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Development Process of New Bumper Beam for Passenger Car: A Review

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Abstract

Bumper beam absorbs the accidental kinetic energy by deflection in low-speed impact and by deformation in high-speed impact. The safety regulations “low-, and high-speed, and pedestrian impacts” along with new environmental restrictions “end-of-life vehicles” increased the complexity level of bumper system design. The new bumper design must be flexible enough to reduce the passenger and occupant injury and stay intact in low-speed impact besides being stiff enough to dissipate the kinetic energy in high-speed impact. The reinforcement beam plays a vital role in safety and it must be validated through finite-element analysis (FEA) and experimental tests before mass production. The careful design and analysis of bumper beam effective parameters can optimize the strength, reduce the weight, and increase the possibility of utilizing biodegradable and recyclable materials to reduce the environmental pollution. Developing the correct design and analysis procedures prevents design re-modification. On the other hand, analysis of the most effective parameters conducive to high bumper beam strength increases the efficiency of product development. Cross section, longitudinal curvature, fixing method, rib thickness, and strength are some of the significant design parameters in bumper beam production. This study critically reviews the related literature on bumper design to come up with the optimal bumper beam design process. It particularly focuses on the effective parameters in the design of bumper beam and their most suitable values or ranges of values. The results can help designers and researchers in performing functional analysis of the bumper beam determinant variables.

Keywords: Developing process, Bumper beam, Design parameters
1. Introduction

Design is the preliminary stage of product development and analysis. The embodiment stage of the design process fairly predicts the failure(s), if any, before mass production. Passenger vehicles make up over 90% of the fleet of registered vehicles. In 2009 it was estimated that 9,640,000 vehicles were involved in police-reported crashes, 95% (9,161,000) of which were passenger vehicles. Furthermore, there, 45,435 vehicles of these were involved in fatal crashes and eighty percent of which (36,252) were passenger vehicles. More than 23,000 passenger vehicle travelers lost their lives in traffic crashes in 2009 and an estimated 1.97 million persons were injured [1]. Therefore, vehicle safety requirements forced by Governments and insurance companies increase frequently [2]. In most of the accidents, the bumper system is the first vehicle part that receives the collision and which may to some extent protect the car body and passengers. This system comprises three main parts: fascia, energy absorber, and bumper beam [3]. The fascia is a non-structural aesthetics component that reduces the aerodynamic drag force while the energy absorber dissipates part of the kinetic energy during collision. The bumper beam is a structural component which absorbs the low-impact energy by bending resistance and dissipates the high-impact energy by collision [4].

There are some investigations of new material development, property improvement, and FEA of bumper beam structures by researchers and car manufacturers. These parties are mainly interested in substituting the conventional material with lighter and stronger material[5]. Renault used SMC in a passenger car bumper in 1972 instead of steel [6] and General Motors (GM), used the sheet-moulding compound (SMC) beam in Pontiac Bonneville Cadillac Seville and Cadillac Eldorado instead of steel which was used in previous models [7]. Cheon, Choi JH [8] found that the polymer composite bumper beam offers 30% less weight than steel without scarifying the bumper beam’s bending strength. Wakeman, Cain [9] found that holding time pressure is the most effective parameter among five processing parameters in microstructure and macrostructure properties of glass mat thermoplastic (GMT) in a bumper beam. Peterson, Spencer [10] from Azdel company developed the GMT with a high surface finish for aesthetic components. Raghavendran and Haque [11] also developed a lightweight GMT composite containing long-chopped fiber strands to be used in headliner and other automotive interior applications. Suddin, Salit [12] used the weight analysis method to select fascia for a desired vehicle. He used the knowledge-based system (KBS) approach to select
the material for bumper beam development [13]. Sapuan, Maleque [3] studied the conceptual design and material selection for development of a polymeric-based composite automotive bumper system. Hosseinzadeh, Shokrieh [14] studied the shape, material, and impact conditions of the bumper beam and compared the results with conventional metals like steel and aluminium. He found that GMT can replace SMC as a recyclable material. Kokkula, Langseth [15] experimentally studied bumper beam performance at 40% offset impact crashworthiness and concluded that materials with moderate strain-hardening properties are preferable over the higher strain-hardening materials for his studied system. Hambali, Sapuan [16] studied employed the analytical hierarchy process (AHP) in concept selection of bumper beam during the conceptual design stage of product development. Marzbanrad, Alijanpour [17] studied bumper beam crashworthiness improvement by analyzing bumper beam material, thickness, and shape as well as impact condition parameters. He found that a modified SMC bumper beam is preferable to the ribbed GMT bumper beam as the former has the potential to minimize the bumper beam deflection, impact force, and stress distribution and to maximize the elastic strain energy while exhibiting almost the same energy absorption of the unribbed SMC bumper beam. Park, Jang [18] 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. Most of the abovementioned research emphasizes on material and concept selection for, and numerical analysis of, bumper beam. However, no articles regarding procedure(s) for new bumper beam development could be found in the open literature. This study therefore focuses on the process of bumper beam development and summarizes the method of design and analysis of the new bumper beam in new vehicle development based on the previous research and the authors’ personal experiences. In consequence, this article helps the designer to follow the right procedure for bumper beam development. It emphasizes on the parameters that have to be considered in the design of bumper beams and illustrates the procedure for FE analysis the bumper system.

2. Bumper system

2.1. Bumper system definition

A bumper system is a set of components in the front and rear parts of the vehicle designed for damping the kinetic energy without any damage to the vehicle in low-speed impact and for energy dissipation in high-speed impact conditions besides serving aesthetic and aerodynamic
purposes [19, 20]. A bumper system mainly comprises three components: fascia, energy absorber, and beam [3]. The bumper system has changed over the last three decades due to new government safety regulations and styling concepts. The ability to maintain the vehicle intact at high-speed impact conditions and to damp the kinetic energy are the most important factors in bumper system selection besides its weight, manufacturability, cost, reparability, and formability of materials [21] (Fig. 1).

**Fig. 1. Common Bumper systems**

The American Iron and Steel Institute [22] offered four proposals for bumper systems: (1) metal face bar, (2) plastic fascia and reinforcing beam, (3) plastic fascia reinforcing beam and mechanical energy absorbers, and (4) plastic fascia reinforcing beam and foam, or honeycomb, energy absorbers. According to the new regulation, the pedestrian leg impact test was due to be enacted and implemented starting from 2010. Some research has been carried out to offer methods for complying with the pedestrian impact test. The energy absorption density in the low-impact test approximately doubled in comparison with the pedestrian impact [23]. Choi, Shin [24] came up with the concept of locating the energy absorber between the bumper fascia and the reinforcement beam to absorb the impact energy when the second energy absorber is subjected to an impact greater than its critical elastic force. Therefore, this concept (to be referred to hereafter as concept number 5 or concept No. 5) can be added to the four bumper system components which the American Iron and Steel Institute (AISI) offered in 2003 (Fig. 2) which is a schematic view of a concept No. 5 system modified from AISI for car bumper system. In this method, two types of energy absorbers are considered: firstly, a low stiffener absorber, which is called the reversible absorber, is designed for protection against low and pedestrian impact; and secondly, the irreversible energy absorber, which comprises the beam and the crushable energy absorber and is usually located at the back of the beam and attached to the main face bar.

**Fig. 2. Pedestrian, low impact and crash impact system**

2.2. *Bumper beam definition and function*

The bumper beam is the backbone of the energy-absorption mechanism of the bumper system [8]. It is usually located in the front, and sometimes in the rear, sides of the vehicles.
However, the testing process for both sides is almost the same; the forward system should be stronger than the backward one for driver safety. On the other hand, the current trends in bumper design focus on aerodynamic efficiency where the designed curve should be embraced with the same style in other parts of the bumper system [22]. So, the conformable composite material solves this dilemma by providing the required curvature and lowering the manufacturing cost, e.g., by multi-stage stamping of the metallic bumper beam, and decreases the beam weight [25].

Dissipation of energy by the bumper beam can be determined both by material and structural energy absorption [26]. The effective parameters in energy absorption of composite materials depend on type of fibre [27], matrix [28], fibre orientation [29], fabricating conditions [30], inter-laminar bond quality [31], and toughness [32]. The effective parameters of structural energy absorption are longitudinal curvature, cross-section profile [33], strengthening ribs [34], thickness [35], and the overall dimensions of the cross-section [36]. The energy absorption of material and structure was investigated by [37, 38]. The crashworthiness of the vehicle and bumper system, which identifies the safety and performance of the vehicle in response to impact load, is a challenging issue. The enhanced performance of crashworthiness presents low damage to the vehicle and to occupants [39]. The impact energy in the bumper system can be dissipated reversibly (low impact) or irreversibly (crashworthiness) [40]. If the magnitude of the load does not exceed the elastic region “low-impact condition,” then the structure returns to its previous position after releasing the load [4]. However, if the impact load goes beyond the elastic region “crashworthiness,” then most of the collision load is absorbed by plastic deformation (irreversible energy absorption). The bumper system should overcome both scenarios and sustain the intense load which results in large deformation, strain hardening, and various interactions between different deformation modes such as bending and stretching [41] (Fig. 3).

**Fig. 3. GMT bumper beam of Samand [42]**

The proportion of energy reversibly absorbed by the bumper beam should be confined and the high kinetic energy should be preferably dissipated by plastic deformation. Otherwise, the collision energy maximizes the structural strain energy and release the same kinetic energy in return, which causes subsequent damage to the occupants or adjacent vehicles. Accordingly, the structural strain energy of the bumper beam should be optimized during the design
process. Besides, ductility of material improves the plastic energy absorption. Within this context, plastic composites, polymer foams, and aluminium alloys are commonly used in the bumper systems when plastic energy damping and weight are critical design and performance criteria [41, 43].

2.3. Bumper beam design parameters

The stream of new materials, products, and process development has enforced a rethinking of the role of structural design and of the effective parameters for their improvement. The bumper beam can be improved by adjusting a number of effective parameters. The efficiency of the parameters can be identified by any of a number of methods such as design of experiments (DOE) [44], reliability-based design optimization (RBDO) [45], and design sensitivity analysis. However, the current study is not intended to identify the viability of the parameters. Variables such as thickness, bumper beam curvature, rib strength, and cross-section profile are some of the most important parameters which can improve the energy absorption of the bumper beam and sustain the desired deflection of the bumper system as defined in the product design specifications (PDSs). The optimal thickness of a bumper beam can construct a balance between the weight and strength of the structure in order to provide further effective energy absorption [46]. The nominal thickness of the bumper beam is 4 mm. However, it is not completely constant in all beam parts. Surplus thickness of the polymer products has some manufacturing constraints. As an illustration, it increases the cooling time and makes warps in the flat surfaces and sink marks on the surface of the ribs’ interface, which is not suitable in visible products.

Strengthened ribs increases distortion resistance, rigidity, and structural stiffness through using little material in the slender walls [47] and providing the required impact severity [48]. Pattern, thickness, tip, and end fillet of the ribs should be designed according to load direction, impact position, material, and the manufacturing process available. Since the material thickness is high at the rib’s contact area, it causes sink marks, but this is not much important a consideration, as a non-aesthetic part, for the bumper beam. It has been reported that the strengthened ribs increase the impact energy by 7% and decrease elongation by 19% [14, 17, 49]. Zhang , Liu [20] showed that the optimized reinforced ribs have higher-energy absorption performance than the empty and foam-filled beams.
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 [27, 37]. The right cross section can increase bumper beam strength and dimensional stability. Kim and Won [50] found that the section height is the most effective variable in torsional stiffness of the bumper beam. Additional strength permits more energy absorption with less consequent bumper beam distortion [51].

Frontal curvature increases the room between fixing points and top extremity beam curvature and increases the stability of the beam and the energy absorption. It enhances the beam stability and extends the required collision displacement. Besides the aesthetic purposes, the curve facilitates additional load impact distribution through the frontal beam and fixing points during the energy damping process. When an impact load is applied to the bumper, the beam initial curvature tends to restore its original shape. So, some designers mounted a bar link between the beam fixing points in order to strengthen the outward motion and the energy absorption tendency [51, 52]. The bumper beam is an offset of the front bumper fascia that is intended to provide a consistent level of protection across the vehicle [53].

3. Material selection steps

Selecting a suitable material in bumper beam development is crucial and bad selection may cause poor performance, frequent maintenance or failure. Proper material selection for bumper beam requires information about type of loading (axial, bending, torsion or their combination), mode of loading (static, dynamic, fatigue, impact), operating environment (temperature, humidity, chemical conditions), manufacturing process, cost (raw material, manufacturing, assembly) [54].

Environmental constraints, economical demands, and performance enhancement are main issues for material selection [55]. Material usually should be finalized in preliminary design stage, while the material properties requirements are coupled with main structural function [56]. The product function requirements usually identify through product design specification (PDS) prior to development process to guide the designer for precise selection of design parameters and material selection. Then based on the translated of product design specification, constraints, objectives, geometry and process, which have interaction together
the list of material should be narrow down to the best candidate to comply with the defined properties [57].

Physical, chemical, and mechanical properties along with manufacturing and economic issues should be considered in selection of a favorite material for a bumper beam [58]. Proper material selection can be achieved by constructing a balance or compromise between function, material, shape, and process [57]. The general properties, processing, and performance of materials are considered in the conceptual design phase and are refined into specific requirements in the subsequent steps to ensure the performance of the final product. Material selection of a bumper system usually considers new environmental constraints, safety regulations, cost reduction, reliability improvement, and performance enhancement. Normally, the results of the failure analysis of previous products enable the designer to be more aware of material selection for the next product (Fig. 4).

Fig. 4. Material selection in bumper beam design process [57, 59, 60]

There are two approaches for material selection of the bumper beam. Since manufacturing of the bumper beam is costly, the designers usually attempt to find the most consistent material for the available process that offers the desired properties. Otherwise, the material is selected initially and the optimized favorable manufacturing process is developed to meet the desired performance. Incorrect material selection and manufacturing method may lead to product failure, performance reduction, and cost increase.

The material selection process requires knowledge about structural mechanics, material strength, material thermal properties, economics, and market demand. It entails knowledge of the types of loading (axial, bending, torsion, or a combination of all or any two), mode of loading (static, fatigue, or impact), environmental conditions (temperature and humidity), manufacturing processes (structure or components) and cost of manufacturing and assembly [54].

Review of the literature points out that there are some studies where discussion of material selection of automotive products has been provided. For instance, Sapuan [61] selected the appropriate material for polymeric-based composite automotive pedal box system using an expert system with a comfortable graphical user interface. He developed a prototype KBS for material selection of ceramic matrix composites for engine components such as the piston,
connecting rod, and piston ring [62]. In another example, Sudin, Harun [13] used the KBS for material selection in bumper beam design.

4. Design process of bumper beam

The design process is the solution steps for developing new products in a very specific way to prevent rework and reduce the production time and cost. It compromises between market requirements and production and converts the customer requirements into a product within the optimum economic conditions. The engineering design is combination of knowledge for generating new ideas, evaluating these ideas, and selecting the best concept. A successful bumper beam design needs interdisciplinary team work, mainly involving product design engineer, manufacturing engineer, materials specialist, quality assurance specialist, and an analyst [63].

A successful bumper beam design starts with market research and customer requirement investigation so as to develop an idea about the available products and their manufacturing technologies. These requirements are then finalized by converting the customer’s requirements into technical demands, i.e., PDSs. The design process usually starts with conceptual design generation followed by parameter identification in order for concept evaluation to come up with reliable and feasible concept [64]. In a later stage; the design embodiment design stage, the separated components, configuration of subassemblies [65], and layout of the new bumper beam must be refined and evaluated against the related technical and economic criteria. In the last stage, detailed design, precise dimensioning, tolerancing, material specification, configuration, and weight must be finalized[66, 67]. This means that by this stage the final drawing of the whole parts with the specified materials and dimensions is obtained.

Since the bumper beam surface should follow the style of the fascia (inner surface), the new concept of the bumper beam will be released when the final version of fascia surface is issued. At the final stage of vehicle development, the latest clay model of the vehicle (full-scale) is released and the outer surface is scanned with a digitizer and a separation line for every visible component is identified as well. Then, the 3D model of every separated part, which is extracted from the clay model after reconstruction, is transferred to the appointed original equipment manufacturer (OEM) [68]. The appointed OEM makes the inner surface
(B-surface) and designs other components such as bumper beam, absorbers, brackets, and bumper grills in addition to specifying the method of fixing them to the body in white (BIW), mainframe, or elements together. The positions and fixing method(s) of the fog lamps, toe cap, and rubbing strip’s too should be considered during the bumper design stage. Besides, design for assembly (DFA), design for manufacturing (DFM), maintenance, and other parameters have to be considered [69]. To release the final product, finite-element analysis should be employed to virtually validate the structural strength of the developed product under working conditions. However, it is essential to make the soft mould for the main parts to fabricate some samples under similar production conditions with the selected material so as to obtain the exact shrinkage and conduct the actual structural test (Fig. 5).

Fig. 5. Bumper beam design process flowchart

4.1 Product design specifications (PDSs)

The design validation of the bumper beam is subject to material and structural acceptance and should be presented in functional approval under working conditions. The design criteria compromise between the margins of safety value, damage criteria, environmental issues, manufacturing process, and maintenance [70]. The new composite structure should be precisely analyzed before going through the fabrication. It must be assured that all criteria and customer requirements (that’s, PDSs) are satisfied. The finalized designed structure should be analyzed by FEA software followed by production of a prototype for real test and analysis before mass production.

The PDSs are a list of the product specifications corresponding to customer’s requirements or expectations compiled in a detailed technical document [71]. The PDSs must present the margin or exact value of each property clearly. It is quite difficult to prepare perfect PDSs in the early stage of product development wherein knowledge of design requirements is imprecise and incomplete [72]. The PDSs are prepared by a disorganized brainstorming team with various specialities and experiences, e.g., manufacturing, design, sales, assembly, and maintenance. Nonetheless, the PDSs can be modified in response to unforeseen changes in product or manufacturing specifications or constraints. In the case of the bumper beam, the PDSs address safety, performance, weight, size, cost, environmental issues, and appearance (Fig. ). In other respects, the PDS parameters in general can be classified into three main
subdivisions: material, manufacturing, and design. Since energy absorption of different bumper beam ideas and designs is the core competency of this study, it is emphasized in the safety parameters of the PDSs. Some of the specifications of the mechanical and physical properties presented here has been drawn from experimental results while others were managed from existing PDS data.

Fig. 6. Product design specification of bumper beam [12, 73]

Safety: A number of different bumper safety regulations for passenger’s cars have been issued by governmental safety organizations, insurance companies, or OEMs [74]. Insurance companies usually offer more rigorous conditions than other engaged organizations in order to decrease their own monetary losses. Examples on safety regulations for the passenger’s cars bumper systems include those issued by The United Nations Economic Commission for Europe (ECE) Regulation No. 42 [75]; the International Highway Traffic Safety Administration (NHTSA) [1]; and the Canadian Motor Vehicle Safety Regulation (CMVSR) [76]. Size: Dimensions of the bumper beam depend on the size and weight of the vehicle and on the target value of energy absorption. Maintenance: Design for assembly and DFM should be considered during product design. Performance: The defined goal of the product should be attainable [77]. Installation: Design for manufacturing and assembly (DFMA) helps in minimizing the bumper components in the product or assembly to allow for easy assembling with optimized fixing point. The material should be selected according to the preset properties or desired problem solution. Materials of the bumper should be light, cost-competitive, accessible, producible, recyclable, and rather biodegradable.

4.2 Conceptual design of the bumper beam

The preliminary stage of every product development starts with conceptual design, which is derived from the customer requirements “voice of the customer” [65, 78], in order to find a solution that satisfies the design criteria [64]. Inaccurate engineering calculation in bumper beam design and material selection can lead to an increase of up to 70% of the total product cost for redesigning, selecting material, or changing the manufacturing equipment [79]. In other words, the designer has to select the most suitable idea from different possible solutions to meet the desired PDSs in each design stage, i.e. total design, subsystem or component’s level total design, and subsystem level [77, 80], to decrease the rework expenses to less than
twice the design and manufacturing costs [80-82]. Therefore, bumper beam design concept selection (DCS) has recently been under focus of the designers. Many tools have been developed for DCS to evaluate and compromise different effective factors such as customer requirements, designer intentions, and market desire to eventually propose the best conceptual design.

4.2.1 Concept design selection

Developing different concepts drives decision makers to narrow down the selected concepts to the best feasible solution and to cut the redesign cost and production delay in the early stage of the design process. The previous research presented different approaches to selection of the best concepts. The decision matrix-based methods (e.g., Pugh’s method [77]) offer a qualitative comparison and quality function deployment (QFD) to perform the best concept selection [83]. Selecting the most suitable concept by analysis and manipulation of experimental tests along with comparisons with the product standards help the designer in selecting the optimal solution with the minimum risk [84]. The fuzzy ANP-based approach is useful for valuation of a set of conceptual design alternatives to satisfy both customer’s satisfaction and the engineering specifications [85]. The AHP developed a mathematically-based technique for analyzing complex situations [86]. Multi-criteria decision-making (MCDM) is an effective method for single selection when mixed criteria are involved. The multi-attribute decision-making technique (MADM) was developed to solve conflicting preferences among criteria for single decision makers. The TOPSIS is a technique well suited to dealing with multi-attribute or multi-criteria decision-making (MADM/MCDM) problems in real world ideal solutions [87]. Its methodology is based on the principle of selecting an alternative having the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. It helps in organizing problems and in comparing and ranking alternatives to search for better options [88]. This method has been used to select the best concept in this research.

4.2.2 Embodiment

In the embodiment design stage, the bumper beam is investigated with reference to technical and economic criteria. It makes highly accurate modeling of the values of forces when analyzing the final dimensions of components. The appropriate function and safety
requirements must be approved before evaluating other parameters such as ease of production; low investment; ease of assembly, transportation, maintenance; material recyclability; and cost.

The best shape, size, arrangements, and layouts stem from the combined ideas and solutions from other professions’ points of view. This can eliminate the weak spot or combine the appropriate solutions to propose the best layout. It is often crucial that the designer produces several preliminary methods of bumper system layout with whole components to analyze and compare their advantages or disadvantages and select the most proper one. The best layout is the one that can fulfill the required function with the minimum parts, process, and optimum possible standard parts in order to decrease the production cost. The selected material should have the desired strength, corrosion resistance, energy absorption, service life, availability, and recyclability.

4.2.3 Detailed design

In the detailed design phase, all the information about the parts must be placed on the drawing. All the individual component drawings of the bumper system must have the required manufacturing dimensions, material specifications, tolerance, surface roughness, part list, and bill of material (BOM) [89]. Use of 3D CAD software facilitates implementation of the various processes involved in the detailed design phase since by this stage all parts have been modeled with the real dimensions in their position and with the required fitting tolerance. Hence, a 2D drawing can be extracted easily from the assembly model and fully dimensioned. Moreover, it allows for using the data for manufacturing, production planning, and toll making. The detailed design must be critically checked and approved by an experienced designer to validate the fit and function of the final design and prevent any error in the fabrication phase. However, the perfect detailed design cannot cover the poor conceptual design, if any, and investigation showed that most of the errors during production are caused by flawed conceptual design [66, 90].

Shrinkage (mold shrinkage, post-molding shrinkage, and end-use shrinkage)[91] of the polymer material depends on a variety of parameters (thickness, geometry, temperature, flowing speed) and cannot be exactly estimated in complicated parts. The moulding operation could not make a uniform temperature in the fabricated products. A small-scale deviation in
shrinkage percentage in huge parts such as bumper results in unfitness in the adjacent parts after production. Consequently, it is essential to make a real sample from the big parts by soft-mould with the same material and production conditions in order to find the exact value of shrinkage, provide a proof-of-concept, and implement a mechanical test as well [92].

5. Analyzing the bumper beam

Two main analyses of a bumper beam should be carried out in. First, the designer must be confident about that the selected material fulfills the defined PDS properties (material properties). Then, it must be assured that the structure developed with the selected material can achieve the main functions, safety parameters, and the desired performance.

5.1. Analysis of material

Based on the desired product design specifications (PDSs) the plan for testing the material should be written to confirm that the test method addresses loading sequence, gauge placement, and acceptance criteria of the material [69]. The test plan is usually prepared by a material developer and approved by an authorized certifying agency.

Since the performance of the material is closely related to the manufacturing conditions, the manufacturing parameters should be set to achieve the anticipated specification. However, the final approval of the bumper beam can be issued after the structural test. Sometimes a manufacturer modifies the production parameters for different applications or various conditions. Totally, the test may include mechanical tests such as tensile and compressive strength, yield strength, and toughness [93] with a consideration of the environmental conditions, like humidity (20%-95%) and temperature (-30 °C to 85 °C) [94], to which the bumper beam may be exposed. Besides, advances in numerical methods for product analysis and material processing analysis made it possible to optimize the product, manufacturing process, and structural components.

5.2. Structural analysis

The next step in bumper beam analysis is to ensure the proper structural performance of the selected material. The most reliable method is to fabricate the samples from selected
materials and appointed production methods and to carry-out the test under real conditions, which is cost-, and time-consuming. The FE analysis does not offer 100% reliable results, but its cost is considerably less than that of the experimental test.

Numerical analysis of the developed bumper beam is the preliminary stage of approving the bumper beam. The final geometry with defined longitudinal curvature, thickness, cross section profile, material, rib strength, and overall dimensions should be performed to obtain the final geometry of the bumper beam FE model. A reasonable prediction of the bumper beam performance depends on the accuracy of the simulated geometry, i.e., the longitudinal curvature, cross section, thickness, ribs, and material model. However, the real-scaled bumper beam with defined material and geometry should be tested under actual conditions for final verification. The value of numerical analysis is strongly dependent on a validated modelling technology with accurate material models and fracture criteria.

5.2.1. Low speed impact test

The procedure of low speed impact test in European countries is different compare with American countries. Three low speed impact tests with their criteria explained as follows. The criteria for the low-impact test in European countries is a pendulum test at 4.0 km/h (2.5 mph) with no damage to the bumper, and in the USA and North America, it is the same test at 8 km/h (5 mph), but damage to the fascia is not considered [1, 75, 95].

The United Nations Economic Commission for Europe (ECE) Regulation No. 42: Requires that a car’s safety systems continue to operate normally after the car has been impacted by a pendulum or moving barrier on the front or rear longitudinally at 4 kilometers per hour (about 2.5 mph) and on the front and rear corner at 2.5 kilometers per hour (about 1.5 mph) at 455 mm (about 18 inches) above the ground under loaded and unloaded conditions, which calls for no serious damage (light bulbs may be changed) [75].

National Highway Traffic Safety Administration (NHTSA) - Code 49 Part 58: Longitudinal pendulum impact test 4 km/h at the curb position of bumper and 2.5 km/h bumper at the corner [96].
Canadian Motor Vehicle Safety Regulation (CMVSR): Canadian safety regulation has the same limitation and safety damage as NHTSA (pendulum test 4 km/h of bumper face and 2.5 km/h bumper corner), but the speed is double [96].

After the test, any damage to bumper visual and functional should not occur. The lights, bonnet, boot, doors operate in the normal manner, and all the essential features for safe operation of the vehicle must still be serviceable. EU regulation allows greater damage in the car in low-impact test compare with US regulation. Moreover, US regulation uses lower speed, permits running lamps, fog lamps and equipment on the bumper face bar to be removed if they are optional and requires no visual damage to all non-bumper parts, while Canadian uses higher regulation speed, and does not allow anything to be removed, and it requires no damage to safety and functional items.

5.2.2. High-speed impact test

Besides the low-impact test, the bumper system has to be able to absorb enough energy in high-speed impact to meet the OEM’s internal bumper standard in design stage. The new bumper systems are not design to overcome entire of the high-speed impact energy. However, systems are being developed that can damp about 15% of energy under the high-speed impact. The design criterion for a high-speed impact for bumper system is defined as follows [22]:

- No bumper damage or yielding after 8 km/h (5mph) frontal impact into a flat, rigid barrier. This criterion does not apply to low speed bumpers, where controlled yielding and deformation are beneficial.
- No intrusion by the bumper system rearward of the engine compartment rails for all impact speeds less than 15 km/h (9mph).
- Minimize the lateral loads during impacts in order to reduce the possibility of lateral buckling of the rails.
- Full collapse of the system during Danner (RCAR), NCAP, and IIHS high speed crash without inducing buckling of the rails.
- Absorb 1% of the total energy every millisecond and 15% of the total energy in the NCAP crash, including engine hit.
5.2.3. Pedestrian impact test

The pedestrian impact test needs lower stiffness in dissipation of impact energy over a longer time span. Bumper system requires elastic energy absorption before any plastic yielding of the bumper beam takes place.

The second phase of pedestrian impact test consists of three test procedures and each using different sub-system impactors.

- A leg-form impactor representing the adult lower limb to indicate lateral knee-joint shear displacement and bending angle, and tibia acceleration, caused by contact of the bumper.
- An upper leg-form impactor representing the adult upper leg and pelvis to record bending moments and forces caused by contact of the bonnet leading edge.
- Child and adult head-form impactors to record head accelerations caused by contact with the bonnet top [23, 97]

**Fig. 7.** Pedestrian ‘leg-form’ injury criteria [23]

In pedestrian leg impact test, a ‘leg-form’ impactor is propelled toward a stationary vehicle’s longitudinal velocity of 40 km/h parallel to the vehicle’s longitudinal axis. The test can be performed at any location across the face of the vehicle; between the 30° bumper corners (Fig. 7).

The above regulation is defined for bumper system not specifically for bumper beam, but since the bumper is the main components in energy absorption, so the regulation can be extended for bumper beam. It might be used another mechanism between bumper beam and fascia to fulfill the pedestrian criteria.

6. Future trend in automotive bumper

The automotive safety and environmental legislations became more stringent in last few decades. On the other hand, the high production demand besides raising the cost of the petroleum resources encourage the automaker to exploit the natural resources in their new products for staying in the competitive edge. Other impact for future bumper is new safety regulation. There are totally two parallel trends for future bumper safety system. Passive
safety which emphasize on helping to the occupants during the crashes by improving the structure of the vehicles, bumper damping system, seatbelts and primarily airbags and active system to prevent of crash by using intelligent mechanism.

Fig. 8. Automotive intelligent pre-collision system [98]

Development of new material to comply with safety and environmental regulations, and development of various intelligent pre-crash systems to prevent or decrease the injury (pedestrian impact test) by fully automated controlled of car safety mechanism (Fig. 8)[99]. In first approaches, based on the environmental regulation, automakers investigated to utilize the natural fiber in their new product, but poor mechanical properties of natural fibers do not allow to be used in automotive structural components. There is plenty of research to improve the mechanical properties of natural fibers in order to improve their performance. Increasing the interfacial adhesion between fiber and matrix [100], incorporating Z-direction fibers (3D composite) [101], improving the properties of the matrix [102], and manufacturing method [103]. The investigation trends shows that in early future the natural fiber will be used in automotive structural components.

In second approaches based on the EU Parliament regulation, automakers should use the advanced emergency braking systems from November 2015 for all new light and heavy commercial vehicles. Also National Highway Traffic Safety Administration (NHTSA) began studying “lane departure warning systems” and “frontal collision warning systems” on vehicles [104]. These recent investigations are an intelligent preventing system (pre-crash system) with non-contact safety mechanism to reduce the severity of an accident. However, it is not more sufficient to prevent injury or damage at higher operating speeds [105].

7. Conclusions

The new safety regulations concerning bumper system specifications besides the automaker environmental legislations (end of life vehicle) make it quite complicated and much costly for the design of this structure to fulfil all broad requirements. Finding the best procedure for bumper beam development poses extra loads on the designer and may influence his/her performance. The previous research discussed the design process, material selection, and analysis and verification of the developed product functionality by FEM tools, but there is
limited information about the approaches to bumper system development. The present study concentrated on the bumper beam development process based on findings of previous studies. It analyzed comprehensive information to determine the optimum method for bumper beam development and to identify the settings for the effective structural variables (thickness, rib strength, cross-section, and frontal curvature) conducive to the optimal bumper beam strength.

References


Fig. 1. Common Bumper systems
Fig. 2. Pedestrian, low impact and crash impact system
Fig. 3. GMT bumper beam of Samand
Fig. 4. Material selection in bumper beam design process
Fig. 5. Bumper beam design process flowchart
Fig. 6. Product design specification of bumper beam
Fig. 7. Pedestrian ‘leg-form’ injury criteria
Fig. 8. Automotive intelligent pre-collision system
The process of new bumper beam development for passenger car is discussed. A new bumper system has been added to the previous developed bumper systems. The flow chart of design and analysis of bumper beam is shown. Different analysis for developing new bumper beam before production is discussed. The process of material selection in bumper beam is discussed.