PASSENGER CAR'S SIDE DOOR IMPACT BEAM: A REVIEW

M. A. Shaharuzaman[1], S. M. Sapuan[2*] , M. R. Mansor[3], M. Y. M. Zuhri[4]

[1,2,4]Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.

[1,3]Fakulti Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

[2]Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.

[1,3]Centre for Advanced Research on Energy, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

Article History: Received 18.4.2018; Revised 8.6.2018; Accepted 30.6.2018

ABSTRACT

This paper discusses the development of side door impact beam for passenger cars from published journals. Side door impact beam is installed in the door of the car to protect occupants in the passenger compartment during side impact collision. The design of the component adheres to regulations stipulated by the FMVSS 214 standards for side impact collision test. Three shapes of side door impact beam were applied to passenger car can be categorized as, namely tubular beam, panel, and belt. Apart from that, various materials such as alloys, composites, and metal/composites hybrid were used to manufacture the component. Essentially, the selection of materials affects its strength, stiffness and weight. In addition, this study also covers the connection of side door impact beam to the door in order to analyse the occurrence of failures during side impact collision. To ensure that the beam has maximum energy absorption, the mechanically joint connection or adhesive must remain intact before the beam break. Finally, the conclusion of this review is formulated based on data from previous studies.

KEYWORDS*: Energy absorption; FMVSS 214; impact energy; side door impact beam, side impact, specific energy absorption*

* Corresponding Email: sapuan@upm.edu.my

1.0 INTRODUCTION

Crashworthiness is one of the most important aspects to consider in designing vehicles. Initially used in the aerospace industry, the term provides a measure for the ability of a structure and any of its components to protect the occupants during survivable crashes (Bois, Chou, Fileta, King, & Mahmood, 2004). This concept is similar to the automotive industry in which it measures the vehicles' structural ability to deform plastically and yet, maintain sufficient survival space for its occupants during crashes involving reasonable deceleration loads .

Road vehicles will be run for a crash test and the result will be published to give the information to the consumers about the safety of the car. The crash tests are (i) frontal impact, (ii) side impact, (iii) pole side impact, (iv) rear impact, and (v) rollover. In general, two organisations are recognised to run these crash tests, namely the New Car Assessment Program (NCAP) and Insurance Institute of Highway Safety (IIHS).

National Highway Traffic Safety Administration (NHTSA) is a department under the United States Department of Transportation that runs the NCAP testing procedure using Federal Motor Vehicle Safety Standards (FMVSS) (US Department of Transportation, 2007), whereas IIHS is an independent research organisation sponsored by the insurance companies that also run the crash test (Lukaszewicz, 2013). The organisations share the same objective to provide information on the safety aspects of a car to the consumers in effort to reduce the number of fatality and serious injury to the occupants in the event of an accident (Brumbelow, Mueller, & Arbelaez, 2015).

2.0 SIDE IMPACT TEST

Annual reports on accident cases depicted that side impact collision is the second major cause of fatality after frontal impact (Černiauskas, Keršys, Lukoševičius, & Sapragonas, 2010; Teng, Chang, & Nguyen, 2008). Approximately 25% of total road accidents in the United States (Brumbelow et al., 2015) and Australia (Stolinski, Grzebieta, & Fildes, 1998) were attributed to side impact collision, and 35% from that portion were fatal cases (Černiauskas et al., 2010).

In early 1960, researchers realised that the side impact collision was vulnerable due to a small gap in the passenger side compartment area compare to the frontal collision. Accordingly, General Motors placed a beam inside the side doors of their cars later that year to prevent them from compromising the passenger compartment and risking the occupants (Hedeen & Campbell, 1969). Subsequently in 1973, carmakers need to comply with the requirements set for side impact collision in the static Federal Motor Vehicle Safety Standards 214 (FMVSS 214S). Nonetheless, this effort did not result in significant reduction to the fatalities caused by side impact collision (Kahane, 1999) and thus, Kahane (1982) suggested that the regulations must be improved.

Therefore, NHTSA introduced a new requirement – dynamic FMVSS 214 – that includes Moving Deformable Barrier (MDB) impact on the side of the vehicle in 1990. By 2012, the organisation established a procedure with complete guide and setup for advance test dummies (Jones, 2012). Accordingly, car manufacturers incorporate the side door impact beam to improve the strength, stiffness and energy absorption of the side door during collision, projecting that this may reduce serious injuries and fatalities (Tanabe, Yamazaki, Akada, Akihiro, & Iwasaki, 1995). This development ignited numerous studies to achieve better side door impact beam; the classifications and results of these studies are discussed in this research.

2.1 Side Door Impact Beam

Side door impact beam is a component assembled to a car door together with other parts as in Figure 1 such as (i) door trim, (ii) inner member, (iii) end pieces, (iv) door hardware, (v) door beam, and (vi) outer skin. Generally, a small distance exists between the car door and the occupants in the car. Apart from that, a small area in the car door itself contains numerous components such as the side door impact beam (number 6), door hardware (number 5) include speaker, scissor linkage window guide rail, window motor, and wiring. As a result of the complex setup in a small space, the geometry of the side door impact beam needs to be optimised.

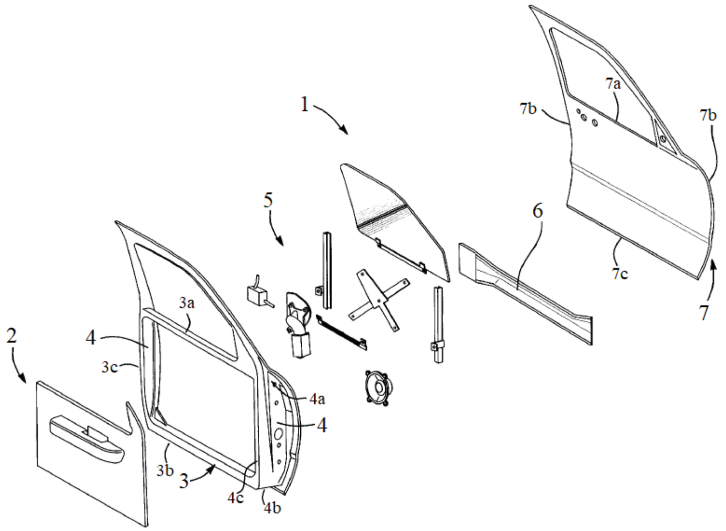


Figure 1. Components In Side Door of a Car (Palazzolo & Hui, 2000)

One of the function of side door impact beam is to absorb as much kinetic energy as possible during side impact collision to prevent serious injuries and fatalities to the occupants in the vehicle besides its other function to controls deformation, connects the hinges to the latch and provides additional load path between the hinge face and latch face. Additionally, the component needs to be ductile to avoid crack and failure that may injured the occupants although the break of the beam will reduce the velocity of impact load on the occupants. The challenging of the side door impact beam is to have high peak crash load (peak force) and energy absorption capability.

3.0 CLASSIFICATION OF SIDE DOOR IMPACT BEAM

Figure 2 presents the classification of side door impact beam based on previous researches. Overall, side door impact beam can be divided into three categories: shape, material, and joint type. All of these categories are discussed in this paper for continuous and effective improvement in the technology of future developments for side door impact beam. This is vital to ensure better safety for the occupants in the passenger compartment.

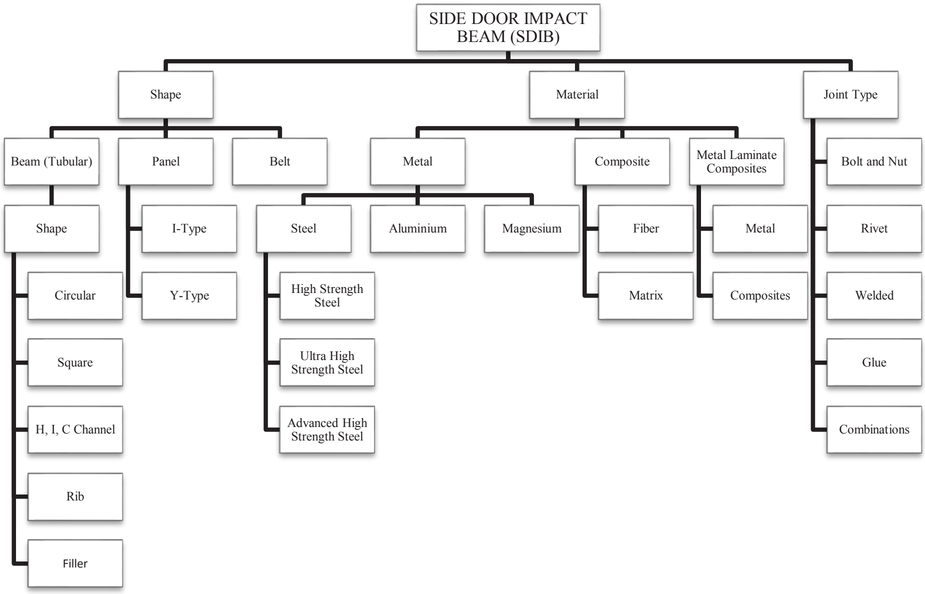


Figure 2. Classification of Side Door Impact Beam

3.1 Shape

As depicted in Figure 2, the shapes of side door impact beam are categorised into three, namely the beam or tubular shape, panel shape, and belt shape. Tubular and panel shapes are the most common application compared to the belt shape which is still in the research stage. The tubular shape can be further divided into three different categories: different cross section, beam with rib, and beam filled with energy absorber. The most common cross section for the tubular impact beam is circular ; nevertheless, several advanced cross section will be discussed further.

Panel shape differs from tubular shape, particularly in terms of cross section where panel shape has open-end profile compared to tubular shape which has close-end profile. Apart from that, the manufacturing process of the two shapes is also different. Stamping of sheet metal is used in manufacturing panel shape which is subsequently transferred to the side door impact beam using punch and die moulding method. Conversely, tubular shape is mainly processed using tube-mill method (Yoon, Kim, Heo, & Kwon, 2016).

Furthermore, belt shape is installed between two fulcrums that can rotate. Hence, if the door endures high impact deformation, it will transform the side impact load on the belt to tensile load as shown in Figure 3(c). Figure 3 illustrates the three types of side door impact beam discussed above.

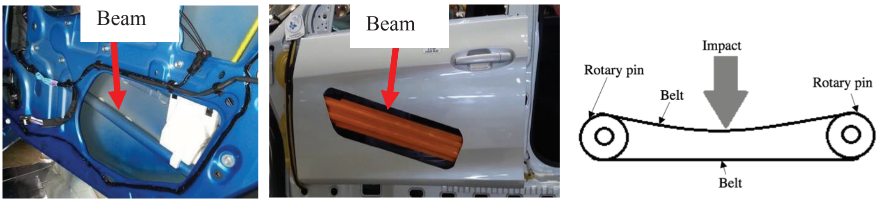


Figure 3. a) Tubular Type, b) Panel Type, c) Belt Type

3.1.1 Tubular Beam

As shown in Table 1, Abdollah and Hassan (2013) investigated 4 different cross sections and further included the length of 830 mm and thickness of 3 mm for the side door impact beam . Based on the simulation conducted for three-point bending test, it is found that square hollow beam sustained the highest bending load, followed by I-type, C-type, while the circular cross section demonstrated the lowest bending load.

In addition, Lashlem, Wahab, Abdullah, and Cheharon (2014) studied the energy absorption characteristic of the beam by using various weight of impactor: 10 kg, 20 kg, 30 kg, 40 kg, and 50 kg. As the impactor weight increased beyond 30 kg, the absorption of energy for I-type and II-type was higher compared to the circular cross section beam. Moreover, they found that II-type beam is less affected in displacement when the impactor weight increased, unlike the other two cross sections, which increases in displacement when the weight of impactor increased.

Ab Ghani, Kee, Othman, Koslan, and Zaidi (2013) performed an analysis based on the information in Table 1. The length of the beam was fixed to 550 mm, while the cross section was 55 mm x 55 mm. Using finite element analysis software, 14 m/s speed, and 5 kg impactor mass, a square hollow shape with 1 mm thickness was compared to 1-groove beam. From the finite element analysis done by Ab. Ghani, the groove shape produced shorter crushing distance, indicating its superiority in preventing harm to the occupants. Plus, the grooved beam also had higher specific energy absorption (SEA) compared to the square one (with no groove). Consecutively, they analysed different thickness of groove-shaped beam and discovered that the initial peak force increased with increasing thickness. On the contrary, the displacement and SEA showed a decreasing trend.

Research on a range of groove height (H) starting from 3 mm until 15 mm with 3 mm increment demonstrated that the H of 6 mm had the shortest crushing distance followed by 3 mm, 9 mm, 12 mm, and 15 mm. Notably, SEA decreased with increasing H. Furthermore, the effect of changing the groove width (W) from 10 mm to 50 mm with 10 mm increment was simulated for the grooved beam with 1 mm thickness and 6 mm depth. The displacement of the beam with 10 mm, 20 mm, and 30 mm width was almost similar. Nonetheless, the beam with 40 mm and 50 mm width showed higher displacement. SEA of the 10 mm to 30 mm beams was almost similar but significant reduction was evident for 40 mm and 50 mm beams.

In addition, they also simulated double grooved beam that was separated by spacing (S). The S varied from 5 mm to 25 mm with increments of 5 mm, respectively. The specification of the beam was: 1 mm thick, 6 mm depth, and 10 mm W. Notably, shorter displacement was achieved for 10 mm S compared to 5 mm, followed by 15 mm, 20 mm, and 25 mm. Moreover, the SEA for 5 mm and 10 mm S was almost similar, whereas the remaining S exhibited lower level. These studies proved that beam thickness, groove depth, groove width, and number of groove affect beam deflection and SEA.

Yoon et al. (2016) also investigated the effect of beam cross section. In this simulation, the thickness of the beam was 1.8 mm, while its length was 600 mm. The beam was assumed to be symmetrical and hence, the total length was 1200 mm. The first shape was the common circular hollow and the result for shapes case-5 and case-6 in terms of reaction force at the same deflection was higher than circular hollow by 61% and 31%, respectively. In the next simulation, the beam was assumed to be spot welded with different length and pitch. Consequently, the beam from case-5 produced the highest force reaction compared to circular beam case-1 with 99% higher. Subsequently, the case-5 beam was fabricated and tested on a real door. The result from the experimental analysis shows great improvement in weight and impact displacement which were 9% and 11%, respectively.

Furthermore, Ghadianlou and Abdullah (2013) researched circular beam with vertical or horizontal 1 and 2 ribs. They claimed that rib arrangements are related to rib numbers. Three-cell horizontal rib absorbed the highest energy compared to two-cell vertical, two-cell horizontal, and three-cell vertical ribs. The percentage difference between three-cell horizontal rib and unribbed beam for internal absorbed energy was 14% and for deflection was 20%. Consecutively, another four different types of rib arrangement were compared to the three-cell horizontal rib. The simulation results revealed that the door plate had lesser absorbed energy when it was equipped with rectangular-crossover rib. Notably, curve profile and crossover profile ribs performed poorer than the three-cell horizontal rib.

K.-H. Lee, Joo, Song, Cha, and Park (2004) adopted design of experiment (DOE) using orthogonal arrays and response surface method (RSM) to optimise the beam cross section in terms of thickness (t), major length (a), and minor length (b). This produced ellipse while the same beam weight was applied as a constraint within the specified weight. Ultimately, the optimum design consisted of 17 mm major length, 11 mm minor length, and 2.4 mm thickness. Compared to the initial design, the crush stiffness improved by 19.6% and the weight improved by 10.4%.

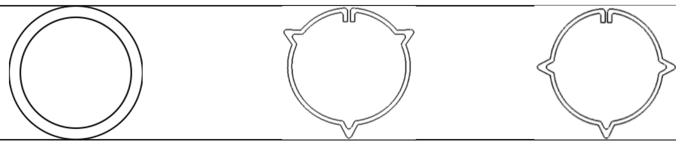
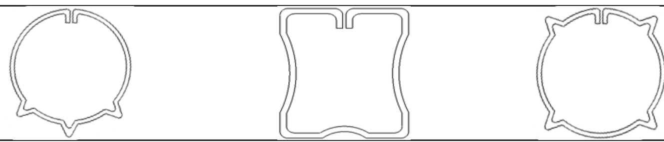
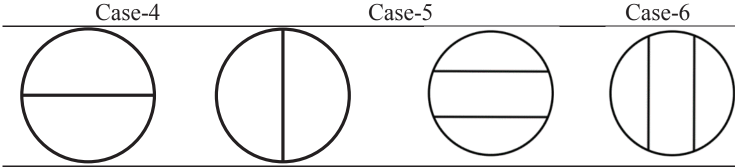
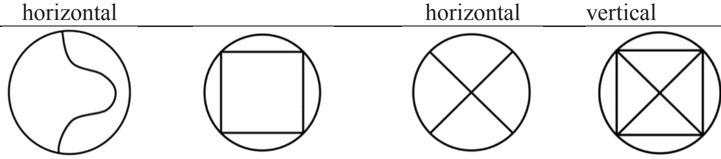
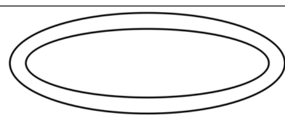
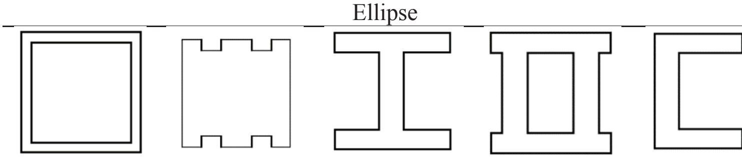
On the contrary, Rasooliyazdi et al. (2014) investigated the circular and ellipse shapes by applying different thickness starting from 2.5 mm to 4.0 mm with increments of 0.5 mm. Ratio of the radius minor length was divided by major length started from 1.0 mm and was reduced until 0.25 mm with decrements of 0.25 mm. The radius ratio of 1.0 had equivalent minor and major lengths, indicating that the shape was circular in cross section. Furthermore, the results demonstrated that 2.5 mm thickness and radius ratio of 0.25 yielded the maximum SEA (453.43 J/kg), lowest peak load (146.5 kN), and lowest weight (0.26 kg).

The review from previous studies concludes that shapes affect impact load and energy absorption capability. The results for circular or ellipse illustrated that the optimum thickness for the tubular shape was between 2.3 mm and 2.5mm (Husin, Lile, & Yaacob, 2012; K.-H. Lee et al., 2004; Rasooliyazdi et al., 2014). Additionally, beam length also affects the deflection as the latter is proportional to the former. Equation (1) below explains a simple supported beam on three-point bending test:

$$\partial = \frac{FL^3}{48EI} \tag{1}$$

where F = Force acting on the center of the beam
L = Length of the beam between supports
E = Modulus of elasticity
I = Area moment of inertia of cross section

Table 1. Cross Section of Tubular Beam

 Circular/ Case-1; Case-2; Case-3  Case-4; Case-5; Case-6	(Yoon et al., 2016; Abdollah & Hassan, 2013; Lashlem et al., 2014)
 Two-cell horizontal; Two-cell vertical; Three-cell horizontal; Three-cell vertical  Curve profile; Rectangular; Crossover; Rectangular crossover	(Ghadianlou & Abdullah, 2013)
 Ellipse	(K.-H. Lee et al., 2004; Rasooliyazdi et al., 2014)
 Square; Square groove; I-Beam; II-Beam; C-Beam	(Abdollah & Hassan, 2013; Lashlem et al., 2014; Ab Ghani et al., 2013)

3.1.2 Panel

Teng et al. (2008) explained the different results of side impact to door that was installed with side door impact beam and to door without the component. Notably, car without side door impact beam experienced higher impact load when involved in a collision compared to the one equipped with side door impact beam.

Apart from the tubular beam type discussed in previous section, Lashlem et al. (2014) also examined the panel shape of side door impact beam. The cross section is shown in Table 2. Simulation using PAM-CRASH showed that panel shape had greater energy absorption capability compared to the tubular type of side door impact beam. Using 50 kg impactor, the energy absorption of the panel beam was 1386.1 J which is 40% higher than the tubular shape. Consequently, Lashlem et al. concluded that panel shape beam was a better side door impact beam.

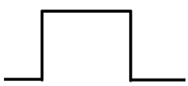
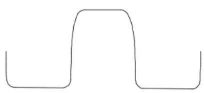
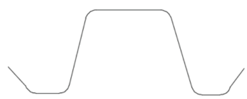
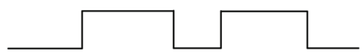
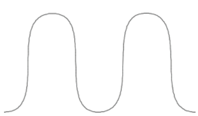
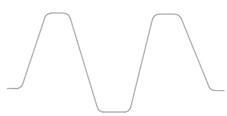
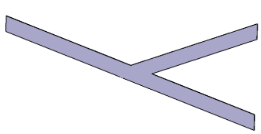
Moreover, H. W. Lee et al. (2010) and Li, Chiang, Tseng, and Tsai (2014) investigated hot stamping steel as side door impact beam,. Lee et al. found that hot stamping procedure increased tensile strength and yielded higher strength for the steel. The geometry of the beam was set to have 400 mm length, 30 mm height, and 1.2 mm thickness. In addition, the steel was punched to the shape portrayed in Table 2. The beam underwent three-point bending test pressed in 50 mm/min. From the simulation, the two-hat side door impact beam had 34% weight reduction and up to 102% increase in strength compared to the tubular shape of side door impact beam.

In contrast, Li et al. (2014) discovered that the results of three-point bending test using punch speed at 2 mm/s for this panel type was lower than the current tubular shape. The maximum load by the panel shape was lower by 24.3% and the energy absorbed was 21.0% lower compared to the tubular type. Černiauskas et al. (2010) agreed with Li et al. (2014) and claimed that panel shape for side door impact beam did not meet minimum stiffness requirement. Nevertheless, both claims need to be studied in details to solve the contrasting findings between tubular and panel shapes of side door impact beam.

Additionally, Xu, Zhang, and Zhu (2014), Zhou, Wang, Lin, and Fu (2013) and Zhou, Wang, Lin, Fu, and Ma (2014) simulated and fabricated hot stamping panel for side door impact beam and discussed the fabrication process. These studies depicted that simulation of blank sheet can predict the failure of side door impact beam fabrication. This assists the manufacturer in preventing failure or defect on the parts in early stages.

Moreover, Tao, Weigang, Ding, and Wenqiang (2016) developed a new type of side door impact beam deemed as Y-type panel. This type originated from the topology optimisation of double side door impact beams in a door which resulted in better safety to the occupants in the passenger compartment. Using Pareto Solutions, angle was set to be 60.3°, with 47.47 mm height, and 386.62 mm length. Meanwhile, the total length of the beam was 900 mm. The simulation proved that Y-type panel can reduce the distance of intrusion by as much as 22.5% compared to the initial single panel beam. Notably, Tao et al. (2016) agreed with Li et al. (2014) and Černiauskas et al. (2010) on the fact that panel type beam reduces the stiffness. On the whole, panel shape of side door impact beam reduces the stiffness of the beam but improves the weight to be lighter.

Table 2. Panel Shape of Side Door Impact Beam

One-hat (Černiauskas et al., 2010; H. W. Lee et al., 2010)
  
Two-hat (Teng et al., 2008; Lashlem et al., 2014; H. W. Lee et al., 2010; Li et al., 2014; Xu et al., 2014; Zhou et al., 2013; and Zhou et al., 2014)
   
Y-type (Tao et al., 2016)


3.1.3 Belt

Aoki, Kim, and Ben (2009) examined this shape of side door impact beam which is shown in Figure 3(c) to replace the conventional side door impact beam. Simultaneously, they aimed to reduce the weight of the beam and provide better energy absorption in side impact collision. The geometry of the belt was set to have 0.23 mm thickness, 50 mm width, and 1642 mm length, with two free fulcrums for rotation that can change the impact load to tensile load during collision. Comparison between the belt type side door impact beam and the tubular type showed that the SEA was almost 30 times higher but the energy absorbed was lower by 41.2%. Nevertheless, it can be improved by making the belt thicker and wider; despite the reduction shown, the SEA was still higher than the tubular type beam. Therefore, the belt type reduces weight and increases SEA for side door impact beam.

3.2 MATERIAL

3.2.1 Metal and Alloy

Steel is the most common material used in cars, attributing to more than 50% of the whole structure (Zetsche, Hohmann-Dennhardt, & Weber, 2014; Ji, 2015). Until today, various studies have been done to strengthen the side door impact beam depending on the type of material used. For instance, Tanabe et al. (1995) and Ishizawa et al. (1994) researched the tubular type of steel using three-point bending test and examined the load applied and energy absorption characteristics. Consequently, Tanabe et al. developed new electric resistance welded (ERW) steel tube to overcome the high tensile of the steel to be more ductile. This served to prevent the beam from cracking and compromising the passenger compartment.

Apart from that, Yoon et al. (2016) adopted Advanced High Strength Steel (AHSS) which was considered as Ultra High Strength Steel (UHSS) by World Auto Steel to improve energy absorption and reduce deflection in preventing injuries to the passengers. They hybridised the design of the tube and panel type to be a one-body side door impact beam with tube type cross section. Meanwhile, panel type was attached at both ends of the side door impact beam. From the results, they concluded that the new design of hybrid cross section of side door impact beam was lighter compared to the previous tube type. Moreover, both designs had similar energy absorption and thus, the new side door impact beam had higher SEA.

Several researchers analysed the differences of three types of material used in side door impact beam, namely steel, aluminium, and magnesium (Ghadianlou & Abdullah, 2013; Rasooliyazdi et al., 2014; Farhaninejad, Zahari, Sahari, Aziz, & Rasooliyazdi, 2012). All of them agreed that magnesium produced the highest SEA compared to the other materials, whereas steel yielded the lowest displacement or deflection due to the high load. The properties of aluminium are mixture between the other two materials in terms of SEA and displacement; hence, aluminium was chosen as the material to be studied. Abdollah and Hassan (2013) suggested that aluminium was more significant in impact energy absorption compared to steel. The result of their research which applied Charpy impact test showed that the average impact energy absorption for aluminium was 125 J compared to high strength steel which recorded 78 J.

Azim et al. (2012) adopted aluminium alloy in side door impact beam and set the steel properties of internal energy (IE) as the target for the improvement of aluminium alloy. Apart from that, they also focused on reducing the beam displacement under the load and reducing the mass of side door impact beam. Three new designs were proposed and consequently, significant reduction was recorded in terms of displacement (43.9%) and total mass (49.5%). Nevertheless, the IE only improved by approximately 2.25% compared to the current steel.

Moreover, Ayhan, Genel, and Ekşi (2012) simulated the three-point bending test on various lengths of aluminium alloy beam using different sizes of punch diameter. The results determined that the tube length had higher significance in energy absorption that affecting the beam than the punch diameter. The energy absorbed decreased significantly with increasing tube length, but showed an increase when the punch diameter increased. In addition, Husin et al. (2012) examined the optimum design of specific energy absorption for the beam cross section using Response Surface Method (RSM) for aluminium alloy and found that the best design for 900 mm length tube type was 30 mm diameter and 2.34 mm of thickness.

3.2.2 Composites

Apart from metal and alloy materials, researches were performed on polymer composite material application on side door impact beam. This was triggered by regulations set on fuel efficiency and gas emission that were applied to the carmakers (The European Parliament and The Council of The European Union, 2014; The European Parliament and The Council of The European Union, 2009). Accordingly, these carmakers need to produce lighter car without sacrificing the safety features. This can be achieved by using the composite material as suggested by Beardmore (1986); the whole component may be replaced with composites or steel parts may be integrated into one composite structure. Depending on the structure and fiber orientations, fiber reinforced plastic offered high strength and stiffness, as well as higher energy absorption to automotive structures in general (Jambor & Beyer, 1997).

Few studies on composites side door impact beam aimed to ensure that reduction on total weight of the beam when using composites material will not sacrifice the side impact safety collision performance to the occupants inside the vehicle. Cheon, Lee, and Jeong (1997) compared high strength steel beam with the composites beam in terms of static bending (three-point bending) and dynamic impact test. The three-point bending test revealed that square cross section of glass fiber/epoxy composites with rib can hold the same load as high strength steel beam with 30% weight reduction. Furthermore, the dynamic test showed that 50% weight reduction via application of fiber glass/epoxy composites can absorb around 53% of energy compared to high strength steel which can absorb 55% of energy. Notably, the influence of the cross section was very minimal.

Moreover, D. G. Lee, Lim, and Cheon (2000) claimed that the dynamic strength was 80% higher than the static test. Lim and Lee (2002) fabricated the square hollow fiber glass/epoxy that had the highest bending strength with enhancement at the beam center using satin weave prepreg and steel caps. The 30% weight reduction corresponded with 20% increase in the strength of the side door impact beam. In addition, Terada, Yang, Nakajima, Okano, and Nakai (2009) developed a new square glass fiber/epoxy composites side door impact beam with circular glass fiber/epoxy inside the beam as shown in Figure 4. Consequently, the beam had higher energy absorption capability.

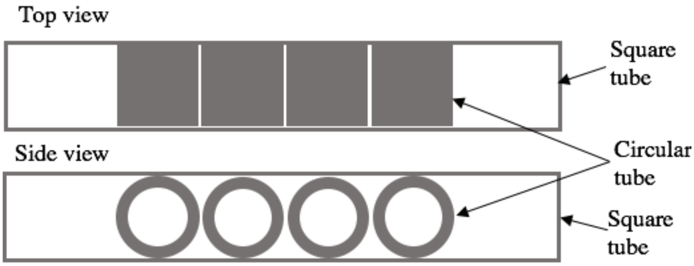


Figure 4. Square Tube Glass Fiber/Epoxy Composites with Circular Glass Fiber/ Epoxy Composites Inside (Terada et al., 2009)

Djojodihardjo and Khai (2013) and Erzen, Ren, and Anzel, (2002) investigated the panel type of composites side door impact beam compared to steel. Both researches showed positive results in reducing the weight and improving energy absorption. The weight of the side door impact beam reduced from the range of 5% up to 11.8% and the energy absorption capability improved by 146% than the steel beam. Composites belt type of side door impact beam was introduced by Aoki et al. and presented in the previous section [Figure 3(c)]. Notably, the component exhibited significant improvement in terms of weight reduction (Aoki et al., 2009).

3.2.3 Metal - Composites Hybrid

In previous sections, metal and composites were discussed and metal was identified to have high strength while composites are ideal in reducing weight. Aluminium was the most common material studied to replace steel in effort to produce lighter side door impact beam (Abdollah & Hassan, 2013; Azim et al., 2012; Strano, Villa, & Mussi, 2013; Yang, 2011; Zhou et al., 2013, 2014). Unfortunately, its strength was not comparable to steel. Thus, a hybrid of metal and composites may improve the strength of side door impact beam while simultaneously reducing its weight.

Jang, Kawai, and Sato (2005) examined square hollow aluminium beam with laminated carbon fiber reinforced polymer (CFRP) which was also enhanced by foam as filler inside the beam as portrayed in Figure 5. Four types of specimen were studied: (i) beam with CRFP laminate (type A), (ii) beam with filler foam (type B), (iii) beam with CFRP laminate and with foam (type C), and (iv) standard aluminium beam (type D). The beam with laminated CFRP composites displayed significant improvement on flexural stiffness and energy absorption capability, while the addition of foam inside the beam resulted in little improvement. The beam with foam experienced reduction in the absorbed energy compared to the standard hollow beam because the foam prevented the plastic deformation of the beam.

On the contrary, Ben, Aoki, and Sugimoto (2007) and Ben, Sugimoto, and Aoki (2010) investigated the type, thickness, and width of the CFRP, as well as the type of adhesive used as the laminates on the aluminium alloy. Eighteen specimens were prepared and consecutively impacted to find the highest absorbed energy until 150 mm displacement. The result illustrated that beam with T800 type of CFRP, 3 mm CFRP thickness, 36 mm CFRP width, and high elongation type of adhesive produced the highest energy absorption capability. Moreover, Aoki, Ben, and Iizuka (2007) researched the different thickness of CFRP laminates on the aluminium alloy ranging from 0.5 mm to 2.5 mm with increments of 0.5 mm. They concluded that at 2.5 mm thickness, CFRP laminates absorbed 25% more energy compared to aluminium alloy alone.

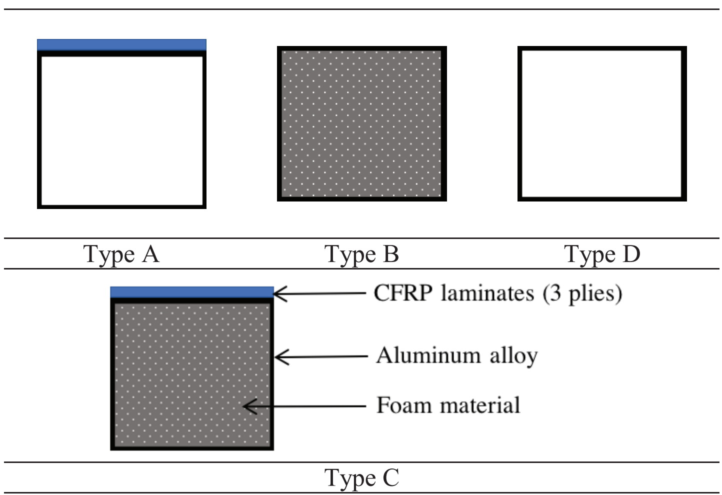


Figure 5. Aluminium Alloy Enhancement (Types A, B, and C), Aluminium Alloy (Type D)

3.3 DISCUSSION

Figure 6 shows number of research on the beam cross section. As shown in Figure 6, circle cross section is the most common shape that has been studied from researchers including the enhancement of it either inserting a rib or change the shape a little bit but still in circle cross section as the main (Table 1). From Figure 6, circle and circle-enhanced gives 40%, square and square-enhanced gives 27%, while others give the other 33% with panel type in total contribute 16% from the research studies. We can conclude that research study for the cross section are normally for the common shape circle and square but it is not the barrier to others to study other than the common cross section that have been discussed in the review.

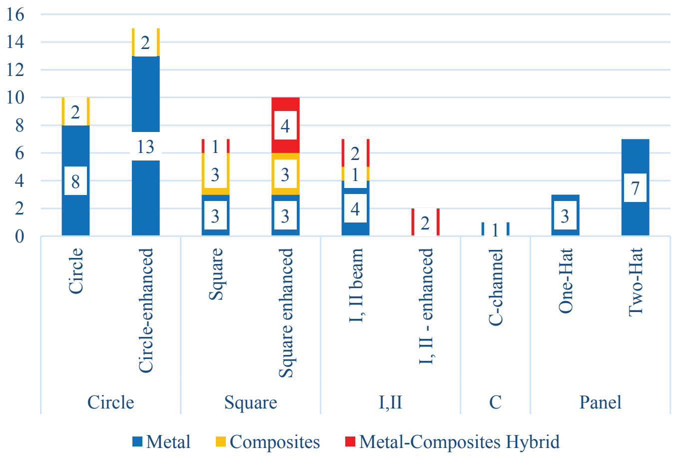


Figure 6. Number of Design vs Beam Cross-Section

The review outlined three types of material that have been studied to be incorporated into the side door impact beam: metal, composites, and metal-composites hybrid as shown in Figure 7. Commonly, metal such as high strength steel, aluminium, and magnesium; composites such as carbon and glass fiber reinforced composites; and hybrid of aluminium / composites were discussed. Previous research in. shows that metal is the most studied material which contribute 67% from the total research studies of side-door impact beam compared to composites and metal-composites hybrid which are 19% and 14% respectively.

Nevertheless, no proper material selection strategy has been examined thus far. Therefore, Ashby (2011) suggested using four steps of material selection in mechanical design: translation, screening, ranking, and documentation. Material selection is vital due to the rapid development of new materials, especially in the composites category. Notably, printed datasheet are considered as obsolete compared to the more advanced computer database system that can store vast data consisting the complex material properties (Ali, Sapuan, Jawaid, & Sanyang, 2017).

To date, numerous composite materials such as nanocomposites and biocomposites may be applied to side door impact beam. High strength and lightweight nanocomposites technology such as carbon nanotubes (Das, 2013; Esbati & Irani, 2016; Hiremath, Mays, & Bhat, 2016; and Ulus et al., 2016), nanolattices (Meza, Das, & Greer, 2014; Bagal et al., 2015) and graphene sheet (Bortz, Heras, & Martin-Gullon, 2012; Fadavi Boostani et al., 2015; and Liu et al., 2016) can be study to be the side door impact beam if cost, manufacturing, repair and supply are neglected as the composites increase strength, stiffness and corrosion resistance.

In addition, biocomposites including natural based fibers are developing swiftly with robust interest from researchers in the area (Bledzki, Faruk, & Sperber, 2006, (Koronis, Silva, & Fontul, 2013), (Dunne, Desai, Sadiku, & Jayaramudu, 2016; Gurunathan, Mohanty, & Nayak, 2015). Historically, researches on application of natural fiber in automotive components included (i) dashboard (Sapuan et al., 2011), (ii) car bumper beam (Davoodi et al., 2010), (iii) car bumper energy absorber (Davoodi, Sapuan, & Yunus, 2008), (iv) hand brake lever (Mansor, Sapuan, Zainudin, Nuraini, & Hambali, 2013), and (v) automotive anti-roll bar (Mastura, Sapuan, Mansor, & Nuraini, 2016). This development may be extended to include side door impact beam as well.

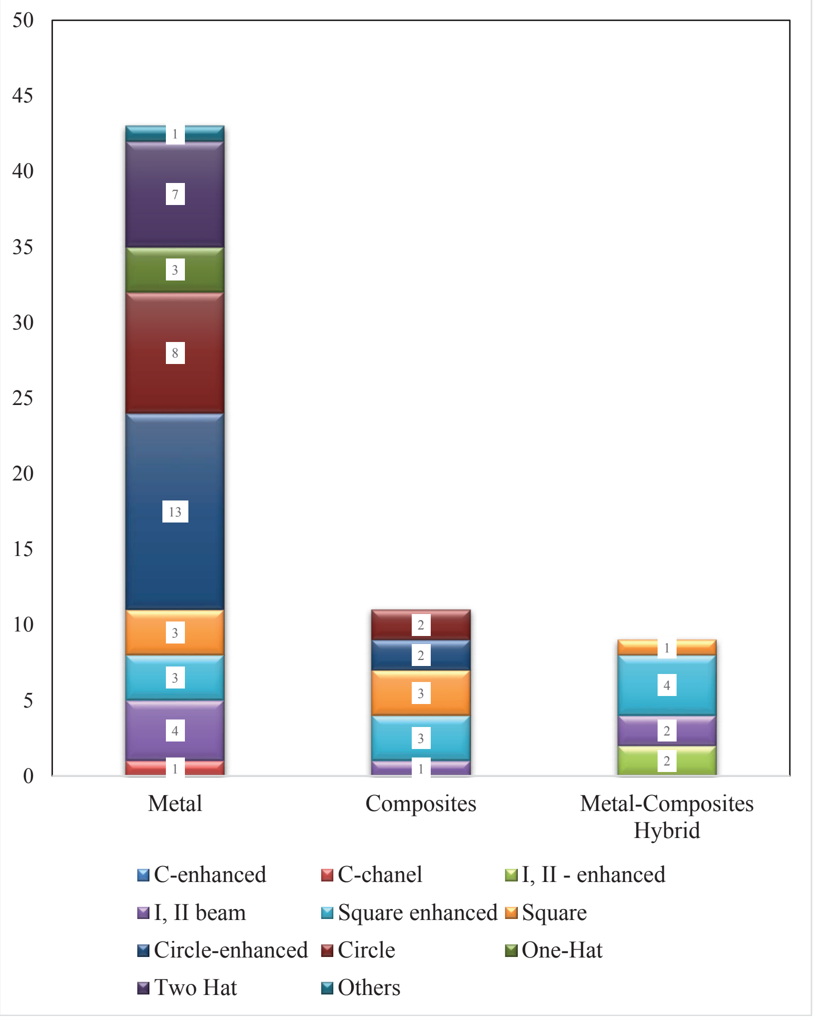


Figure 7. Number of Design in Research vs Type of Materials for Side-Door Impact Beam

3.4 TYPE OF JOINT

Joint type to the door or door panel for side door impact beam is crucial because the joints should not fail prior to the bending and breakage of side door impact beam in order to prevent injury to the occupants. Yoon et al. (2016) suggested to use one body door beam without using bracket to connect the beam to the door but spot weld was used in this method. One body door impact beam was found to improve the maximum displacement of the beam by 10.7% with 9% weight reduction compared to the tubular type.

Lim and Lee (2002) studied the simulation of mechanical joint for composites side door impact beam to the bracket using bolts or rivet that can hold higher tensile load during bending impact. They tested the shear out failure and identified that the bracket failed when the pin was located far from the end of the bracket (15 mm). The optimum distance for the pin from the end of the bracket was equal to or more than 20 mm. This distance ensured that the bracket will hold the composites beam until its failure.

Apart from that, Ben et al. (2010) connected the beam to the door panel using bolts and found that the impact energy absorption was 3368 J for 150 mm displacement. Meanwhile, the other type of joint which applied socket ribs and bonded with high elongation adhesive recorded 4134 J in impact energy absorption. Furthermore, Erzen et al. (2002) studied the panel type of side door impact beam and simulated the joint of the beam as welded (rigid) to the door and deformed together with the door as spring constraint. Consequently, spring constraint resulted in better strain energy for composite panel beam with 7279 J as compared to rigid which recorded 2864 J.

On the whole, connection of the beam to the door panel also has significant effect on the impact load and energy absorption of the side door impact beam. In order to ensure that the beam has maximum energy absorption, the mechanically joint connection or adhesive should not be broken prior to the failure of the beam.

4.0 CONCLUSION

This paper reviewed the development of side door impact beam on passenger car. Three types of side door impact beam – tubular, panel, and belt – were discussed. From the discussion, tubular shape was identified to have better performance than panel and belt types. Nevertheless, this may be improved further with the development of knowledge and technology in the area. In the materials category, aluminium/composites hybrid displayed significant improvement in strength and reduction of weight for the side door impact beam. In the future, this area may be explored further to discover the best material composition for side door impact beam that can reduce injuries and fatalities. Apart from shapes and materials, connection of the beam to the door panel also affect the impact load and energy absorption of the side door impact beam. Notably, this connection should not be broken prior to the failure of the beam so that the beam can absorb maximum energy. Bumper beam which act similar to side impact beam, but for the front collision can be explored for the future works so the passenger compartment will be safe when it involves in an accident.

As a conclusion, side door impact beam is one of the structures that is responsible to absorb kinetic energy and reduce door intrusion to the occupants when a vehicle is involved in side impact collision. Accordingly, it should be sufficient to withstand the impact loading. Hence, the component needs to have high strength to prevent the passenger compartment from being compromised and it also needs to be ductile to prevent the intrusion to the passenger's compartment. To that end, extensive research on the combination of types, materials, and joints of side door impact beam should be conducted properly by engineers to avoid injuries and fatalities to the occupants. This will reduce the statistics of fatality in side impact collision.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Putra Malaysia for the financial support provided through the Putra Grant IPS (GP-IPS/2016/9515100), as well as Universiti Teknikal Malaysia Melaka and Ministry of Education Malaysia for providing scholarship to the principal author to carry out this research project.

REFERENCES

Ab Ghani, A. R., Kee, C. S., Othman, M. Z., Koslan, M. F. S., & Zaidi, A. M. A. (2013). Impact response of multi-grooved square column. *Modern Applied Science*, 7(11):12–25.

Abdollah, M. F., & Hassan, R. (2013). Preliminary design of side door impact beam for passenger cars using aluminium alloy. *Journal of Mechanical Engineering and Technology*, 5(1):11–18.

Ali, B. A. A., Sapuan, S. M., Jawaid, M., & Sanyang, M. L. (2017). Expert Material Selection for Manufacturing of Green Bio Composites. In M. Jawaid, S. M. Sapuan, & Othman Y. Alothman (Eds.), *Green Energy and Technology Green Biocomposites: Manufacturing and Properties* (pp. 1–12). Switzerland: Springer International Publishing AG 2017.

Aoki, Y., Ben, G., & Iizuka, Y. (2007). Development and impact behaviors of aluminium door guarder beam reinforced with CFRP for side collision of automobiles. *Key Engineering Materials*, 334–335:197–200.

Aoki, Y., Kim, H.-S., & Ben, G. (2009). Impact strength and response behaviour of CFRP guarder belt for side collision of automobiles. *International Journal of Crashworthiness*, 14(5):469–476.

Ashby, M. F. (2011). *Materials Selection in Mechanical Design* (4th editio). Burlington: Elsevier Ltd.

Ayhan, A. O., Genel, K., & Ekşi, S. (2012). Simulation of nonlinear bending behavior and geometric sensitivities for tubular beams with fixed supports. *Thin-Walled Structures*, 51:1–9.

Azim, A., Ali, A., Sahari, B. B., Nuraini, A. A., Faieza, A. A., Ismail, H. T., … Norhidayah, M. H. (2012). Performance of Aluminium Alloy Side Door Subjected to Pole Impact Test. *Applied Mechanics and Materials*, 165:280–284.

Bagal, A., Zhang, X. A., Dandley, E. C., Shahrin, R., Zhao, J., Oldham, C. J., … Chang, C. H. (2015). Lightweight Multifunctional Nanolattice Materials. In *MRS/ASM/AVS* (p. 41). North Carolina.

Beardmore, P. (1986). Composite Structures for Automobiles. *Composite Structures*, 5:163–176.

Ben, G., Aoki, Y., & Sugimoto, N. (2007). Impact Properties of Cfrp / Al Hybrid Beam for Absorbing Impact Energy in Side Collision of Automobiles. In *16th International Conference on Composite Materials* (pp. 1–8).

Ben, G., Sugimoto, N., & Aoki, Y. (2010). Development of Simulation Technology for Impact Behavior of CFRP/Al Alloy Hybrid Beams in Side Collision of Automobiles. *Advanced Composite Materials*, 19(4):363–379.

Bledzki, A. K., Faruk, O., & Sperber, V. E. (2006). Cars from bio-fibres. *Macromolecular Materials and Engineering*, 291(5):449–457.

Bois, P. D., Chou, C. C., Fileta, B. B., King, A. I., & Mahmood, H. F. (2004). Vehicle crashworthiness and occupant protection. *American Iron and Steel Institute*, 372.

Bortz, D. R., Heras, E. G., & Martin-Gullon, I. (2012). Impressive fatigue life and fracture toughness improvements in graphene oxide/epoxy composites. *Macromolecules*, 45(1):238–245.

Brumbelow, M. L., Mueller, B. C., & Arbelaez, R. A. (2015). Occurrence of Serious Injury in Real-World Side Impacts of Vehicles with Good Side-Impact Protection Ratings Occurrence of Serious Injury in Real-World Side Impacts of Vehicles with Good Side-Impact Protection Ratings. *Traffic Injury Prevention*, 16(1):125–132.

Černiauskas, E., Keršys, A., Lukoševičius, V., & Sapragonas, J. (2010). Investigation of anti-intrusion beams in vehicle side doors. *Mechanika*, 86(6):11–16.

Cheon, S. S., Lee, D. G., & Jeong, K. S. (1997). Composite side-door impact beams for passenger cars. *Composite Structures*, 38(1–4):229–239.

Das, S. (2013). A review on Carbon nano-tubes - A new era of nanotechnology. *International Journal of Emerging Technology and Advanced Engineering*, 3(3):774–783.

Davoodi, M. M., Sapuan, S. M., Ahmad, D., Ali, A., Khalina, A., & Jonoobi, M. (2010). Mechanical properties of hybrid kenaf/glass reinforced epoxy composite for passenger car bumper beam. *Materials and Design*, 31(10):4927–4932.

Davoodi, M. M., Sapuan, S. M., & Yunus, R. (2008). Conceptual design of a polymer composite automotive bumper energy absorber. *Materials and Design*, 29(7):1447–1452.

Djojodihardjo, H., & Khai, S. L. (2013). Modeling, Analysis and Comparative Study of Side Impact Beam. *International Journal of Engineering and Innovative Technology*, 3(5):283–292.

Dunne, R., Desai, D., Sadiku, R., & Jayaramudu, J. (2016). A review of natural fibres, their sustainability and automotive applications. *Journal of Reinforced Plastics and Composites* , 35(13):1041–1050.

Erzen, S., Ren, Z., & Anzel, I. (2002). Analysis of FRP side-door impact beam. In *Proceedings of the 2nd IMechE Automobile Division Southern Centre Conference on Total Vehicle Technology, How Do We Get The Innovation Back Into Vehicle Design?* (pp. 109–120).

Esbati, A. H., & Irani, S. (2016). Mechanical properties and fracture analysis of functionalized carbon nanotube embedded by polymer matrix. *Aerospace Science and Technology*, 55:120–130.

Fadavi Boostani, A., Yazdani, S., Taherzadeh Mousavian, R., Tahamtan, S., Azari Khosroshahi, R., Wei, D., … Jiang, Z. Y. (2015). Strengthening mechanisms of graphene sheets in aluminium matrix nanocomposites. *Materials and Design*, 88:983–989.

Farhaninejad, A., Zahari, R., Sahari, B. B., Aziz, F. A., & Rasooliyazdi, E. (2012). Simulation of Square Beam Subjected to Side Impact. In *Proceedings of the World Congress on Engineering and Computer Science* (Vol. II, pp. 8–12). San Francisco, USA.

Ghadianlou, A., & Abdullah, S. Bin. (2013). Crashworthiness design of vehicle side door beams under low-speed pole side impacts. *Thin-Walled Structures*, 67:25–33.

Gurunathan, T., Mohanty, S., & Nayak, S. K. (2015). A review of the recent developments in biocomposites based on natural fibres and their application perspectives. *Composites Part A: Applied Science and Manufacturing*, 77:1–25.

Hedeen, C. E., & Campbell, D. D. (1969). Side Impact Structures. *1969 International Automotive Engineering Congress and Exposition*.

Hiremath, N., Mays, J., & Bhat, G. (2016). Recent Developments in Carbon Fibers and Carbon Nanotube-Based Fibers : A Review Recent Developments in Carbon Fibers and Carbon. *Polymer Reviews*, 1–30.

Husin, R. S. R., Lile, N. L. T., & Yaacob, S. (2012). Optimization of Circular Side Door Beam for Crashworthiness Analysis. *International Journal on Advanced Science, Engineering and Information Technology*, 2(3):256.

Ishizawa, Y., Maeda, T., Takamura, T., Watanabe, T., Murata, N., & Sugayoshi, T. (1994). Ultra-high strength ERW tubes for use as automobile door impact beams. *NKK Technical Review*, (70):8–15.

Jambor, A., & Beyer, M. (1997). New cars — new materials. *Materials & Design*, 18(4/6):203–209.

Jang, S. M., Kawai, Y., & Sato, C. (2005). Energy Absorption Characteristics on Aluminum Beams Strengthened with CFRP Laminates under Impact Loading. *Key Engineering Materials*, 297–300:1344–1349.

Ji, J. (2015). *Lightweight Design of Vehicle Side Door*. Politecnico di Torino. https://doi.org/10.6092/polito/porto/2598565

Jones, J. (2012). *National Highway Traffic Safety Administration Laboratory Test Procedure for FMVSS No.214, Dynamic Side Impact Protection - Moving Deformable Barrier Test Requirements*.

Kahane, C. J. (1982). *An Evaluation of Side Structure Improvements in Response to Federal Motor Vehicle Safety Standard 214*. Washington DC. Retrieved from http://www.nhtsa.gov/Vehicle+Safety/

Kahane, C. J. (1999). *Evaluation of FMVSS 214 - Side Impact Protection: Dynamic Performance Requirement. NHTSA Technical Report* (Vol. October). Washington DC.

Koronis, G., Silva, A., & Fontul, M. (2013). Green composites: A review of adequate materials for automotive applications. *Composites Part B: Engineering*, 44(1):120–127.

Lashlem, A. A., Wahab, D. A., Abdullah, S., & Cheharon, C. H. (2014). The Effect of Geometry in End-of-Life Vehicle Recovery of Safety Beams. *Applied Mechanics and Materials*, 663:614–621.

Lee, D. G., Lim, T. S., & Cheon, S. S. (2000). Impact energy absorption characteristics of composite structures. *Composite Structures*, 50(4):381–390.

Lee, H. W., Hwang, J. B., Kim, S. U., Kim, W. H., Yoo, S. J., Lim, H. W., & Yum, Y. (2010). Construction of Vehicle Door Impact Beam Using Hot Stamping Technology. *Transactions of the Korean Society of Mechanical Engineers A*, 34(6):797–803.

Lee, K.-H., Joo, W.-S., Song, S.-I., Cha, I.-R., & Park, G.-J. (2004). Optimization of an automotive side door beam, considering static requirement. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 218(1):51–57.

Li, M. F., Chiang, T. S., Tseng, J. H., & Tsai, C. N. (2014). Hot stamping of door impact beam. *Procedia Engineering*, 81:1786–1791.

Lim, T. S., & Lee, D. G. (2002). Mechanically fastened composite side-door impact beams for passenger cars designed for shear-out failure modes. *Composite Structures*, 56(2):211–221.

Liu, J., Khan, U., Coleman, J., Fernandez, B., Rodriguez, P., Naher, S., & Brabazon, D. (2016). Graphene oxide and graphene nanosheet reinforced aluminium matrix composites: Powder synthesis and prepared composite characteristics. *Materials and Design*, 94:87–94.

Lukaszewicz, D. H.-J. A. (2013). Automotive Composite Structures for Crashworthiness. In A. Elmarakbi (Ed.), *Advanced Composite Materials for Automotive Applications: Structural Integrity and Crashworthiness* (1st ed., pp. 99–127). Chichester, UK: John Wiley & Sons Ltd.

Mansor, M. R., Sapuan, S. M., Zainudin, E. S., Nuraini, A. A., & Hambali, A. (2013). Hybrid natural and glass fibers reinforced polymer composites material selection using Analytical Hierarchy Process for automotive brake lever design. *Materials and Design*, 51:484–492.

Mastura, M. T., Sapuan, S. M., Mansor, M. R., & Nuraini, A. A. (2016). Environmentally conscious hybrid bio-composite material selection for automotive anti-roll bar. *The International Journal of Advanced Manufacturing Technology*, 89(5–8):2203–2219.

Meza, L. R., Das, S., & Greer, J. R. (2014). Strong, lightweight, and recoverable three-dimensional ceramic nanolattices. *Science*, 345(6202):1322–1326.

Palazzolo, J. A., & Hui, A. (2000). Energy Dissipating Body Panel Assembly. *US Patent*, (6164716).

Rasooliyazdi, E., Zahari, R. Bin, Ghadianlou, A., Farhaninejad, A., Sahari, B. Bin, Aziz, F. A., & Jamali, H. (2014). Crashworthiness Design of Vehicle Side Door Beam Based on Elliptical Geometry Modification Using Multi-Objective Optimization. *International Review of Mechanical Engineering (IREME)*, 8(1):28.

Sapuan, S. M., Mun, N. K., Hambali, A., Lok, H. Y., Fairuz, A. M., & Ishak, M. R. (2011). Prototype expert system for material selection of polymeric composite automotive dashboard. *International Journal of the Physical Sciences*, 6(25):5988–5995.

Stolinski, R., Grzebieta, R., & Fildes, B. (1998). Vehicle far-side impact crashes. In *International Technical Conference on the Enhanced Safety of Vehicles (ESV)* (pp. 1819–1826).

Strano, M., Villa, A., & Mussi, V. (2013). Design and manufacturing of anti-intrusion bars made of aluminium foam filled tubes. *International Journal of Material Forming*, 6(1):153–164.

Tanabe, H., Yamazaki, K., Akada, H., Akihiro, M., & Iwasaki, T. (1995). High Strength steel tubes for automobile door impact beams. *Nippon Steel Technical Report*, (64):55–61.

Tao, T., Weigang, Z., Ding, C., & Wenqiang, Z. (2016). Crashworthiness Optimal Design of Automotive Side Door under Pole Side Impact. *China Mechanical Engineering*, 27(2):278–283.

Teng, T. L., Chang, K. C., & Nguyen, T. H. (2008). Crashworthiness evaluation of side-door beam of vehicle. *Technische Mechanik*, 28(3–4):268–278.

Terada, S., Yang, Y., Nakajima, K., Okano, M., & Nakai, A. (2009). Development of New Side Impactor. In *International Conferences on Composite Materials ICCM* (Vol. 1, pp. 2–6).

The European Parliament and The Council of The European Union. (2009). Regulation (EC) No. 443/2009 on setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO2 emissions from light-duty vehicles. *Official Journal of the European Union*, 1–15.

The European Parliament and The Council of The European Union. (2014). Regulation (EU) No 333/2014 to define the modalities for reaching the 2020 target to reduce CO2 emissions from new passenger cars. *Official Journal of the European Union*, 15–21.

Ulus, H., Ustun, T., Sahin, O. S., Karabulut, S. E., Eskizeybek, V., & Avc, A. (2016). Low-velocity impact behavior of carbon fiber/epoxy multiscale hybrid nanocomposites reinforced with multiwalled carbon nanotubes and boron nitride nanoplates. *Journal of Composite Materials*, 50(6):761–770.

US Department of Transportation. (2007). *The New Car Assessment Program Suggested Approaches for Future Program Enhancements*.

Xu, H., Zhang, M. R., & Zhu, L. J. (2014). Numerical and Experimental Investigation on Hot Stamping of Ultra-High Strength Steel. *Advanced Materials Research*, 941–944:1720–1725.

Yang, J.-H. (2011). Optimization of the Aluminum Door Impact Beam Considering the Side Door Strength and the Side Impact Capability. *Journal of the Korea Academia-Industrial Cooperation Society*, 12(5):2025–2030.

Yoon, T. H., Kim, H., Heo, C., & Kwon, J. (2016). An experiment and FE simulation for the development of a SPFC1180 AHSS one-body door impact beam about a car side collision. *International Journal of Precision Engineering and Manufacturing*, 17(1):81–89.

Zetsche, D., Hohmann-Dennhardt, C., & Weber, T. (2014). *Daimler Sustainability Report 2014*. Stuttgart, Germany. Retrieved from http://sustainability.daimler.com/dai_nachhaltigkeit2014/static/export/docs/Daimler NB 2014 EN.pdf

Zhou, J., Wang, B., Lin, J., & Fu, L. (2013). Optimization of an aluminum alloy anti-collision side beam hot stamping process using a multi-objective genetic algorithm. *Archives of Civil and Mechanical Engineering*, 13(3):401–411.

Zhou, J., Wang, B., Lin, J., Fu, L., & Ma, W. (2014). Forming defects in aluminum alloy hot stamping of side-door impact beam. *Transactions of Nonferrous Metals Society of China*, 24(11):3611–3620.