Concept Design of Twin-Sheet Thermoplastic Cellular Structures for Vehicle's Bumper System

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Abstract The 2013 World Health Organization's Report on road safety shows that from 1.24 million fatalities recorded each year there are 270,000 pedestrian related events. Although the most severe injuries are produced when the pedestrian's head is striking the bonnet or the area surrounding the windshield, lower limbs injuries do commonly result. The present study is focused on the development of an energy absorbing structure based on cellular configurations manufactured by vacuum forming thermoplastic sheets that finally define a unitary part. A parametric analysis is performed in order to evaluate internal energy accumulated during deformation. The numerical model of the front end structure of 2001 Ford Taurus model with the EC No 78/2009 specialised legform impact was investigated and the results discussed. Two configuration for energy absorber were defined and investigated using numerical simulation. The first configuration uses a single layer of four rows of cellular structures, while the second configuration uses a double layered structure of twin sheet cells on three rows. For the first case of cellular structure the bending angle of the impactor recorded a value of 19° while for the second case the value decreased to 14°. In all cases the shear displacement was well below the maximum accepted value. The maximum acceleration recorded during simulation using the single layer cellular structure was of 122 g while for the double layered structure the value was of 106 g. Compared to the original solution in both cases there was an improvement of the impactor's response.

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Introduction

In 2013 World Health Organization released the latest Report on road safety (WHO 2013a) accompanied by a document dedicated to pedestrian safety (WHO 2013b). By summarizing the outlines of the Report (WHO 2013b), it shows that from 1.24 million fatalities recorded each year, there are 270,000 pedestrian related events thus special measures are required, perhaps mandatory, in order to increase the safety.

Although the most severe injuries are produced when the pedestrian's head is striking the bonnet or the area surrounding the windshield (Shojaeefard et al. 2014), lower limbs injuries do commonly result in case of a vehicle–pedestrian impact (Mo et al. 2014). The European Parliament and the Council released in 2009 *Regulation (EC) No 78 on the type approval of motor vehicle with regard to the protection of pedestrians and other vulnerable road users* (European Commission 2009) that states the required structural response in case of a vehicle–pedestrian impact. As a consequence, by 24th of February 2013, the bumper systems of M1 type vehicles should fall under the following prescriptions: the maximum dynamic knee bending angle shall not exceed 19.0°; the maximum dynamic knee shearing displacement shall not exceed 6.0 mm; and the acceleration measured at the upper end of the tibia shall not exceed 170 g.

Literature and patent data were reviewed by Schuster (2004) and the following trends for safety improvement were identified: bumper mounted sensors and pedestrian airbags; alternative energy absorbers; flexible beams and bull bars. Regarding the development process of a vehicle bumper beam, the rigid structure behind the frontal fascia, the work of Davoodi et al. (2012) summarizes the major requirements. Although steel is the most preferred construction material for the bumper beam, composite materials were investigated by Belingardi et al. (2013) and Davoodi et al. (2011) as a viable, alternative, solution. The energy absorbers can be adapted to various configurations of existing solutions. This may be a reliable and less expensive solution, for existing vehicle, meant to comply with the prescriptions of EC Regulation 78/2009.

Cellular Twin Sheet Structures

Cellular or patterned structures are of a particular interest due to impact performances. Cellular configurations provide good energy absorption characteristics while maintain a low specific weight as shown by Bartl et al. (2008), Kathiresan et al. (2012), Zou et al. (2009) and Sashikumar et al. (2012). The egg-box structures prove to be a reliable solution for energy absorption devices as presented by Lam et al. (2004) for thermoplastic composites, Yoo and Chang (2008) for fabric composites and Chung et al. (2007) for carbon/glass fibre reinforced polymers.

A specialized cellular structure that uses the SKYDEX® material was investigated by Zhu et al. (2014).

Twin sheet thermoplastic structures are highly efficient solutions that provide outstanding performance by means of using small amounts of materials (shaped in rather complex geometry) and high-tech, low energy consumption equipments. The structures are manufactured using vacuum formed sheets that finally define a unitary structure. The manufacturing process is presented in Fig. 1.

Although a wide range of patterns can be formed, the structures with circular frusta were investigated using numerical methods. Akisanya and Fleck (2006), Gupta et al. (2006), Gupta and Venkatesh (2007) and Mamalis et al. (2001) investigated the deformation process and structural performances of conical frusta structures providing the background of the present study. A Matlab (Matlab Inc. 2009) code was developed in order to define the numerical model for the design analysis. The numerical simulations were performed using the general-purpose finite-element explicit-solver LS-Dyna (Hallquist 2003) (available in the ANSYS ACADEMIC RESEARCH LS-Dyna package).

The following parameters were investigated (Fig. 2): cell size (the diameter of the cone is half length of a cell); sheet thickness; draft angle and column height. The length of the cell ranges from 20 to 35 mm, the draft angle is set to 5° and 10° while the thickness of the formed part ranges from 0.5 to 2.0 mm. The following parameters were investigated: cell size (the diameter of the cone is half length of a cell); sheet thickness; draft angle and column height. The length of the cell ranges from 20 to 35 mm, the draft angle is set to 5° and 10° while the thickness ranges from 0.5 to 2.0 mm.

Material parameters (Young modulus, yield stress and failure strain) were identified from available material databases (http://www.matweb.com/—accessed on 17.09.2014). For the numerical simulation a simple material model (isotropic with kinematic hardening—*MAT_003) was selected and a value of 1.0 GPa was
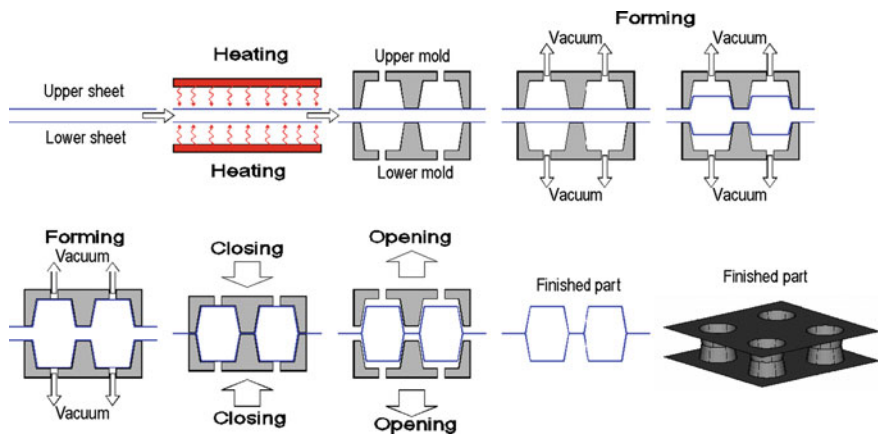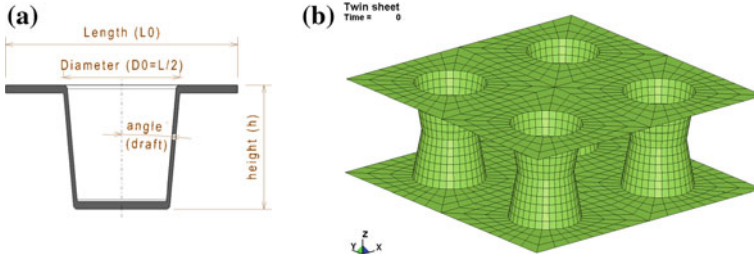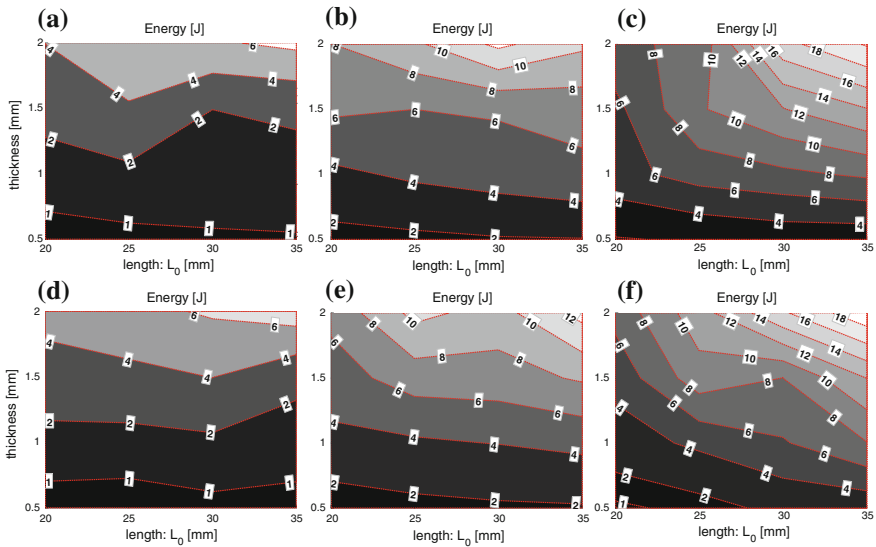

Fig. 1 Twin sheet structures. Manufacturing process

Fig. 2 The numerical model of the cellular structure **a** main dimensions; **b** model for the design analysis (2 × 2 cells pattern)

assigned to the Young's modulus, 0.020 GPa for the yield stress and 1.5 (150 %) for the strain at failure. The cellular structure was crushed by a flat rigid wall, travelling with a constant velocity of 1.0 m/s. It was found that the mean crush force is dependant of the value of yield stress and part's dimensions (Abramowicz and Jones 1986; Jones 1989; Wierzbicki et al. 1992). The value of the strain at failure gives the amount of internal energy accumulated by the structure. Figure 3 presents the internal energy accumulated by the structure during crushing. Results are represented as a function of total height of the cell $(2 \cdot h)$ and wall thickness.

Fig. 3 Internal (deformation) energy. **a** H = 10 mm; θ = 5°; **b** H = 20 mm; θ = 5°; **c** H = 30 mm; θ = 5°; **d** H = 10 mm; θ = 10°; **e** H = 20 mm; θ = 10°; **f** H = 30 mm; θ = 10°

Results

Numerical Model Overview

For the investigation of the pedestrian protection a specialized impactor should be used as prescribed by Regulation 78 of the European Commission. The legform impactor is a complex experimental device for system protection analysis as presented by Teng and Nguyen (2010) and Abvabi et al. (2010) and requires special validation as presented by Matsui et al. (2004) and Matsui (2014).

In conjunction with the impactor model, the numerical analysis was performed using the finite element model of the Ford Taurus developed by National Crash Analysis Center. The current release of the numerical model, available from November 2014, shows very good performance for the impact cases used for the validation.

For the pedestrian protection analysis, in order to improve the runtime, a reduced model of the vehicle was used (Fig. 4).

Once the ground level was set using the numerical model of the vehicle the legform model was positioned at 25 mm above this level according to the test requirements.

Analysis of the Existing Bumper System

The vehicle features an energy absorber made of foam. The absorber is placed between the bumper fascia and bumper frame, fixed on the late mentioned structure. Figure 5a shows the numerical model used for the first case. The energy absorber can be identified in the figure and the material information are presented in Fig. 5b. On the midsection of the bumper frame there is and additional metallic structure used to support and guide the absorber.
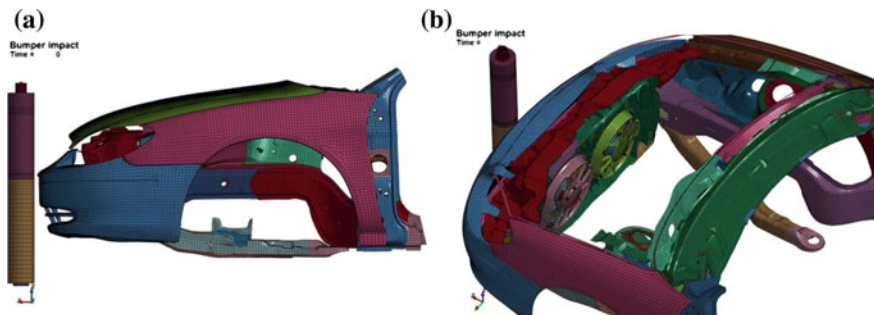
Fig. 4 Numerical model. **a** Side view; **b** view of the engine compartment

(a)

(b)
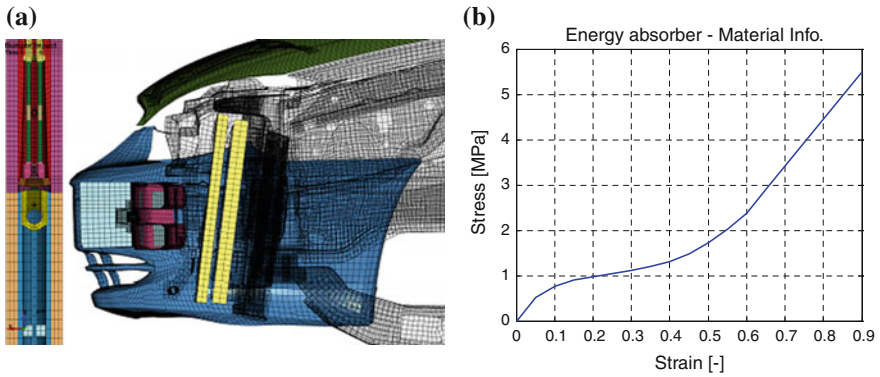
Fig. 5 Numerical model of the existing vehicle. **a** Numerical model; **b** energy absorber—material information

Using this numerical model the maximum acceleration recorded for the tibia was of 153 g, a shear displacement of 2.65 mm and a maximum bending angle of 27.33° (0.477 rad). Although the maximum acceleration and shear displacement fall within the prescription of Regulation (EC) No. 78/2009 the maximum bending angle exceeds the maximum value. No penalty should be addressed given the fact that it represents the Ford Taurus model released in 2001.

Model Without the Energy Absorber

The foam absorber and the auxiliary structure were removed from the existing model in order to investigate the structural performances of the vehicle front end when the pedestrian protection is evaluated. Figure 6a presents the results, at the

(a)

(b)
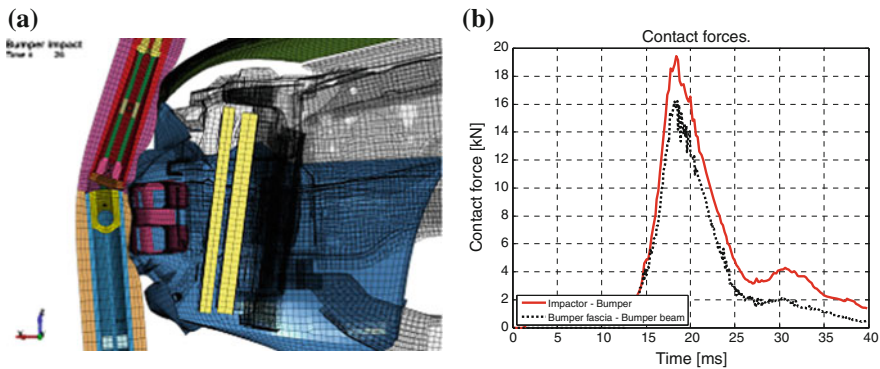
Fig. 6 Numerical model. Model without absorber. **a** Deformed structure (maximum bending angle); **b** interface/contact forces

time step when the maximum bending angle of the impactor was recorded, obtained during the simulation.

Using this numerical model the maximum acceleration recorded for the tibia was of 177 g, a shear displacement of 2.56 mm and a maximum bending angle of 23.26° (0.406 rad). Compared to the previous set of results it can be noticed that the acceleration increased while the shear displacement and the bending angle decreased. This shows that due to the presence of the foam made energy absorber there is a reduced deformation of the bumper. Although it has a cushioning effect it keeps the impactor on a extreme position allowing the upper section of the legform impactor to bend over the hood. The maximum impact force is of 19.5 kN (Fig. 6b) while the energy absorbed by the vehicle structures is about 260 J (from which about 40 J are restored during the rebound phase). This show that a large amount of energy must be consumed by the lefform structures giving the acceleration and bending values. Maximizing the energy consumed by the legform can be a solution to improve the values of the parameters giving the pedestrian protection performance.

Model with Twin Sheet Structure.

The area, measured at the level of the bumper fascia, where the maximum longitudinal displacement was recorded spans over a length of 150 mm (according to diameter of the impactor). The height of the bumper beam is of 130 mm giving the area of the structure recording the major deformations.

Based of the deformed area, deformation energy and contact forces and using the results of the parametric analysis the cell dimensions can be defined. The goal is to maximize the energy absorbed by the structure while maintaining a low crushing force. The analysis pointed to a cell dimension of 35 mm giving a configuration of 4×4 cells.

The thickness of the structure was set to 1.0 mm. This configuration is also supported by the manufacturing process as larger cells are easier to manufacture. The forces required to crush the structure is 12 kN less than the maximum computed force when the foam absorber is absent (Fig. 7b). The cellular structure, with a height of 30 mm, was placed on the bumper frame facing the bumper fascia. Figure 7a shows the deformed structure when the maximum bending angle was recorded.

An additional 130 J are consumed by the cellular structure. Based on the results from the parametric analysis the 4×4 cells highly deformed by the impactor were supposed to consume $(4 \times 4)\ cells \cdot 8\frac{J}{cell} = 128$ J. Same time the energy consumed by the bumper fascia decreased due to the smaller deformations of the structure. Figure 7b presents the computed contact forces. The maximum forces decreased with an important influence of the dynamics of the legform impactor. The maximum acceleration was of 122 g, maximum shear displacement of 1.53 mm and the
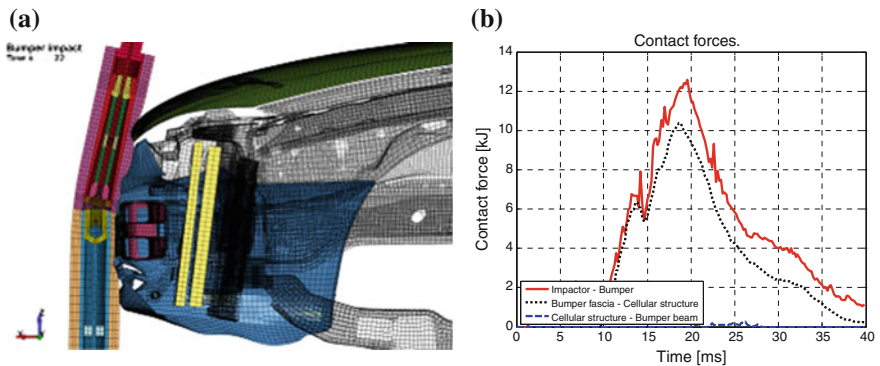
(a)

(b)
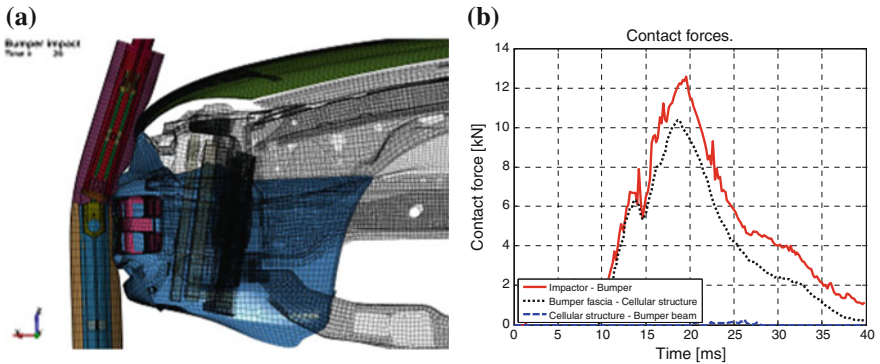
Fig. 7 Numerical model. Model with cellular structure. **a** Deformed structure (maximum bending angle); **b** interface/contact forces

bending angle of 19° (0.33 rad). These values falls within the prescribed values when the pedestrian protection is addressed although the value of the bending angle equal with the maximum accepted value. The real vehicle may show an improved value due to the fact that some parts on the vehicle's front end were not modelled.

A second configuration was used. The second configuration was designed as a two layers cellular structure with three cells on a row. Figure 8a presents the deformed structure when the maximum bending angle was recorded.

The total energy consumed by the structure is of 210 J with a total energy consumed by the vehicle's structures of about 380 J. Based on the results from the parametric analysis the $2 \times 4 \times 3$ cells highly deformed by the impactor were supposed to consume $2\,layers \times (4 \times 3)\frac{cells}{layer} \cdot 8\frac{J}{cell} = 192$ J. Same time, due to the layered configuration of the cellular structure the impact force does not exceeds 10 kN (Fig. 8b). The maximum acceleration was of 106 g, maximum shear

(a)

(b)

Fig. 8 Numerical model. Model with double layered cellular structure. **a** View of the model (without the energy absorber); **b** interface/contact forces

displacement of 1.45 mm and the bending angle of 14° (0.244 rad). These values falls within the prescribed values showing an adequate level of protection.

Conclusions

Twin sheet forming process is mainly focused on forming closed structures with high stiffness and low weight as vacuum forming is a highly productive industrial process. Although it presents some limitations related to the complexity of the geometry of the finished part it can be easily applied for simple parts. Using a custom code developed in MATLAB a tool for parametric design of structures was developed. A set of cellular structures with a conical frusta were investigated in order to define add-on devices for enhanced pedestrian protection. The dimensions of the cells ranges between 20 and 35 mm while the total height of the structure was set to 10, 20 and 30 mm. For the conical section the draft angle was set to 5º and 10º close to the cylindrical shape. Using the average and maximum crush force plots and considering the amount o internal energy that can be accumulated by the structure during deformation a cellular structure was defines.

The numerical model of the front end structure of 2001 Ford Taurus model with the specialised legform impact was investigated. Starting from the original model that features a foam energy absorber the pedestrian protection was evaluated. As a second step the foam absorber was removed and a simulation performed. Results were used in order to define the cellular structure used as an energy absorbing device.

The first configuration used a single layer of four rows of cells. Compared with the model without energy absorber the bending angle decreased from 23° to 19° while the acceleration decreased from 177 to 122 g. For the defined range of cell's dimensions there were no other configurations able to provide a substantial improvement.

As a consequence a cellular structure with two layers was defined. The bending angle recorded a value of 14° while the maximum acceleration recorded a value of 106 g giving a good level of protection for the pedestrians.

Based on the numerical model the foam absorber has a mass of 1.39 kg while the single layer structure has a mass of 0.45 kg while the layered structure has a mass of 0.62 kg. Just adding the highly efficient thermoforming process, the proposed structure for energy absorbing devices may be a reliable solution. One limitation of the single layer configuration may be identified of the thinning of the wall that points to the thickness of the raw sheet used to manufacture the parts that may add some constrains to the manufacturing process. Moreover due to the smaller dimensions of the cells the structure can be easily adapted to other parts (interior trims, dashboard) in order to provide increased protection.

References

Abramowicz W, Jones N (1986) Dynamic progressive buckling of circular and square tubes. Int J Impact Eng 4:243–270

Abvabi A, Nasr A, Noorpoor A, Saeed Kisat M (2010) Investigation on the effect of impact location height on pedestrian safety using a legform impactor dynamic model. Safety Sci 48:660–671

Akisanya AR, Fleck NA (2006) Plastic collapse of thin-walled frusta and egg-box material under shear and normal loading. Int J Mech Sci 48:799–808

Bartl F, Klaus H, Dallner R, Huber O (2008) Material behaviour of a cellular composite undergoing large deformations. Int J Impact Eng 36:667–679

Belingardi G, Beyene AT, Koricho EG (2013) Geometrical optimization of bumper beam profile made of pultruded composite by numerical simulation. Compos Struct 102:217–225

Chung JG, Chang SH, Sutclife MPF (2007) Deformation and energy absorption of composite egg-box panel. Compos Sci Technol 67:2342–2349

Davoodi MM, Sapuan SM, Ahmad D, Aidy A, Khalina A, Jonoobi M (2011) Concept design of car bumper beam with developed hybrid bio-composite material. Mater Des 32:4857–4856

Davoodi MM, Sapuan SM, Aidy A, Abu Osman NA, Oshkour AA, Wan Abas WAB (2012) Development process of a new bumper beam for passenger car: a review. Mater Des 40: 304–313

European Comission (2009) Regulation (EC) No 78 on the type approval of motor vehicle with regard to the protection of pedestrians and other vulnerable road users

Gupta NK, Mohamed Sheriff N, Velmurugan R (2006) A study of buckling of thin conical frusta under axial loads. Thin Wall Struct 44:986–996

Gupta NK, Venkatesh (2007) Experimental and numerical studies of impact axial compression of thin-walled conical shells. Int J Impact Eng 34:708–720

Hallquist JO (2003) LS-DYNA keyword user's manual. Version 970. Livermore Software and Technology Corporation, Livermore CA

Jones N (1989) Structural impact. Cambridge University Press, Cambridge

Kathiresan M, Manisekar K, Manikandan V (2012) Performance analysis of fibre laminated thin conical frusta under axial compression. Compos Struct 94:3510–3519

Lam SW, Tao XM, Yu TX (2004) Comparison of different thermoplastic cellular textiles composites on their energy absorption capacity. Compos Sci Tech 13–14:2177–2184

Mamalis AG, Manolakos DE, Ioannidis MB, Kostazos PK, Hassiotis G (2001) Finite element simulation of the axial collapse of thin-wall square frusta. Int J Crashworthiness 6:155–164

Matsui Y, Ishikawa H, Sasaki A, Kajzer J, Günter S (2004) New biofidelic corridor and biofidelity test procedure for pedestrian legform impactors. Traffic Inj Prev 5:390–397

Matsui Y (2014) Safety assessment characteristics of pedestrian legform impactors in vehicle-front impact tests. Accident Anal Prev 73:65–72

Mo F, Arnoux PJ, Cesari D, Masson C (2014) Investigation of the injury theresold on knee ligaments by the parametric study of car-pedestrian impact conditions. Safety Sci 62:58–67

Sashikumar S, Chirwa EC, Myler P, Qian P, Matsika E (2012) Numerical investigation of the collapse behaviour of an aluminium egg-box under quasi-static loading. Int J Crashworthiness 17:582–590

Schuster P (2004) Current trends in bumper design for pedestrian impact: a review of design concepts from literature and patents. American Iron and Steel Institute

Shojaeefard MH, Najibi A, Ahmadabadi MR (2014) Pedestrian safety investigation of the new inner structure of the hood to mitigate the impact injury of the head. Thin Wall Struct 77:77–85

Teng TL, Nguyen TH (2010) Assessement of the pedestrian friendliness of a vehicle using subsystem imapct tests. Int J Auto Tech—KOR 11:67–73

The MathWorks, Inc. (2009) MATLAB. Natick, Massachusetts, USA

Wierzbicki T, Bhat SU, Abramowicz W, Brodkin W (1992) Alexander revisited—a two folding elements model of progressive crushing of tubes. Int J Solids Struct 29:3269–3288

World Health Organization (WHO) (2013a) Global status report on road safety 2013: supporting a decade of action

World Health Organization (WHO) (2013b) Pedestrian safety: a road safety manual for decision-makers and practitioners

Yoo SH, Chang SH (2008) An experimental study on energy absorbing structures made of fabric composites. Compos Struct 86:211–219

Zhu F, Dong L, Ma H, Chou CC, Yang KH (2014) Parametrized optimal design of a novel cellular energy absorber. Int J Mech Sci 86:60–68

Zou Z, Reid SR, Tan PJ, Li S, Harrigna JJ (2009) Dynamic crushing of honeycombs and features of front shock. Int J Impact Eng 36:165–176