USING A NEW COMPOSITE ENERGY-ABSORBER BUMPER TO IMPROVE AUTOMOTIVE CRASHWORTHINESS

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Abstract

It is known in the automotive industry to provide a bumper on the front and rear of an automotive vehicle to absorb impact energy and prevent damage to other vehicle components such as fenders, frames, and the like. A new cost-effective lightweight composite energy-absorbing structure has been developed in order to obtain a high degree of crashworthiness in automotive bumper. Assembly system includes a crushable beam cut to desired form of bumper and retrofitted between front and back composite cover/flange of bumper. Crushable energy-absorber beam was consisted of a rectangular multi-celled thin wall composite structure and internal polyurethane foam cores. Polyurethane foam was employed to fill the cells of the structure to eliminate any hypothesis of global buckling.

Quasi-static axial crushing behaviour of the composite structures is investigated experimentally and numerically. A finite element explicit dynamic analysis code module, incorporeity ANSYS/LS-DYNA implemented to the simulation of the quasi-static crash behaviour and energy absorption characteristics of the developed crashworthy composite structure. Experimental results indicated high crushing force efficiency achievement. Theoretical and experimental results showed good similarities in peak load, average load and energy absorption with and without use of two types collapse trigger mechanism.

Background

Collapsible impact energy absorbers made of fibre reinforced composite materials are structural elements used in a broad range of automotive and aerospace applications. The energy absorption capability of an exposed crashworthy element or system is greatly affected by its structural design and material properties. There are a number of potential economic and functional benefits to be derived from the use of fibre reinforced plastic (FRP) composite materials in automobile and aircraft construction. The gains arise through increased strength and durability features to weight reduction and lower fuel consumption [1, 2].

Crash energy management is one of the primary design requirements that the body structure must meet. In particular, researcher's attention has been directed towards the improvement of structural vehicle crashworthiness by using FRP composites in specific vehicle parts as collapsible absorbers of crash energy i.e. as structural members that are able to absorb large amounts of impact energy, while collapsing progressively in a controlled manner [3, 4]. FRP composite bumper beam is one of the main structures of automotives that protect passengers from front and rear collision [5].

Conventional sandwich panel under high energy impact loading, often collapse in a brittle and somewhat unpredictable manner. Using everting devises to control failure of sandwich panel has been reported previously by Taher et al. [6]. Also a set of designs are based on the concept of the double-layered [7] and triple-layered [8] sandwich block, i.e. the use of additional internal reinforcements layers that act to tie the opposing facings of a sandwich block together had been tested by Taher et al.

Nowadays most of the research on the energy absorption of composite materials has been limited to the axial compression of tubular structures and most of the research done has been experimental [9]. With no doubt, the validation of analytical and numerical tools for accurate simulation of structural response to crash impacts is an important aspect of crashworthiness research.

This paper describes the experimental and finite element analysis of a series of novel cost-effective lightweight composite energy-absorbing beam structure, which includes a crushable beam and positioned under a bumper cover of the automotive and directly connected to a chassis frame of the vehicle, has been developed to improve car crashworthiness performance. Energy-absorber beam includes a series of energy absorber blocks arranged in a line and each of them consist a rectangular multi-layered thin wall composite structure and some internal polyurethane foam cores. Polyurethane foam was employed to fill the cells of the structure to eliminate any hypothesis of global buckling. The design, manufacturing and crush testing of beams fabricated are described. In addition two different types of trigger mechanism are evaluated. Meanwhile a simulation which is dealing with the implementation of the finite element explicit dynamic analysis code module incorporated ANSYS/LS-DYNA computer software to the simulation of the crash behaviour and energy absorption characteristics of a novel multi-cell cost-effective crashworthy composite sandwich structure. The obtained numerical results are compared with actual experimental data.

Material and Design

Conceptual Design

During edgewise crushing, the fibreglass facings of conventional sandwich structures have a tendency to debond from the foam-core leading to a sudden loss of all load-bearing capacity and subsequent catastrophic failure.

In block structure fibreglass fabric wrapped around some foam layer cores that prevent from core-to-facing debonding, i.e. during axial crashing debonding tendency control by hoop stress in fibreglass layers. In these designs, internal layers of fibreglass are integrated within the core. Not only does this extra reinforcement provide increased stiffness and strength, but it also acts to tie the opposing facings of the sandwich together. The geometric configuration of blocks is covered with more fabric fibre reinforcement in order to integrate the blocks in a beam configuration. In applications where post-crash integrity is necessary, ductile fibres can be used to integrate the cells in the beam configuration. Crushable beam cut to desired form of bumper and retrofitted between front and back composite cover/flange of bumper. Assembly system connected to frontal tubes of chasse. To improve aerodynamic shape and fuel efficiency of the automotive, a plastic stylish shape covers the bumper as depicted in Figure 1. These assemblies are made of a composite energy-absorber beam structure mounted on aluminium or steel beam base covered with a stylish plastic material which is painted to match the colour of the body. As an assembly, this new design offers the greater protection than the current designs. The added advantage comes with the reduced weight thus providing greater fuel economy to the vehicle.

Failure Mechanism

Figure 2 is an attempt to show, pictorially, progressive failure of the self-stabilized bumper beam of this concept. As shown in Figure 2a, an embodiment of a crushable beam is illustrated extending between the bumper cover and the chassis. During the event, crushing load applies to bumper cover and load transfers to energy-absorber beam. The beam reinforcement layers are forced between cover and chassis. Trigger cut-outs cause a stress concentration and initial crushing in left end of the beam. Reinforcement layers fold and buckle and low density core layer compresses together but rest of structure remain intact as shown in Figure 2b. Crushing of reinforcement layers and core layers continue to end of the beam as shown in Figure 2c. The core layers are used to prevent from global buckling and they absorb some part of energy during crushing.

Test Specimens

A designation code shows configuration characteristics of test specimen. For example, 23, the first two digit of the block designation 23-120×60×100V, indicate the block type design; 2 indicate two blocks in beam specimen and 3 shows triple-layered configuration. The next data, i.e. 120, 60 and 100 indicate width, thickness and length in mm respectively. Also the last character shows trigger type; “V” for bevel trigger or V type, “I” for groove trigger or I type and blank indicates a specimen without triggering modification. An overall picture of the shape and the dimensions of the test specimens is given in Figure 3.

The fibre reinforcements were made from composite material formed by of a woven roving E-glass fabric and epoxy resin. One hundred parts by weight of epoxy resin mixed with 50 parts by weight of epoxy hardener was used for the matrix. The fibre type used was E-glass woven roving cross ply fabric, 200 g/m^2 with approximately 0.2 mm thick. Core of the block specimens is made of polyurethane foam with density of 47 kg/m^3.

The width, *W* of blocks was also variable, taking three distinct average values that were equal to 80, 120 and 160 mm. For specimens two different thickness, *T* was used approximately equal to 40 and 60 mm and a specimen length, *L* equal to 100 mm considered. Fibre orientation was ±45° to the block axis.

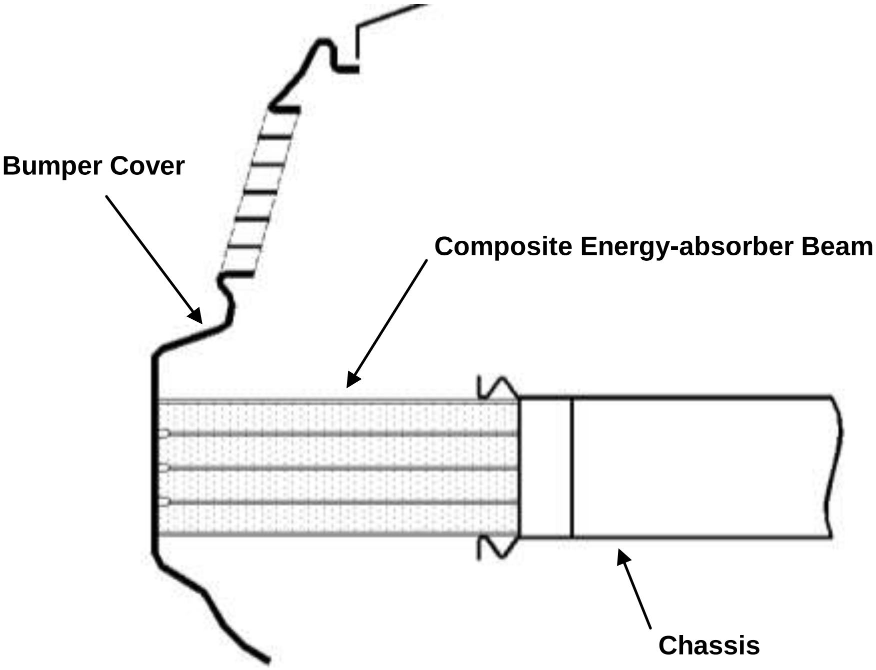

Figure 1: schematic of stylish bumper configuration

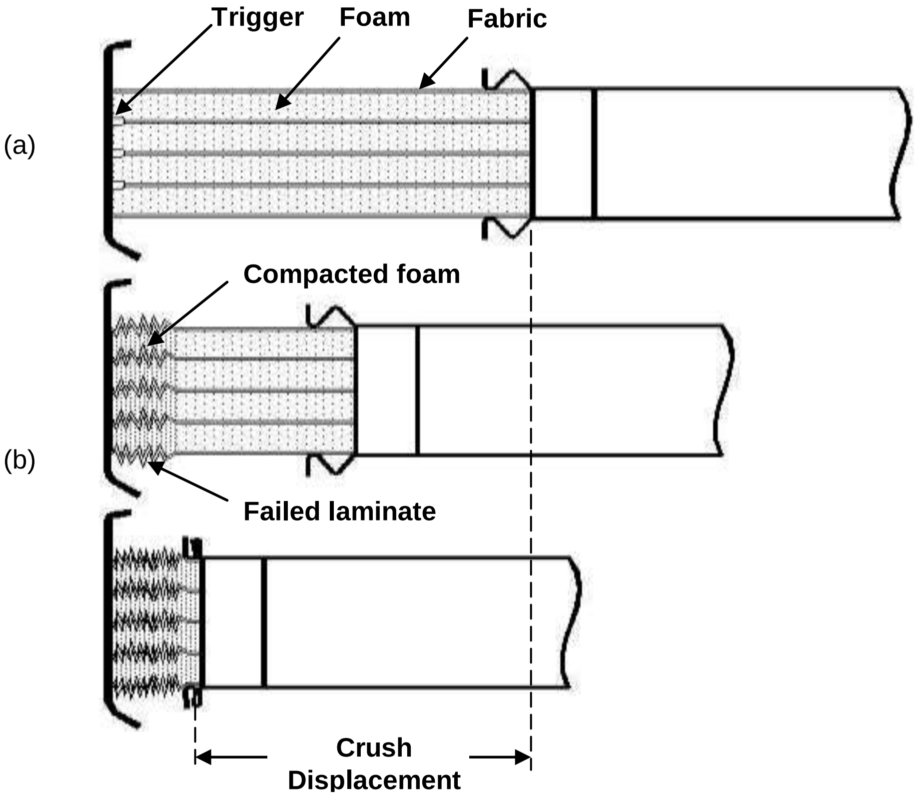

Figure 2: Schematic representation of targeted beam crushing mechanism

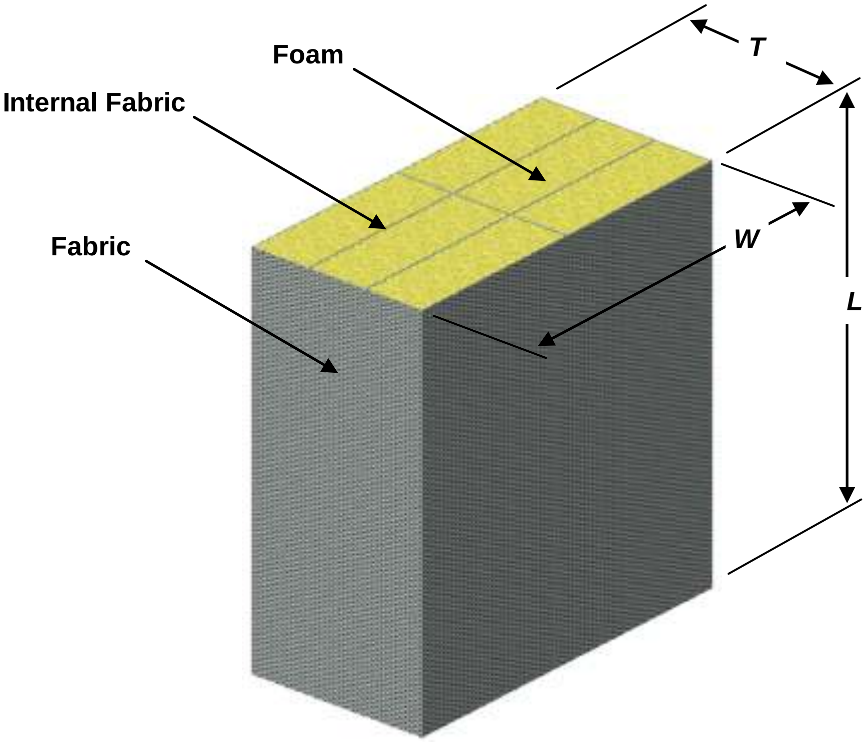

Figure 3: General layout and dimensions of the sandwich beam tested specimen

Triggering Mechanism

As reported by Thornton [3], composite structures generally require a collapse trigger mechanism to promote stable, progressive crushing. Otherwise, sudden catastrophic failure can occur. Generally, collapse trigger mechanisms create a region of locally elevated stress at one end of the block from which failure initiates and then propagates. Two types of collapse trigger mechanism were investigated:

I type trigger – Some straight cut-outs with width and depth 3 and 5 mm respectively to one end of the specimen that trim internal fibreglass laminates so called groove trigger or I type trigger as shown in Figure 4a.

V type trigger – Chamfer cut-out (5×5 mm) to two opposite corners of one end of the each block in beam specimen perpendicular to intermediate fibreglass reinforcements in the name of bevel trigger or “V” trigger as depicted in Figure 4b.

Specimen Manufacturing

The main fabrication steps for the keel beams are described in Figure 3 and Figure 4 and consist of:

Core preparation – Core of the sandwich block is made of polyurethane foam with density of 47 kg/m^3. Foam sheets with required thickness cut to desired size and were ready to cover by reinforcement fibres as shown in Figure 5a.

Fibre reinforcement – The fibre type used was E-glass woven roving cross ply fabric, 200 g/m^2 with approximately 0.2 mm thick mixed by epoxy resin and wrapped about core layers to fabricate a multi-layered block (Figure 5b). Fibre orientation was ±45° to the block axis, due to fabrication constraints.

Sizing – After curing, block was cut to desired length (Figure 5c).

Beam assembling – Inline assembly of the fibre-reinforced blocks is covered with fabric glass fibre reinforcement in order to integrate the blocks in a beam configuration as depicted in Figure 6. The fibre type used was E-glass woven roving cross ply fabric, 200 g/m^2 approximately 0.2 mm thick mixed by epoxy resin. In applications where post-crash integrity is necessary, other ductile fibres like Kevlar can be used to integrate the blocks in the beam configuration. Fibre orientation was ±45° to the blocks axis. Finally specimens glued on a rectangular plywood base.

Triggering modification – for specimen with groove trigger (I type trigger), straight cut-outs with width and depth 3 and 5 mm respectively grooved by machining or bench saw to one end of the specimen that trim internal fibreglass laminates (Figure 4a). Bevel trigger cut-out by machining or belt saw with 5×5 mm dimensions over two opposite corners of one end of the each block in beam specimen perpendicular to intermediate fibreglass reinforcement (Figure 4b). For specimen without triggering mechanism no modification was needed.

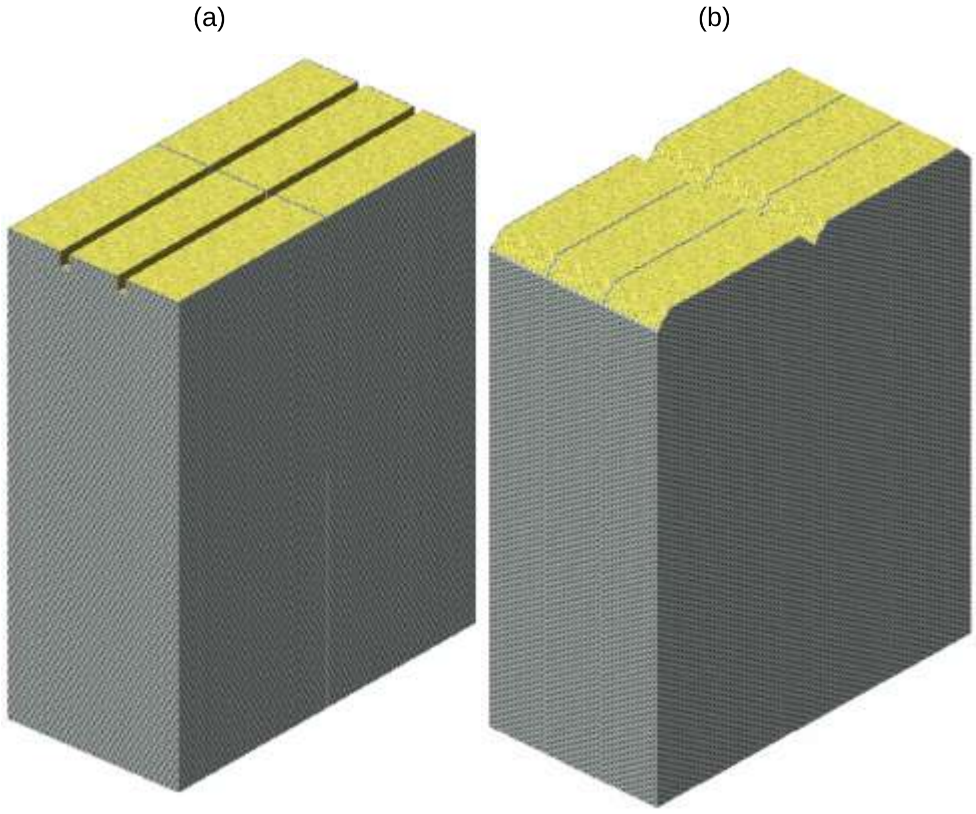

Figure 4: Different types of end modification as collapse mechanism on beams; (a) groove trigger or I type and (b) bevel trigger or V type.

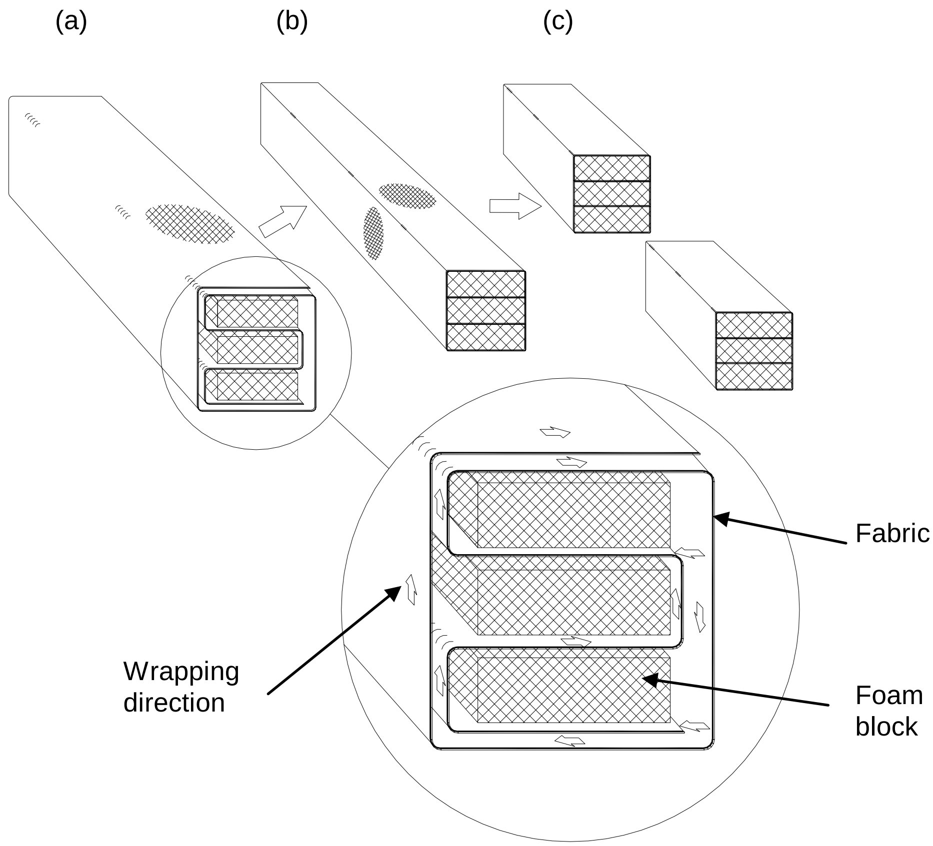

Figure 5: Schematic view of the fabrication procedure of the triple-layered energy absorbing block; (a) wrapping a fabric around foam sheets, (b) cured long sandwich block and (c) final cut to size blocks.

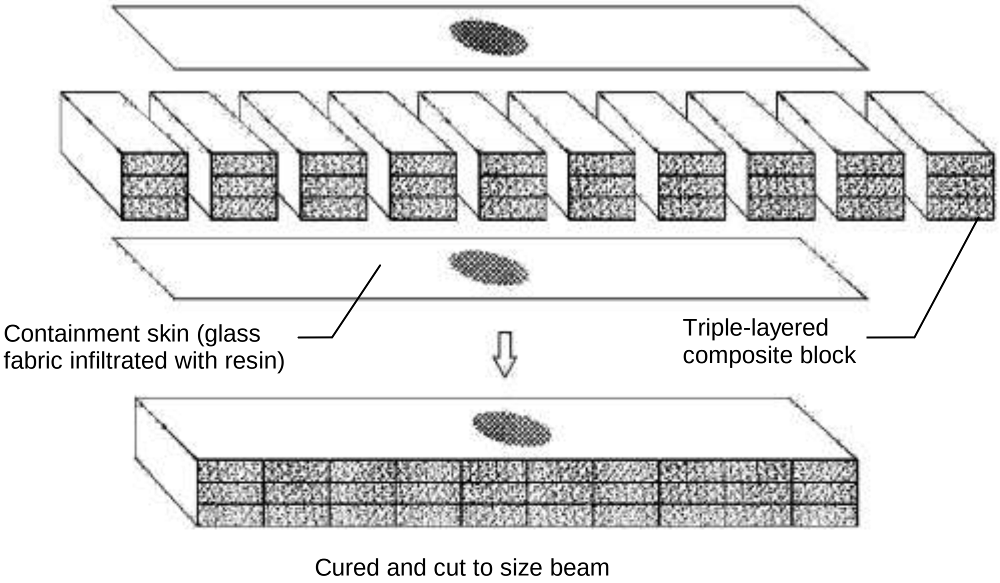

Figure 6: Schematic representation of the beam assembling

Experimental

Equipment and procedure

The axial compressive testing of the composite sandwich blocks was performed in a standard 30kN INSTRON 5567 testing machine. No special fixtures—such as clamping devices—were used for the tests apart from the flat crossheads of the press. All tests were performed at quasi-static conditions i.e. at constant throughout the test crosshead speed equal to 20 mm/min. From the load-displacement curves that were recorded directly during the testing works the following compressive characteristics of the test specimens were calculated and recorded:

Peak load, Pmax – Absorbed crash energy E, is the area under the load-displacement curve up to compaction zone, defined as:

$$E = \int_0^{\delta} P ds \qquad (1)$$

The post-crush displacement, δ – δ is total displacement up to start of compaction zone;

Specific absorbed energy, SAE – SAE is the absorbed crash energy per unit of the crushed specimen mass, defined as:

$$\text{SEA} = \frac{\int_0^{\delta} P ds}{m_c} \qquad (2)$$

Average crushing load, $\overline{P}$ – $\overline{P}$ is the ratio of absorbed energy, E to the post-crush displacement, δ defined as:

$$\overline{P} = \frac{\int_0^{\delta} P ds}{\delta} \qquad (3)$$

Crush force efficiency, CFE – Defined as the ratio of the average crushing load, $\overline{P}$ to the peak load, Pmax.

Stroke efficiency, SE – Defined as the post-crush displacement, δ to the total length of specimen, L;

Maximum compressive strength, σmax – Defined as the peak load, Pmax to block cross section area, A;

Energy per stroke, EPS – Defined as the absorbed crash energy E to the post-crush displacement, δ.

Experimental Results

Compressive and high strain rate properties of low density foams are widely studied in the published literature [10-13]. Polyurethane foam-core samples (120×60×100 mm) with density of 47 kg/m^3 were tested to study their energy-absorbing performance under quasi-static loading condition at 20 mm/min loading speed.

The load–displacement curves obtained by the axial compression test of the triple-layered specimens are depicted in Figure 7. V triggered specimens did not show high initial peak load but specimen 23-120×40×100I with I trigger had highest peak load relative to other specimens. All samples presented a fluctuating load around a constant average load showing a progressive and stable damage. Representative photographs at various steps of the compression were taken during the testing of the beams for test specimens with I triggering system and V type triggering collapse mechanism. Combined diagram of load, P and crash energy absorption, E variation during the test for specimen 23-120×40×100V are shown in Figure 8. Results show SAE and CFE of beam are up to 25 kJ/kg and 0.7 respectively.

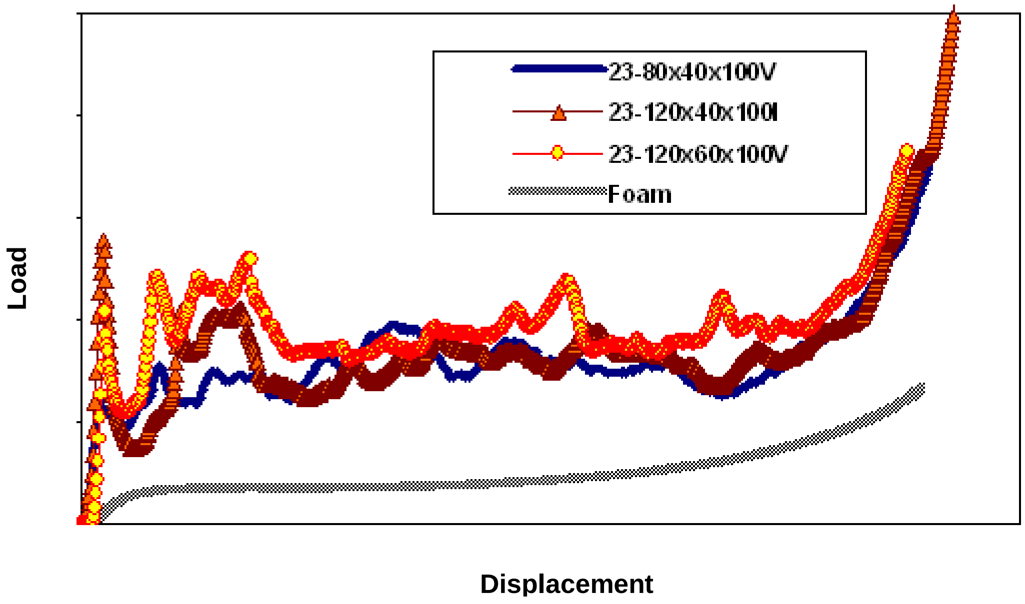

Figure 7: Load–displacement curves of triple-layered beam specimens and 120×60×100 mm foam-core.

Finite Element

The main objective of numerical modeling is dealing with the implementation of the finite element explicit dynamic analysis code module incorporated ANSYS/LS-DYNA [14] computer software to the simulation of the crash behaviour and energy absorption characteristics of a novel multi-cell cost-effective crashworthy composite sandwich structure. The obtained numerical results are compared and correlated with actual experimental data.

Finite Element Model

The model comprised two types of finite elements: shell and brick elements. The composite faceplates and internal laminates were modelled with four-node thin shell elements, while the hollow composite shell structures have uniform thicknesses of 0.2 mm all over their cross-sections except to 0.4 mm over external surfaces of beams.

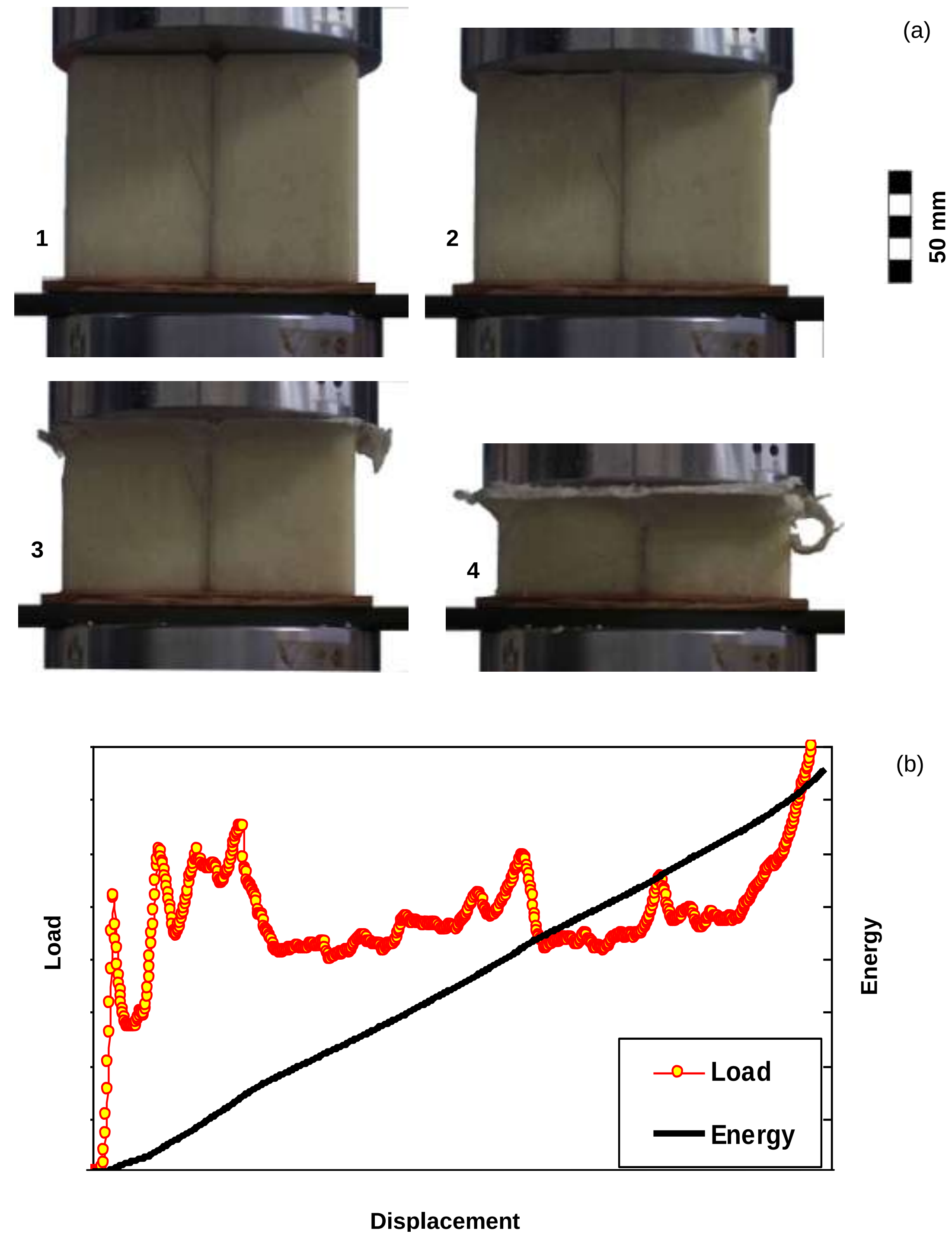

Figure 8: Axial compression test of beam specimen 23-120×40×100V with V triggering mechanism: (a) views of the progressive failure of test sample, (b) combined diagram of load, P and crash energy absorption, E variation during the test. The sequential number of each picture marks the point of the two curves corresponding to the photographs.

Moreover, eight-node brick elements were employed in the modelling of the sandwich material foam core. Both the upper moving and the lower stationary head of the press used in the experimental testing works were modelled using one four-noded shell element for each of them without any further discretization since the material model assigned to these parts was the rigid one. The mesh of finite elements was not uniform along the specimen axis and was featured by a space ratio during meshing. Therefore, sizes of mesh increases from frontal crushing face toward base of block as depicted in Figure 9.

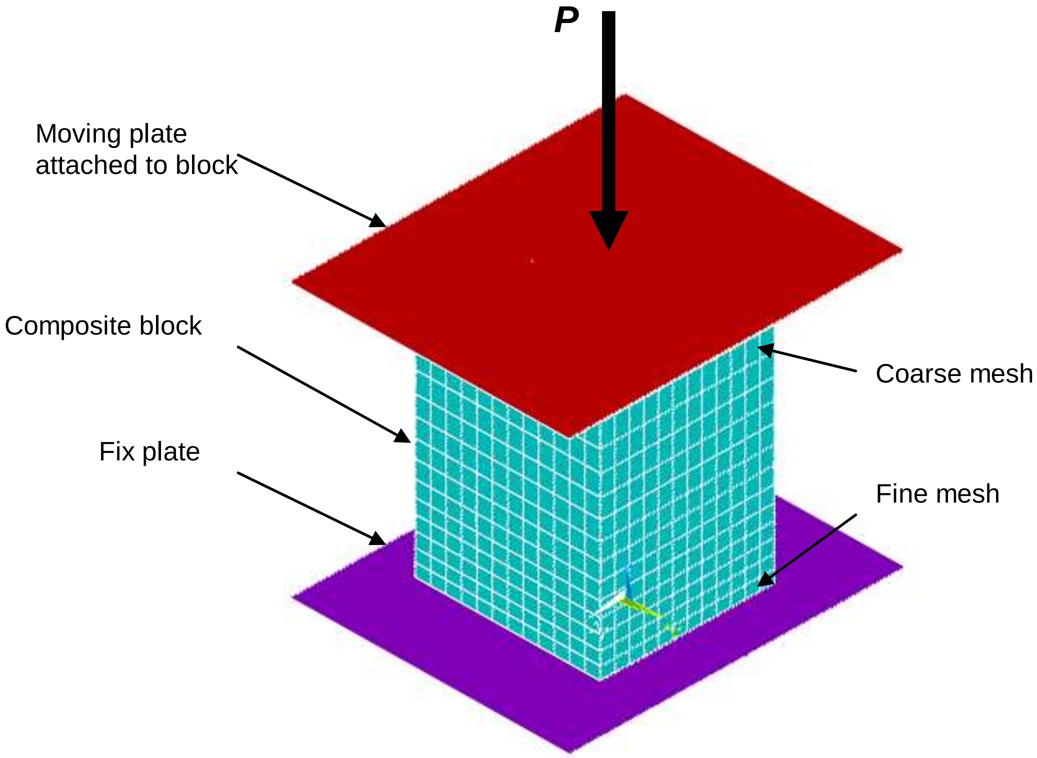

Figure 9: Discretization of the tested specimen

Material Property

This section refers to the material types used to model the distinct parts of the specimen, the moving platen and the stationary base. Three different types of material models were used from the library of the ANSYS/LS-DYNA code in the development of finite element analysis described in the user's guide:

Composite damage model material – To model composite laminates in the structure,

Crushable foam model – To model crushable foam cores in structure, and

Rigid model – To simulate fix and movable rigid crossheads of machine

Contact Interfaces Modelling

The treatment of sliding and impact along interfaces has always been very important in order to simulate a “physical” performance between interacting structural members being in contact, i.e., keeping geometric boundaries without models independent parts penetrating each other. Moreover, from contact treatment point of view, attention must be paid in special cases, as in the current one described herein, where self-contact may occur in an excessively buckled structural member and/or new material boundaries become apparent due to the applied element erosion/deletion modelling technique described above. The contact interface types required for the appropriate processing of any possible contact interaction among all parts of the model are defined below. Five in total different types of contact interface were used in the modelling of the sandwich structure, namely in terms of the ANSYS/LS-DYNA code:

The automatic general contact (AG) interface type – To simulate original contact between specimen and moving crosshead of machine,

The tied surface to surface contact (TDSS) type – To model contact of fix crosshead of machine and end base of specimen,

The eroding single surface contact (ESS) type – Applied to composite laminate to continue self contact and contact to fix rigid plate after eroding of laminate elements,

The eroding surface to surface contact (ESTS) type – implemented to foam core to continue its contact after failing exterior surface nodes or elements, and

The tiebreak surface to surface contact (TSTS) type – The tiebreak contact options are used to simulate bonding of the foam surface and laminate.

Finite Element Results

The validation of the finite element model described so far is made by direct comparison to the results and visual observations of the experimental works pertaining to the quasi-static axial compression of the modelled sandwich structures. The geometry and structure of the specimen, the properties of the specimen and machine crossheads materials and all other testing details used in the finite element model were exactly the same as the ones of the experimental works. The only difference between the compressive tests and the numerical simulation model, was that the actual crosshead speed during the tests was just 20 mm/min instead of the 30 mm/ms that was used in the modelling in order to reduce the calculation time and achieve a reasonable time step that would give correct results in the explicit time integration. Progressive failure views of a triple layered beam model samples as presented in Figure 10. Load–displacement diagrams including the experimental curve and the corresponding one produced by the numerical simulation depicted in Figure 11.

Discussion

A progressive failure mechanism was observed during the composite sandwich specimens compression test i.e. progressive folding with pivot formation similar to the ductile material behaviour like metal and plastic rather than global column buckling which is usually observed when compressing brittle high aspect ratio structures [15]. It can be seen that, regardless of collapse triggering system, all the specimens collapsed in a stable, progressive manner. In each case, there was extensive fragile end-crushing in the region of the crush zone, but away from this zone the sandwich structures remained stable and undamaged.

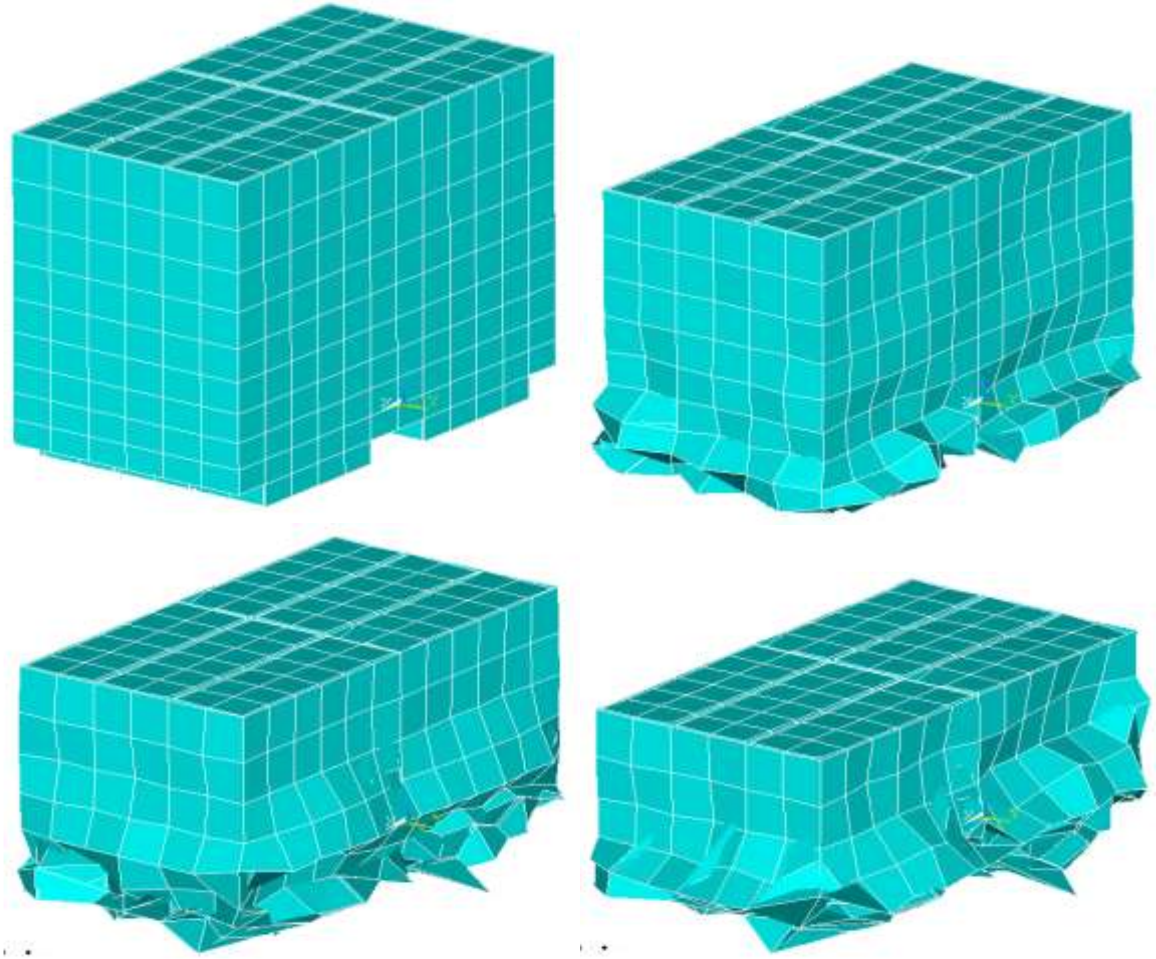

Figure 10: Progressive failure views of a triple-layered V triggered beam model

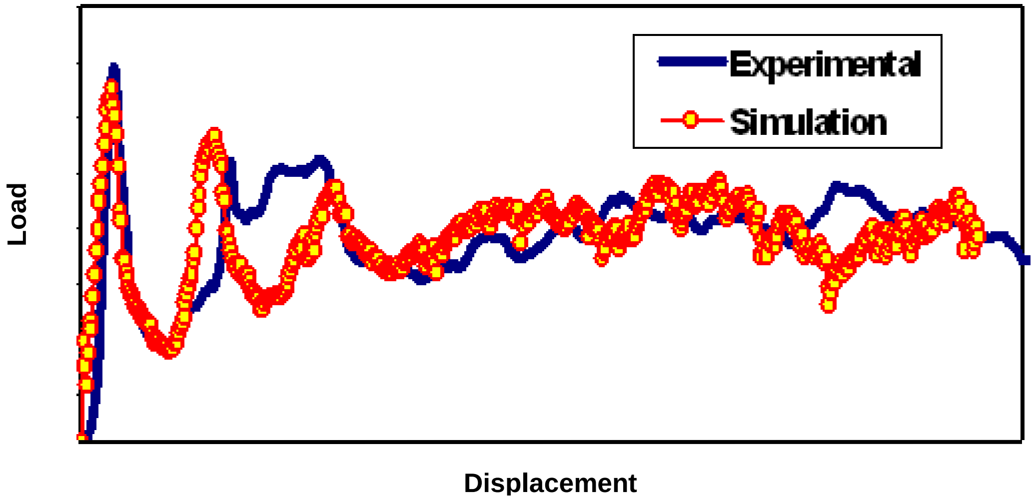

Figure 11: Comparison of axial compression simulation and experimental of triple-layered beam specimen 23-120×40×100I with I triggering system

It is worthy noticing at this point, that the crushing load *P* and the absorbed deformation energy calculated by means of the developed finite element model are almost identical to the absorbed energy and the average crushing load obtained by the experimental works. This feature of the model is of particular importance, since it proves that the simulation model can be effectively used to accurately calculate some of the most significant parameters in the design of sandwich structures.

Multi-layered sandwich concept is a soft energy-absorber means with good level of energy absorption. Specific energy absorptions up to 25 kJ/kg and crush force efficiency about 0.7 were recorded. By other means, an energy-absorber beam weight of 5 kg absorbs total crushing energy of an automotive weight of 1300 kg with 50 km/h speed. Meanwhile by consideration a crush displacement (as shown in Figure 2) equal to 0.31 m, average and pick deceleration of vehicle will be 32 and 45 g respectively which can save other parts of vehicle in crash.

Summary and Next Steps

The objectives of the paper have been achieved. It has been demonstrated that the multi-layered sandwich concept is a practical means of producing cost-effective composite bumper for automotive that crush in a stable, progressive manner with high crush force efficiency.

Moreover, the satisfactory approach of the test results by the developed finite element model especially concerning the calculation of significant parameters of sandwich structures design such as the amount of absorbed deformation energy and average crushing load shows that modelling may effectively be used to predict the response of composite structures in a wide range of different types of loading, reducing in this way the size of the absolutely necessary but expensive experimental works.

Further work could be carried out to generate more data to understand the behaviour of the multi-layered bumper beam under different loading conditions i.e. doing static and dynamic test on assembly bumper and performing standard test for vehicles equipped with new bumper. Also effect of different composite materials and foams could investigate.

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