	
Rectangular	6	2131.6	-2.51	36.4625	-3.89
Rectangular	9	2273.0	3.96	37.2629	-1.78

Looking at the above mesh-dependent rollover performance data, no significant changes are observed in the results. So we selected the average mesh size of 6 mm to proceed further for our optimization study.

5. Optimization study

The current generic B-pillar design is a closed section that cannot be manufactured. So to make the generic rectangular cross-section B-pillar manufacturable, easily stamped, or extruded, some minor modification needs to be done in the cross-section. To make the extrusion and stamping feasible, the rectangular cross-section is modified which is a combination of the two hat sections. The generic rectangular cross section B-pillar is sliced into two open hat cross-sections and added fillet at the corner to make the extrusion and stamping feasible as shown in Figure 13.

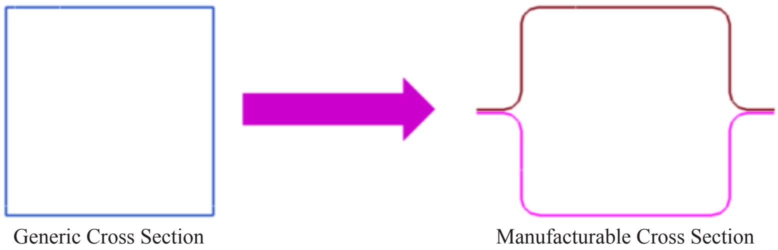

Figure 13. B Pillar cross section update

The updated two cross-section parts are assembled with spot weld on the flange as shown in Figure 14. The B pillar inner and outer is divided into three pieces vertically for further thickness optimization.

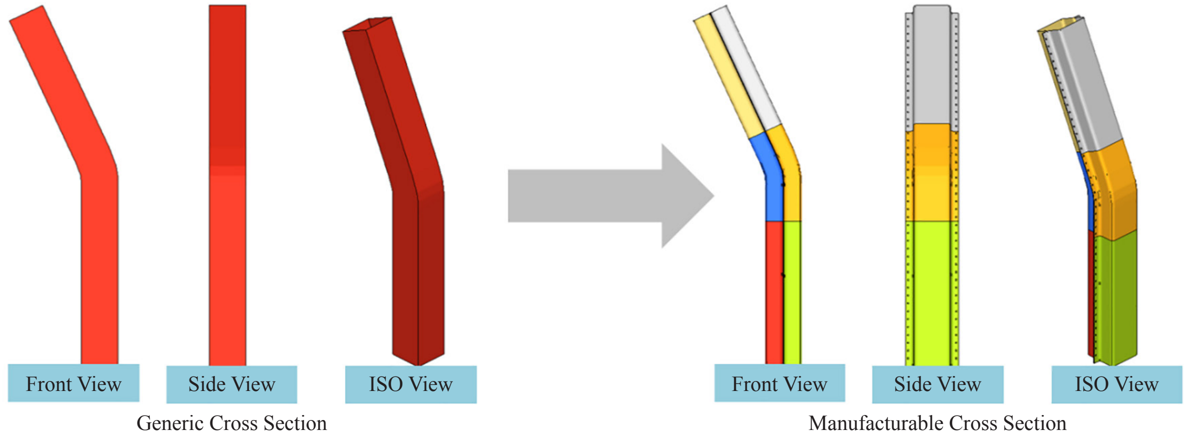

Figure 14. B Pillar design update

With these cross-section updates, no significant changes were observed in the B-pillar performance. Similar plastic strain observed in updated B-pillar design compared to generic design as shown in Figure 15.

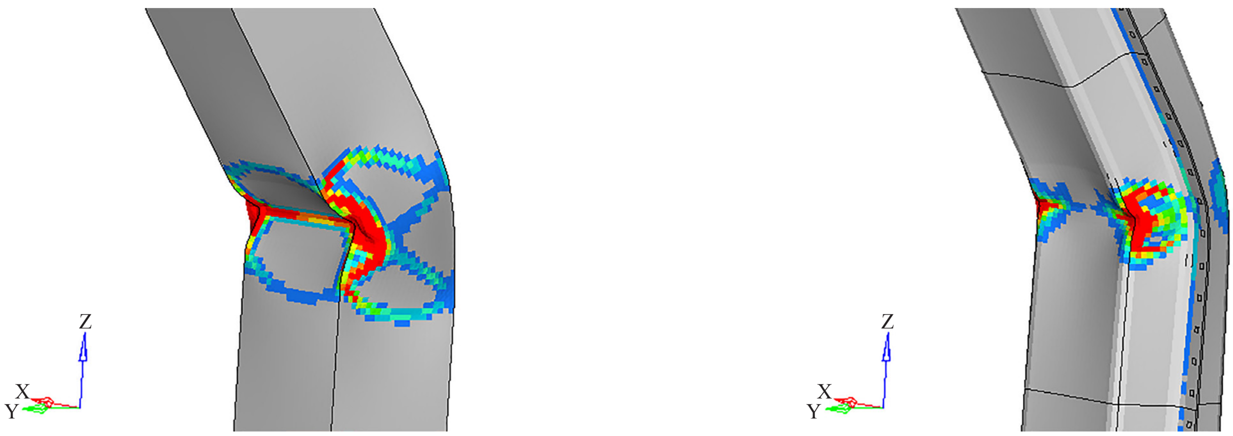

Figure 15. B Pillar design update-plastic strain

Similar crush resistance force (36.6 kN) was observed in updated B pillar design compared to generic design resistance force (36.5 kN) as shown in Figure 16.

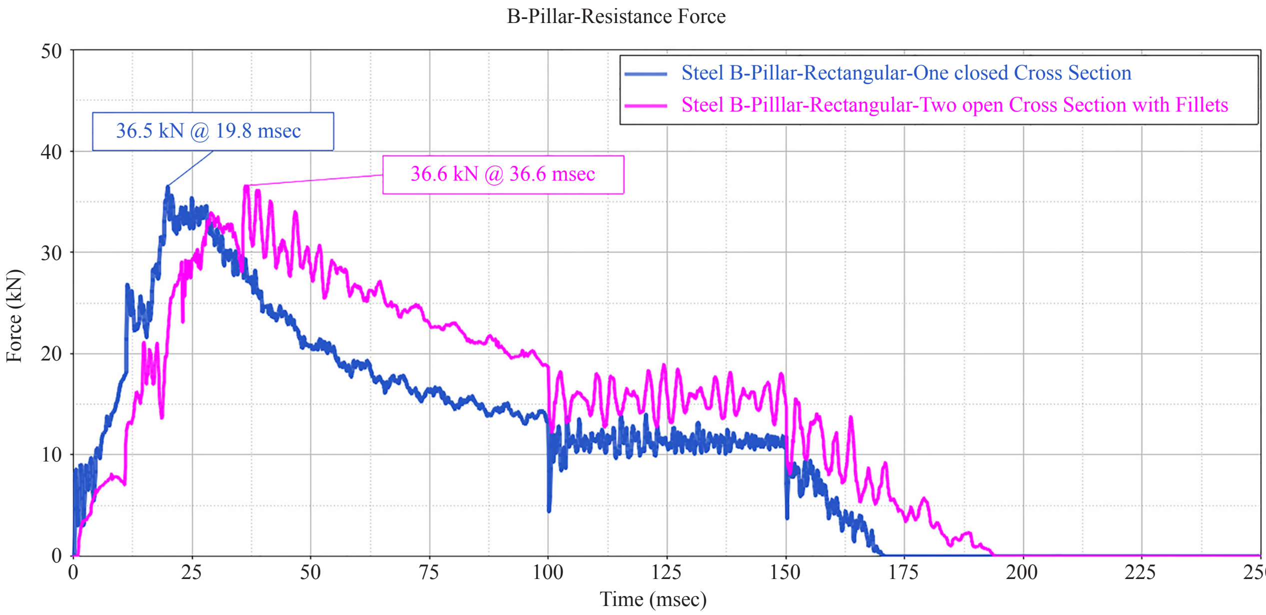

Figure 16. B Pillar design update-resistance force

The crush resistance force curve signature is not exactly the same in the updated B-pillar design compared to the generic design. Also, delay in maximum resistance force time is observed in updated B-pillar design and consequently slightly more intrusion in updated B-pillar design due to softer behavior of additional flange and fillet in the updated B-pillar design.

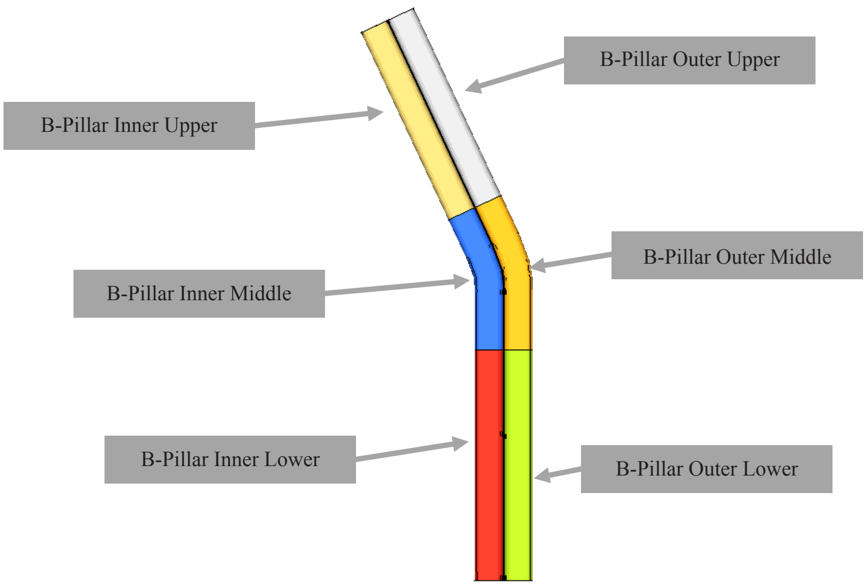

Figure 17. B Pillar parts for thickness optimization

With current generic or manufacturable cross-section, steel material with 2 mm thickness of B-pillar, we are able to get a crush resistance of 36.6 kN, which is far below the target resistance force. To meet the FMVSS216a standard Roof crush resistance (for the highest GVWR of 4536 kg applicable for this regulation), we should get minimum requirements of 58.8 kN (1.5 × UVW × 9.8). We up-gauged the B-pillar inner and outer and found that we can get a crush resistance of 65.85 kN with 2.8 mm thickness of steel material B-pillar with a total mass of 19.55 kg. So we need to optimize the thickness of B-pillar to get a minimum of 58.8 kN crush resistance force with maximum mass savings.

A standard Design of Experiment (DOE) optimization method, Uniform Latin Hypercube design method, is used to optimize the thickness of rectangular updated cross-section B-pillar design to meet the maximum resistance force of 58.8 kN. Figure 17 shows the different B pillar parts, used as a design variable for thickness optimization.

A thickness range of 1.8-3.0 mm is selected for all the six design variables to do the thickness optimization as shown in Table 3.

Table 3. B Pillar thickness design variable list

Variable Id	Design Variable Name	Current Thickness (mm)	Thickness Range (mm)					
			Thickness 1 (mm)	Thickness 2 (mm)	Thickness 3 (mm)	Thickness 4 (mm)	Thickness 5 (mm)	Thickness 6 (mm)
1	B-Pillar Inner Lower	2	1.8	2	2.2	2.5	2.8	3.0
2	B-Pillar Inner Middle	2	1.8	2	2.2	2.5	2.8	3.0
3	B-Pillar Inner Upper	2	1.8	2	2.2	2.5	2.8	3.0
4	B-Pillar Outer Lower	2	1.8	2	2.2	2.5	2.8	3.0
5	B-Pillar Outer Middle	2	1.8	2	2.2	2.5	2.8	3.0
6	B-Pillar Outer Upper	2	1.8	2	2.2	2.5	2.8	3.0

With six parts thickness design variables, a total of 36 DOE analyses are set up to find the best thickness combination. Five experiments result are shown in Table 4. Detailed investigation and study of DOE FEA results are done to select the best performing B -pillar design in terms of high energy absorption and high resistance force with less mass addition to meet the FMVSS216a regulatory requirements. Out of 36 DOE thickness combination analyses, seven thickness combinations are showing more than 58.8 kN of crush resistance.

Table 4. B Pillar thickness optimization-DOE analysis-sample results summary

Exp No.	Design Variable Thickness (mm)						B-Pillar Mass (kg)	Max Resistance Force (kN)	Max Internal Energy Absorbed (kN-mm)
	B-Pillar Inner Lower	B-Pillar Inner Middle	B-Pillar Inner Upper	B-Pillar Outer Lower	B-Pillar Outer Middle	B-Pillar Outer Upper			
1	2.5	2	2.8	2.8	2	2.2	17.00	40.60	3195.03
2	2.2	2	2	2	2.5	2	14.72	41.33	3595.70
3	2.2	2.8	2.2	2.5	2.2	2.2	16.29	53.63	5154.89
4	2.2	2	2.2	1.8	2	2	14.23	37.39	3208.57
5	2.5	2.5	2.5	2.5	2.2	2.2	16.82	50.69	4503.06

Experiment 7 is showing 63.18 kN @ 62.4 msec crush resistance force with 16.61 kg but a high deformation is observed at B-pillar lower, which is not desirable for other applications, so Exp. 7 thickness combination is rejected. Experiment 12 is showing 59.53 kN @ 40.7 msec crush resistance force with 17.44 kg of total B-pillar mass which can be considered as an optimum thickness combination of B-pillar. Experiment 13 is showing 63.76 kN @ 42.7 msec crush resistance force with 18.36 kg of total B-pillar mass but considering B-pillar higher mass compared to Experiment 12, this thickness combination is also rejected. Experiment 18 is showing 61.63 kN @ 36.1 msec crush resistance force with 18.48 kg of total B-pillar mass but considering B-pillar higher mass compared to Experiment 12, this thickness combination is also rejected. Experiment 27 is showing 62.09 kN @ 37.9 msec crush resistance force with 18.42 kg of total B-pillar mass but considering B-pillar higher mass compared to Experiment 12, this thickness combination is also rejected. Experiment 32 is showing 63.31 kN @ 32.4 msec crush resistance force with 18.88 kg of total B-pillar mass but considering B-pillar higher mass compared to Experiment 12, this thickness combination is also rejected. Experiment 35 is showing 63.99 kN @ 68.2 msec crush resistance force with 16.67 kg of total B-pillar mass. The total B-pillar mass is less but considering the delay in B-pillar max force time and consequently high intrusion compared to Experiment 12, this thickness combination is also rejected. So Experiment 12 is selected as the optimum thickness combination to meet the FMVSS216a regulatory requirement of 58.8 kN applicable for GVWR 4356 kg.

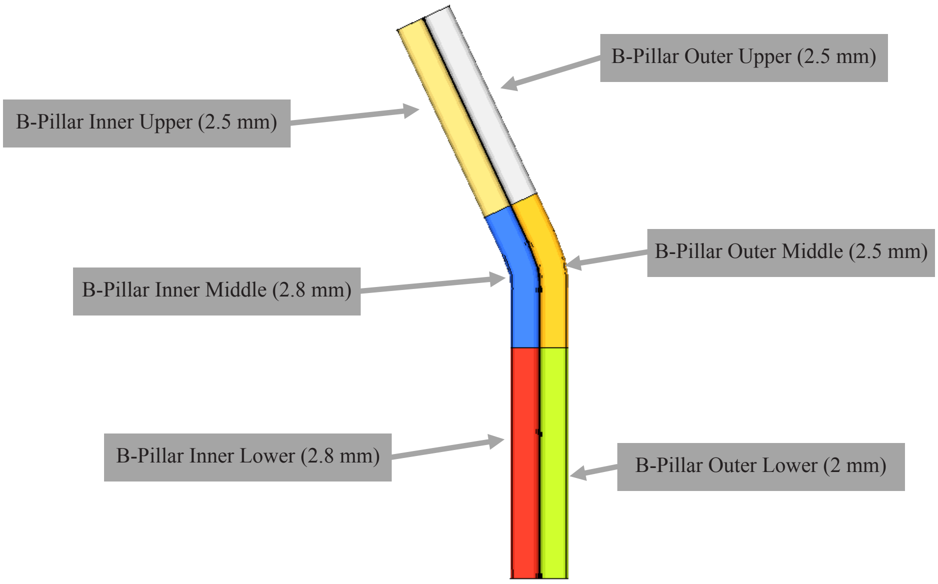

Figure 18. B Pillar optimum thickness design (experiment 12)

Mainly B-pillar inner (Bottom and Middle area) and B-pillar outer (Upper and Middle area) needed more than 2 mm thicknesses, which can be achieved by either variable thickness of B-pillar or by adding reinforcement at respective higher thickness locations.

The Total mass saving from this optimization can be calculated as

The mass of B pillar steel material with 2.8 mm thickness = 19.55 kg

The mass of B Pillar steel material with optimized thickness = 17.44 kg

Total mass savings per vehicle = (19.55 - 17.44) × 2 = 4.22 kg

Total mass saving percentage per vehicle = 10.8%

6. Conclusion

This paper focuses on the selection and optimization of the best performing B-pillar generic cross-section and its design to meet the FMVSS216a rollover regulation requirements for the highest applicable GVWR of 4536 kg by analyzing Circular and Rectangular cross-section design. Less Crush resistance force and internal energy by Circular Cross-section B-pillar compared to Rectangular Cross-section B-pillar as shown in table-1. So Rectangular Cross-section B-pillar design is selected for optimization study to meet the FMVSS216a rollover requirements. With a base thickness of 2 mm, B-pillar generated resistance force is not sufficient to meet the FMVSS216a highest applicable GVWR of 4536 kg requirement resistance force of 58.8 kN (1.5 × UVW × 9.8). To meet the FMVSS216a resistance force of 58.8 kN (applicable for max GVWR of 4536 kg), More than 2 mm thickness is needed. Looking at DOE results, Experiment 12 variable thicknesses of B pillar is the best solution to meet the target. Mainly B-pillar inner (Bottom and Middle region) and B-pillar outer (Upper and middle region) needed more than 2 mm thicknesses, which can be achieved by either variable thickness of B-pillar or by adding reinforcement at respective higher thickness locations. Considering the single continuous 2.8 mm thickness of B pillar which meets the FMVSS216a resistance force requirement, a weight saving of 11% was achieved with this optimization without compromising the rollover performance requirements. This optimized generic cross-section and design of B-pillar concept can be used in any automotive car with minor changes respective to that vehicle to meet the FMVSS216a.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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