

A Review of Energy Absorption of Automotive Bumper Beam

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Abstract

Energy absorption during an impact is very important in automotive bumper system. Bumper beam is one of the main parts in bumper system which is used as protection for passengers and frontal compartment of a car during impact. This paper is carried out in order to determine the factors that affecting energy absorption of automotive composite bumper beam. Studies related to the factors affecting and optimization of bumper beam was reviewed and summarized from year 1995 to 2015. From literatures, the use of natural fiber polymer based composite have been utilized in automotive components but still in studies in bumper beam structure. A further study to use natural fiber polymer based composite in bumper beam structures need to be study.

Keyword- Energy absorption, composite material, automotive, bumper beam, FEA

INTRODUCTION

The main function of a bumper system is to protect the car body and passengers during impact collision. In frontal bumper system consists of three main components called the fascia, the absorber and the bumper beam [1]. Figure 1 shows three main component of a common bumper system. The fascia is usually used for aesthetics and for decreasing the aerodynamic drag force. It cannot tolerate to impact energy, thus it is considered a non-structural component. The absorber is designed to dampen a portion of the kinetic energy from a collision. The bumper beam is a key structure that helps to absorb the kinetic energy from a high-impact collision and to provide bending resistance in a low-impact collision [2]. Bumper beam will absorb the impact collision energy in a controlled manner before the energy gets transferred to the passenger compartment.

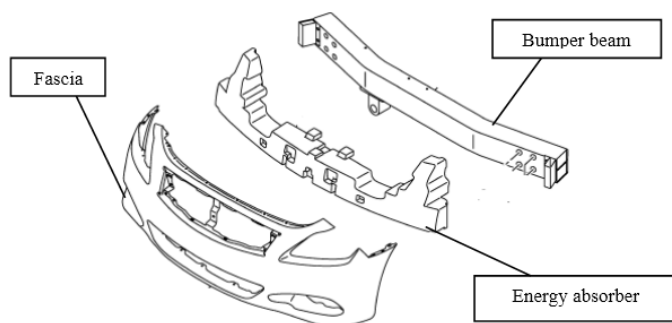


Figure 1: Common bumper system [60]

In automotive industry's energy absorption ability is very important in increasing the safety for passengers as vehicles are used extensively. Structural crashworthiness is an essential requirement in the design of automotive parts. Crashworthiness refers to the response of a vehicle when it is involved in or undergoes an impact. Crashworthiness performance is good when less damaged to the vehicle and passengers after crash. Crashworthiness for structural members is required to be analyze before implementing in the actual field. Many studies have been carried out especially about thin-walled structure in determining the energy absorption [3, 4] and common thin-walled structure being studied are circular tubes [5], square tubes [6, 7], honeycombs [8], and sandwich plates [9].

In determining the crashworthiness, specific energy absorption (SEA), energy absorption (EA), mean crushing force (MCF), and crash load efficiency (CLE) are crashworthiness indicator that have been used to evaluate crashworthiness. SEA denotes the energy absorbed per unit mass of the absorber, which can be calculated as [10]

$$SEA = \frac{EA}{M} \quad (1)$$

Where M represents the total mass of the structure.

EA denotes the energy absorption during crashing and it can be formulated as

$$EA = \int_0^s F(x) dx \quad (2)$$

Where s is the crash displacement and F denotes the impact force. For energy absorbing structure, the higher the SEA the better energy absorption capability. Crash load efficiency (CLE) is another indicator in relation to energy absorption capacity, and it is given as

$$CLE = \frac{MCF}{MIF} \times 100\% \quad (3)$$

Where MIF represents the maximum impact force when impact occurs. Mean crash force (MCF) is expressed as

$$MCF = \frac{EA}{s} \quad (4)$$

Previously, most of the bumper beam is made of steel; however, in mid 80's the application of polymer composite material has been introduced to replace conventional material such as plastic, aluminum, and metal. There are many past research have been conducted using polymer composite [11, 12, 13] where it can offer low weight, easier to produce complex shape, and high impact energy absorption capacity.

The use of natural fiber composite also has been introduced to replace the use of conventional materials because of it has an advantages of low density, high specific strength and stiffness [14]. Table 1 shows some of the composite material used in

automotive components. The objective of this paper is to review the factors that affecting energy absorption of automotive composite bumper beam.

Table 1: Composite materials used in automotive components

Material	Part		Ref.
Epoxy matrix with the addition of jute	Door panels in its E-class vehicles	Mercedes-Benz	[15]
Polyurethane reinforced with a mixed flax/sisal	Door trim panels	Audi	[15]
New bio-based plastic, the latter is replaced with a raw material made from sugar cane	Interior components	Toyota	[16]
Combine bamboo fibers and a plant based resin polybutylene succinate (PBS), and floor mats made from PLA and nylon fibers	Interior components	Mitsubishi	[17]
Soy-based	Seat foam	Toyota	[18]
Sugar cane	Luggage compartment	Toyota	[16]
Hybrid Toughened Kenaf/ Glass Epoxy Composite	Strengthened ribs for bumper beam	-	[19]
Fiber-reinforced composite	Formula One racing car	-	[20]
Thermoplastic	Crash boxes	-	[21]
Glass-fiber-polyester resin composites	-	-	[22]
(FRP) woven fabric in thermosetting epoxy resin	Automotive and aerospace	-	[23]

ENERGY ABSORPTION

Energy cannot be created or destroyed, but it can be changed from one form to another form. During an impact or crash, the energy absorption occurs, which the energy is changing form or converts into the internal potential energy of a system. Theoretical calculation of energy absorption can be calculated using impact theory [24]. Energy absorption can be determined using real-time test, but due to the high cost of conducting real-time tests, finite element analysis (FEA) is used in the automotive industry before conducting real-time test. By using FEA industries have reduced the cost and time of the product development process while increasing the safety, comfort and durability of the vehicles manufactured.

A. Impact Theory

There are two types of impact elastic impact and plastic impact. Total energy is conserved throughout the impact process. Momentum before impact and after impact is equal. After impact, energy and momentum conservation equations can be expressed as follows:

$$\frac{1}{2} m_A v_A^2 = \frac{1}{2} m_A v_{A2}^2 + \frac{1}{2} m_B v_{B2}^2 \quad (5)$$

$$m_A v_A = (m_A + m_B) v_0 \quad (6)$$

Where m_A is the mass of the impactor, m_B the mass of vehicle, v_A the velocity of the impactor before impact and v_0 the final velocity of the impactor and vehicle at maximum deflection point.

The velocities after impact can be determined by the coefficient of restitution (e). The coefficient of restitution (COR) is the ratio of speed of separation to speed of approach in an impact.

$$e = \frac{v_{B2} - v_{A2}}{v_A - v_B} \quad (7)$$

The coefficient of restitution is a number which indicates how much kinetic energy remains after a impact of two body. If the coefficient is high (very close to 1), it means that very little kinetic energy was lost during the impact.

Energy dissipated, E_D can be determined by subtracting the kinetic energy of the two masses after impact, and the kinetic energy of the impactor before impact.

$$E_{Plastic} = \frac{1}{2} m_A v_A^2 + \frac{1}{2} m_B v_B^2 - \frac{1}{2} m_{A2} v_{A2}^2 - \frac{1}{2} m_{B2} v_{B2}^2 \quad (8)$$

B. Finite Element Analysis (FEA)

Currently, automotive industry relies on finite element analysis (FEA) in development of product [37]. Analyzing the energy absorption in real impact is quite complicated and depends on different parameters. The influence of design parameters on the weight, costs or functional properties of new car models can be determine using the FEA. FEA is a suitable method to analyze the energy absorption during impact to determine the approximate deflection behaviour during an impact. Advantages of FEA are numerous. Once a

detailed CAD model of a new design concept has been developed, any refined prior to the creation of drawings and changes are inexpensive. FEA can analyze the design in detail, saving time and money by reducing the number of prototypes required. Because of high cost of physical test and time consuming, by using FEA, thousand of simulation can be done to get satisfied result before conducting the real physical test.

Currently there are many software can be used to simulate the FEA such as ANSYS LS DYNA, LS DYNA, PAMCRASH and ABAQUS. Marzbanrad et al. [24] simulate low speed frontal impact of original bumper under ECE United Nations Agreement, Regulation no. 42, 1994 using LS DYNA. Weight and impact behaviour parameter were compared for composite and aluminum material resulted that modified SMC bumper beam can be replace the used of glass mat thermoplastic (GMT) and aluminum in Marzbanrad study.

Kathiresan et al. [25] used ABAQUS software in his study of crashworthiness of glass fibre/epoxy laminated thin walled composite. Results of energy absorption (EA) predicted by numerical analysis or finite element analysis (FEA) results are mostly matching with experimental results.

Hambali et al. [31] analyze the energy absorption of the bumper beam using ANSYS LS DYNA by replacing the current material by sheet moulding compound (SMC) composite. Small deflection occurs during simulation, but the result obtained is reasonable as its within Economic Commission for Europe (ECE) United Nations standard requirement where the parts still intact and usable after the impact. Hosseinzadeh et al. [32] studied impact modelling of a commercial front bumper beam made of glass mat thermoplastic (GMT) using ANSYS LS-DYNA 5.7 subjected to low-velocity impacts. Cheon et al. [33] developing the composite bumper beam for passenger cars using commercial finite element software ANSYS 5.0 to determine the strength and stiffness. Table 2 shows literature founded from past research search that using FEA.

FACTOR AFFECTING AND OPTIMIZING ENERGY ABSORPTION

There are several factors that have been found affecting the energy absorption in bumper beam. Impact condition [32],

cross section [38, 39], rib [38], thickness [40], material [41, 42, 43], and shape [44] also are significant factors that affecting the energy absorption. These are the common factors that affecting the energy absorption found in literature. Adding rib to the structure is the way to optimize the energy absorption improving the energy absorption capability. Ribs give the structure more strength. Figure 2 shows the effect of rib in energy absorption–displacement curves [38]. From the graph, it shows that rib-reinforced beam exceeds empty square beam and foam filled-beam as the compression goes along.

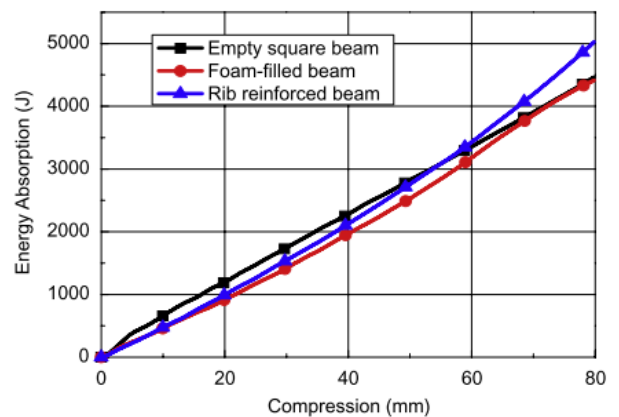


Figure 2. Effect of rib in Energy absorption–displacement curves [38]

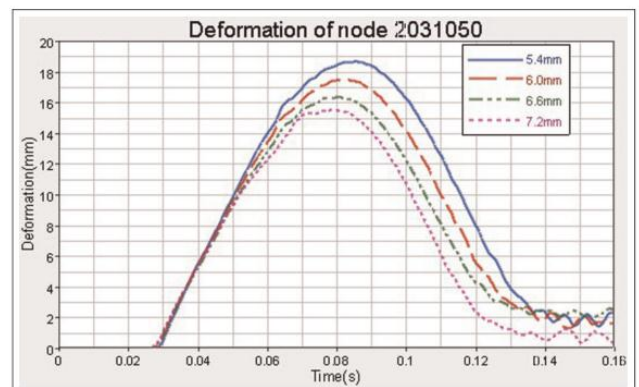


Figure 3. Effect of thickness in the deformation of bumper beam [42]

Table 2: Past research using FEA

Software/ Tools	Study	Result	Ref.
LS DYNA	Design and analysis of an automotive bumper beam in low-speed frontal crashes	Use of materials with low young module cause to low rigidity and use of high-strength materials lead to good impact behavior. Increasing bumper thickness causes a rise in bumper rigidity and impact force. Addition of ribs causes an increase in rigidity of bumper beam center and consequently increases the impact force.	[24]
ABAQUS	Crashworthiness analysis of glass fibre/epoxy laminated thin walled composite conical frusta under axial compression	Experimental results are very closer to those of the developed finite element model, and it was also recognized that the obtained results through FEA procedure deviates about 5.82% error with experimental results	[25]

LS DYNA	Crashworthiness design for foam-filled thin-walled structures with functionally lateral graded thickness sheets	Simulation results agree fairly well with the corresponding experimental results	[26]
LS DYNA	Multi-cornered thin-walled sheet metal members for enhanced crashworthiness and occupant protection	The numerical simulations and quasi-static tests were reasonable and the results were creditable	[27]
LS DYNA	On Functionally Graded Composite Structures for Crashworthiness	The overall deformation of the FE model in terms of collapse mode and number of folds is in good agreement with that of the experiments.	[28]
ABAQUS	Geometrical optimization of bumper beam profile made of pultruded composite by numerical simulation	Low velocity impact finite element simulations are performed in order to optimize beam section profile and beam curvature for crashworthiness. Results obtained shows that pultruded bumper beam has comparable energy absorption capability with respect to the steel normal production solution.	[29]
LS-DYNA	Investigation on structure optimization of crashworthiness of fiber reinforced polymers materials	Simulation values SEA are compared with experimental data SEA, fractional error between those are about 5.67% and 4.89%, respectively, which can meet the precision requirement for engineering application.	[30]
ANSYS LS DYNA	Design optimization of automotive bumper beam through energy absorption analysis	Three main factors have been taken into account to optimize the energy absorption of bumper beam which are cross section of the bumper beam, strengthening ribs and the thickness. It was found that curved D cross section beam has appropriate energy absorption and deflection compares with others design.	[31]
ANSYS LS DYNA	Parametric study of automotive composite bumper beams subjected to low-velocity impacts	The proposed model of the research have equal strength and rigidity of the structure, reduction of material, ease of manufacturing by simplifying geometrical shape and reduction of production cost are studied and proved	[32]
ANSYS	Development of the composite bumper beam for passenger cars	It was concluded that the analysis for the determination of the thickness of the cross section of the composite bumper beam was satisfactory and reliable.	[33]
LS DYNA	Progressive crushing of fiber-reinforced composite structural components of a Formula One racing car	The finite element simulations accurately predict the overall shape, magnitude and pulse duration in all the types of impact.	[20]
PAMCRASH	Motorcycle-car side impact simulation	The qualitative results of the car-motorcycle side impact simulations presented in this paper show close match with the experimental observations	[34]
HYPERMESH, LS-DYNA	BIW safety performance research based on vehicle frontal crash	Research method and the simulation results in this paper have provided certain examples for body longitudinal beams design in future and certain references for optimization of related frontal crash structures.	[35]
HYPERMESH, LS-DYNA	Whole car side impact mode and response evaluation	The experiment of car side impact shows that the simulation result of this paper is of good value in side impact structure and safety evaluation	[36]
LS-DYNA	Analysis of Car Crash Simulation Data with Nonlinear Machine Learning Methods	Reduce the time spent by the engineer analyzing the influences of design parameters on the weight, costs or functional properties of new car models	[37]

Increasing the bumper beam thickness, more kinetic energy transfer from impactor to vehicle and less plastic strain energy dissipates. Increasing thickness decrease the deformation after impact. Figure 3 shows that maximum deformation of the beam decreases with the increase of bumper beam thickness [42]. As the weight of cars are main issues that uses a lot of fuel, light weight material is preferable to be used. Composite materials are currently being replaced the conventional material as it offer more light weight. By using composite material the weight of car can be reduce [45].

According to Marzbanrad et al. [24] studies the modified sheet molding compound (SMC) bumper beam in his study can minimize the bumper beam deflection, impact force and stress distribution and also maximize the elastic strain energy. Hosseinzadeh et al. [32] studies impact property of the GMT and SMC bumper and compare to conventional material steel and aluminum. SMC have been found to have equal strength and rigidity of the structure which shape, material and impact conditions. Table 3 shows factors that affecting energy absorption founded from past literature search.

Table 3: Factors that affecting energy absorption

Factor	Results	Ref.
Shape/cross section	By adding or removing strengthening ribs of bumper, showed their effects in stabilization and rigidity of the structure	[32]
Shape/cross section	Cross-section has significant effects on the energy damping rate and bending resistance which is magnifies its strength	[46]
Shape/cross section	Specimen width, profile radius, and profile constraint. An increase in the radius of the profile block caused a decrease in the specific energy absorption, SEA	[47]
Material	Application of composite materials to automotive front bumper subsystem. Giving better results with respect to the present constructive solution both in term of lightweight.	[48]
Material	SMC bumper beam can minimize the bumper beam deflection, impact force and stress distribution and also maximize the elastic strain energy	[24]
Material	Use of materials with low young module cause to low rigidity and use of high-strength materials lead to good impact behavior	[24]
Material	Utilizing low-cost composite materials and also achieving reduced or equal weight compared with the current bumper beam	[32]
Thickness	Introduced functionally graded structures with changing wall thickness along the longitudinal direction which showed potential advantage as absorber of crushing energy.	[49]
Thickness	Revealed that tubes with graded thickness in cross-section, which can lead up to 30–35% increase in energy absorption under axial loading	[50]
Thickness	Pointed out that the sheet with varying thickness could be more promising structure in the area of crashworthiness.	[51]
Thickness	The bumper beam part which has thinner material such as central portion provides effective energy absorbing characteristics	[52]

As there are factor that affecting energy absorption, researcher tried to improve and optimize the energy absorption of bumper beam. Optimizing the cross section of a bumper beam magnifies its strength, dimensional stability, and damping capability. It has significant effects on the energy damping rate and bending resistance compared with other parameters [53]. Strengthening rib improve the energy absorption of bumper beam. It has been reported that the strengthened ribs increase the impact energy by 7% and decrease elongation by 19% [32, 24]. Zhang et al. [38] showed that the optimized reinforced ribs have higher-energy absorption performance than the empty and foam-filled beams. Multi-objective formulation was used to optimum crash performance of rib reinforced thin walled hollow square beams under three-point bending drop test.

Park et al. [54] developed an optimized bumper beam cross section that satisfies both the safety requirements for a front rigid-wall impact and lower leg injuries in a pedestrian impact test. Farkas et al. [55] found an optimal geometry for dual channel bumper beams impact rigid barriers at 16 km/h for offset frontal impact and at 15 km/h for pole frontal impact. Patel et al. [56] carried out topological optimization of straight and curved bumper beams subjected to static and dynamic loads using hybrid cellular automata (HCA). Duponcheele and Tilley [57] conducted a topology optimization study using genetic algorithm to maximize the area moment of inertia of a bumper beam but not considered a crash event. Table 4 shows optimization factors that affecting energy absorption founded from past literature.

Table 4: Factors that affecting energy absorption

Optimize	Ref
Thickness	Applied feasible range wall thickness between 0.5 and 3.5mm, which is practical for aluminum structures to maximize the SEA [58]
Ribs	Optimized reinforced ribs have higher-energy absorption performance than the empty and foam-filled beams [38]
Cross-section	Satisfies both the safety requirements for a front rigid-wall impact and lower leg injuries in a pedestrian impact test. [54]
Cross-section	Found an optimal geometry for dual-channel bumper beams hitting rigid barriers at 16 km/h for offset frontal impact and at 15 km/h for pole frontal impact. [59]
Cross-section	Optimization of straight and curved bumper beams subjected to static and dynamic loads using hybrid cellular automata (HCA) [56]

CONCLUSION

Energy absorption of automotive bumper beam have been reviewed. From the review it can be concluded that FEA analysis can predict energy absorption even there are a small percent of error FEA simulation, but the result obtained is reasonable as its within standard requirement. There are many factors that affecting energy absorption. Some factors that have been found that are cross section, rib, thickness, material, shape and also impact condition.

From the review, currently the energy absorption capabilities of bumper beam are focused on material. There were researchers proposed the usage of the SMC composite to replace the conventional material, such as steel and aluminum. Natural fibers composite also have capability to be applied in bumper beam. The uses of natural fiber composite in bumper beam can be found in [19] using hybridizations of kenaf with glass fiber. Hybridizations of kenaf did not completely fulfil the required impact property of the developed bio-composite bumper beam to substitute with current material of the bumper beam, but in his study found that the ribbed bumper beam decrease the deflection of the bumper beam by 11% and strain energy by 11.3% and reliable for utilization in automotive structural components.

From the literature, there were none discussion focusing on bumper beam structure been found. Bumper beam have many type of structure which can be categories as open section, close section and I section. This different type of structure absorbs different kinetic energy during impact. Study comparison of these structures in terms of energy absorption can be study. Therefore, a detailed study about the design structure of different types of cross section beam for natural fiber composite material can be studied in the future for automotive bumper beam.

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