Failure Analysis of Off-axis Crushing of Stitched Composite Absorbers

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Abstract: - Despite extensive investigations on the energy absorbing capabilities of fibre reinforced polymer (FRP) composite absorbers under axial loading, the off-axis crashworthy behaviour of composite absorbers remains unknown. The interlaminar crack propagation (delamination failure) is known as one of the factors which affect the progressive crushing modes and energy absorption capability of laminated FRP composite tubular structures. In the present paper the effects of stitching on the crack growth resistance, energy absorption and also off-axis crashworthy behaviour of CFRP composite box sections will be studied. For non-stitched and stitched composite boxes the brittle fracture and transverse shearing crushing modes were observed under off-axis loading of 10 degrees. It was also observed that the position of stitched area can affect the crushing mode and consequently energy absorption capability of composite box structures. The analytical methods are implemented to investigate the effect of various failure modes such as bending, friction, bundle fracture, and interlaminar crack growth for the observed crushing modes.

Key-Words: Composite; Mechanism; Analytical; Stitched; Crush; Off-axis

1 Introduction

According to World Health Organization (WHO), road traffic deaths, disabilities, and injuries are a major global public health issues. Worldwide, the number of people killed in road traffic crashes each year is estimated around 1.3 million. Without action, road traffic crashes are predicted to result in the death of around 1.9 million people annually by 2020. Therefore, vehicle crashworthiness and occupant safety remain among the most important and challenging design considerations in the automotive industry [1].

Crashworthiness of fibre-reinforced polymer (FRP) composite materials is classified based on their deformation, failure and absorption of the crashing energy in a controllable and progressive behaviour. The energy absorbing capabilities of FRP composite structures have been investigated in literature, [2-6] by studying the effect of fibre type, matrix type, laminate architecture, specimen geometry, process conditions, fibre volume fraction and testing speed under axial loading. In a progressive axial crushing of composite box absorbers the applied energy is absorbed by four main crushing modes and their combinations. These crushing modes are transverse shearing (fragmentation), lamina bending, brittle fracturing and local buckling. These crushing modes are strongly dependent on the fibre type, resin type, lay-up, thickness, and loading condition. The high energy absorbing capabilities of FRP composite materials is one of the main factors in their application in vehicular structures.

Excellence energy absorption capability of composite tubes during progressive failure process under axial loading, and the predictable crushing behaviour has made them eligible for crashworthy structures. Many of these composite devices and elements are designed to dissipate large amounts of impact energy under axial crushing, bending or combined loading with controllable collapse manner in the collision event. Most collisions, however deviate somewhat from axial loading. Extensive research during the last decade focused on the axial impact of crashworthy component. Understanding this particular failure mode has a very high significance in aerospace and automotive industry.

Most of these works have studied crushing under axial loading. However, in a real crash event, the more likely scenario is a non-axial collision. A few researches have investigated the energy absorbing capabilities of elements, such as box under two types of non-axial loadings. These non-axial loadings are known as off-axis loading and angled loading. Off-axis loading occurs when a spinning vehicle impacts an object from a direction not along its longitudinal axis. Angled loading occurs when a vehicle moving forward along its longitudinal axis impacts an object tilted away from being perpendicular to the vehicles longitudinal axis.

Authors [7-11] have extensively investigated the axial and off-axis crashworthy behaviour of CFRP and GFRP composite box structures. In their work' the inclination angles of 5º, 10º, 20º, and 30º of loading direction with respect to composite box axis were studied experimentally under quasi-static crushing process. The loading angles were increased incrementally to find the relation between the fracture mechanisms and the behaviour of crushing process at each off-axis loading. They found two fracture mechanisms of bundle fracture and delamination crack propagation in Mode-II for all composite boxes at various off-axis loading. Due to crack propagation in mixed-Mode I/II and more friction and bending resistance at one side of composite box which firstly contacted the crushing platen, the amount of SEA at off-axis loading of 10º was the maximum in comparison with other off-axis crushing loadings. Studies showed that for the winding up twill –weave fabrics composite box, as the winding angles, increases from 5˚ to 30˚, their collapse modes experience transverse shearing and lamina bending. For each off-axis angle, the wedge-shaped base with relevant angle was set for each composite box. In previous work of authors, it was shown that natural fibres running through the thickness of laminated composite structures will increase the resistance to crack propagation and consequently the energy absorption capability of composite absorbers. Recently they showed that natural flax fibres have the main advantage over the synthetic fibres (e.g. carbon and glass) of providing both resistance and progressive failure (effective crack growth resistance) in the wall of composite box absorbers. Progressive failure can provide high energy absorption in a controllable behaviour which reduces the main injuries and death during a crash event.

The present study experimentally and analytically investigates the influence of off-axis loading on the crack growth resistance and SEA of woven CFRP composite box structures and will look at the details of macro-mechanics of the fracture process in the sidewalls.

2 Off-axis crushing process of non-stitched and stitched crush box

The composite boxes were off-axially crushed using Universal Testing Machine with 500k. The specimen was tightly gripped at one end in the clamp-set by screwing up the adjustable bolt. The whole clamped fixture together with the gripped specimen was placed on the lower crushing plane testing machine and was tilted to a predetermined off axis angle with a certain spacer load cell at a vertical cross-head crushing speed of 2mm/min (see Figure 1). Complete compaction of tested tube and load increases sharply. Load and displacement were recorded by an automatic data acquisition system.

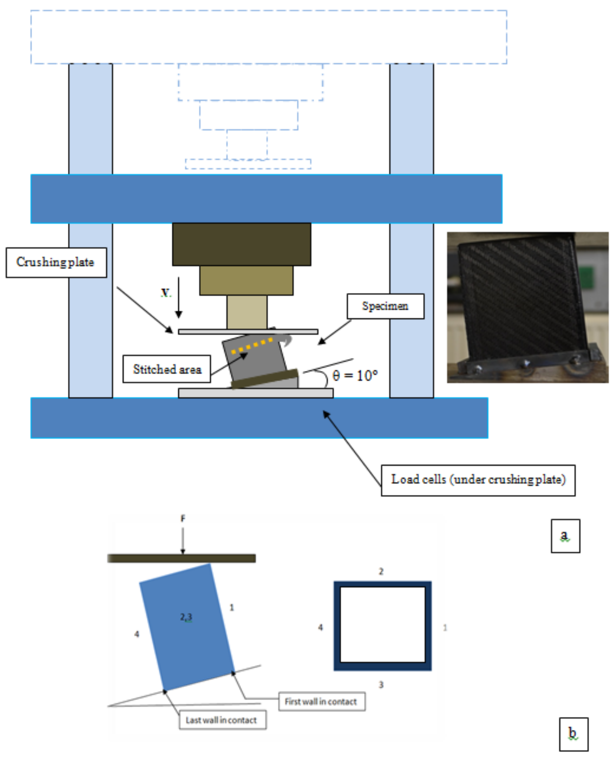

Figure 1. a) Schematic demonstration of off-axis progressive crushing test and b) Indication of wall numbers.

Specimens were crushed off-axially and failure was initiated by pushing a loading plate. In contrast with axial crushing load the off-axis failure is non-symmetrically. Load increased initially to the value of 37kN at the displacement of 5mm (see Figure 2). Macro fragmentation was observed and material splayed to outside of the box (see Figure 3a). First the materials of walls 2 and 3 were splayed with inward fronds in one side and long outward fronds. As load increases, wall 4 was engaged in crush process (see Figure 3b).

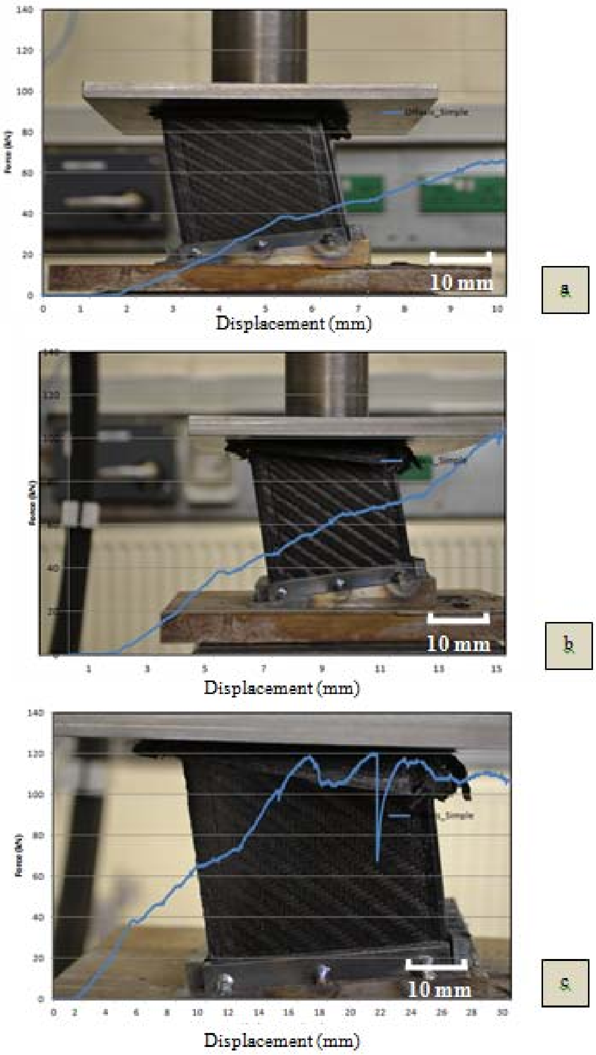

Figure 2. Force (kN) – displacement (mm) curves and deformation history of non-stitched CFRP composite box under off-axial crushing load.

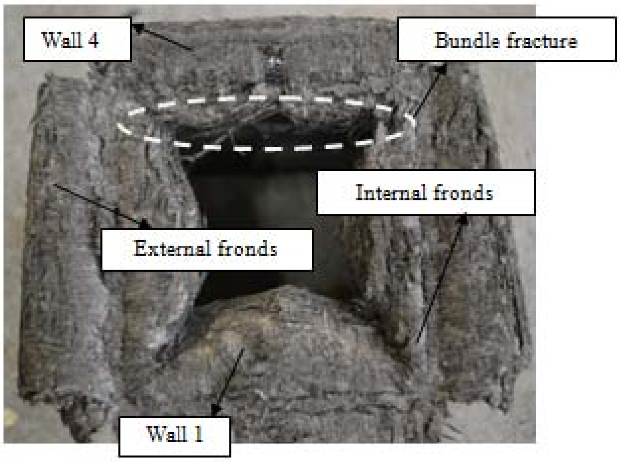

Figure 3. Top view of off-axis crushed non-stitched CFRP composite box

By continueing the crushing process, the longitudinal cracks advanced by splitting the box wall in different segments. As shown in Figure 3, failure starts at maximum load of 119 kN at 15mm. The crushing process of axial and 10º off-axis loading was in brittle fracture mode which debris were created for the crushed specimen. The nature of derbies was somewhat different from axial loading. At this stage the load–displacement curve declined slightly. However, after a small displacement, it remains constant (see Figures 3c and 3d).

The extention of fracture in off-axis loaded box was greater in wall 1, similar walls 2 and 3, and less in wall 4 (see Figure 4). This comparison between force-displacement graphs in Figure 5 shows that stitched composite box has lower mean crushing force in comparison with non-stitched composite box. In this case, the amount of energy absorption is lower than the relevant capability in non-stitched composite box. The transverse shearing (fragmentation) crushing mode was observed for these tests. This crushing mode shows lower energy absorption capability in comparison with brittle fracture mode (see Figure 6).

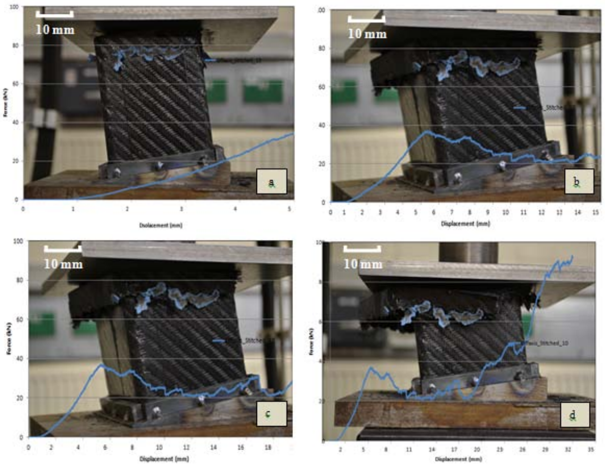

Figure 4. Force (kN) – displacement (mm) curves and deformation history of stitched CFRP composite box under off-axial crushing load.

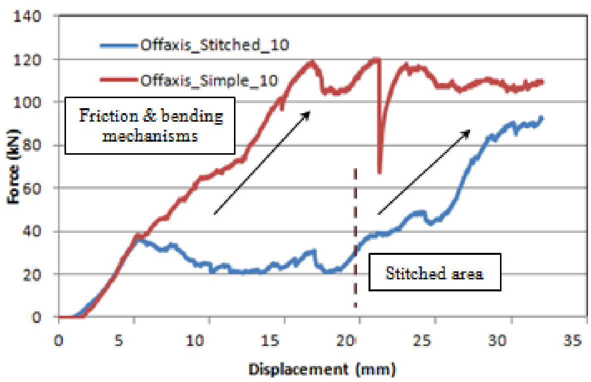

Figure 5. The comparison of force-crush distance in off axis stitched and non-stitched composite crush box.

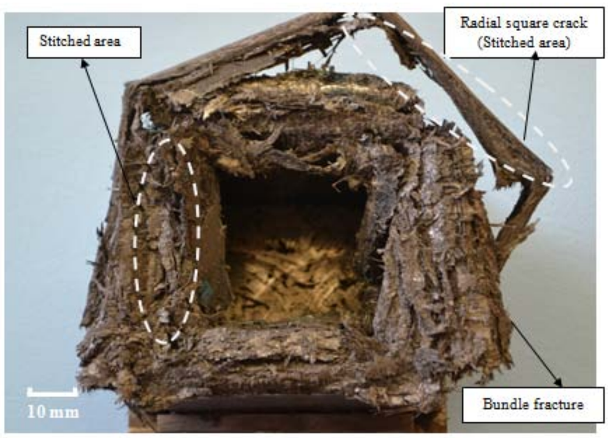

Figure 6. Top view of off-axis crushed Stitched CFRP composite box in transverse shearing mode.

3 Problem Formulation

In previous works of authors [10-11] the combination of crushing modes of lamina bending/brittle fracture and transverse shearing/local buckling were analysed. In the current research off-axis loading caused brittle fracture crushing mode for non-stitched CFRP box while the transverse shearing (fragmentation) mode was observed for stitched composite box. The composite boxes showed progressive crushing failure of lamina in brittle fracture crushing and transverse shearing modes. In the following analytical model which is based on energy balance approach the mean crushing force, Fm, in axial crushing of square composite box is obtained. The external work of crushing platen is dissipated by mechanisms of friction, bending, fracture and shear deformation. The idealised crush zone for our analytical model is shown in Figure 7.

The applied external work by force F during the crush distance z is,

$$U_e = F \cdot z \tag{1}$$

where is the crush distance as shown in Figure 7 and λ is the crush length of a single stroke. The maximum work done by external force happens when φ=π/2, $z = \lambda$.

The energy dissipated by friction between crushing platen and the debris inside the internal and external fronds in brittle fracture crushing mode is assumed into two stages, first is related to triggering stage and second one is related to sustained crushing stage and it can be obtained from,

$$U_f = \left[2 \cdot \mu \cdot \frac{F}{2} \cdot x\right]_{Triggering\ Stage} + \left[2 \cdot \mu \cdot \frac{F}{2} \cdot x\right]_{Sustained\ Crushing\ Stage} = 2 \cdot \mu \cdot x \tag{2}$$

The experimentally measured coefficient of friction is μ=0.35 for CFRP.

The energy dissipated by frond bending was calculated by assuming that the whole cross section of the frond will reach to the flexural bending stiffness, b.

The flexural strength, b, for each lay-ups of CFRP was measured σb = 570 MPa from 3PB experiment.

The energy dissipated in bending for brittle fracture crushing mode at stationary hinge lines is

$$U_b = \left[\int_0^{\frac{\pi}{2}} \frac{\sigma_b (4b) t^2 d\varphi}{8} \right]_{Triggering\ Stage} + \left[\int_0^{\frac{\pi}{2}} \frac{\sigma_b b t^2 d\varphi}{8} \right]_{Sustained\ Crushing\ Stage} = \frac{5\pi b t^2 \sigma_b}{16} \quad (3)$$

The energy dissipated by interlaminar crack propagation in Mixed-Mode-I/II is calculated from interlaminar fracture energies. In brittle fracture mode there is one interwall Mixed-Mode-I/II crack at sides of the box as shown in Figure 6. Therefore,

$$U_d = 4b\lambda (G_{I/IIC}) \quad (4)$$

The Mixed Mode-I/II interlaminar fracture toughness is measured experimentally by ADCB test [8].

Dissipated energy by axial splitting at the four corners of the box for brittle fracture crushing mode is calculated based on the stress intensity factor.

At fibre splitting we assume . The crack assumed to propagate similar to a crack growth in a single edge notched (SEN) plate where Y=1.12. Therefore, the dissipated energy in axial splitting for a fracture area of is,

$$U_c = \frac{5\pi t \lambda^2 \sigma_u^2}{E_z} \quad (5)$$

where Ez is Young's modulus in axial direction of the crush box.

By assuming during the crushing process the shear stress will reach to its maximum shear strength value of the laminate, the energy dissipated in shear deformation of laminate is

$$U_s = \frac{1}{2} \int_V \frac{\tau^2}{G_{12}} dV = \frac{2bt\lambda \tau_s^2}{G_{12}} \quad (6)$$

Dissipated energy due to bundle fracture was obtained by replacing the crush distance,   with the width of box.

$$U_{bu.f} = \frac{2.5\pi t b^2 \sigma_u^2}{E} \quad (7)$$

where, E = Ey

The fracture area of   was assumed for eight internal and external fronds with crack growth assumed to be half the width of the side wall as observed in the experiments and Ez and Ey are Young's modulus in longitudinal and transverse direction of the crush box.

The energy balance for the brittle fracture crushing process during a single stroke crush distance is

$$U_e - U_f = U_b + U_d + U_c + U_s + U_{bu.f} \quad (8)$$

Substituting from Eqs. (1) to (6) in Eq. (8), the energy dissipated by brittle fracture crushing mode, UBF, is

$$U_{BF} = F(1-2\mu)\lambda = \frac{5\pi b t^2 \sigma_b}{16} + 4b\lambda (G_{I/IIC}) + \frac{5\pi t \lambda^2 \sigma_u^2}{E_z} + \frac{2bt\lambda \tau_s^2}{G_{12}} + \frac{2.5\pi t b^2 \sigma_u^2}{E_y} \quad (9)$$

Therefore, the mean oscillatory crushing force in a stable brittle fracture progressive crush is:

$$F = \frac{1}{(1-2\mu)} \left[\frac{5\pi b t^2 \sigma_b}{16\lambda} + 4b (G_{I/IIC}) + \frac{5\pi t \lambda \sigma_u^2}{E_z} + \frac{2bt \tau_s^2}{G_{12}} + \frac{2.5\pi t b^2 \sigma_u^2}{E_y \lambda} \right] \quad (10)$$

A single stroke crush distance for brittle fracture mode can be found from Eq. (11) by setting

$$\lambda = \sqrt{\frac{5bt\sigma_b E_y + 40b^2 \sigma_u^2}{80\sigma_u^2} \frac{E_z}{E_y}} \quad (11)$$

The energy balance for the transverse shearing crushing process during a single stroke crush distance is

$$U_e - U_f = U_b + U_c + U_s + U_{bu.f} \quad (12)$$

Substituting from Eqs. (1), (2), (3), (5), (6) and (7) in Eq. (12), the energy dissipated by transverse shearing crushing mode, UTS, is

$$U_{LB} = F(1-\mu)\lambda = \frac{\pi b t^2 \sigma_b}{4} + \frac{5\pi t \lambda^2 \sigma_u^2}{E_z} + \frac{2bt\lambda \tau_s^2}{G_{12}} + \frac{0.31\pi t b^2 \sigma_u^2}{E_z} \quad (13)$$

Furthermore, the mean oscillatory crushing force in a stable transverse shearing progressive crush is:

$$F = \frac{1}{(1-\mu)} \left[\frac{\pi b t^2 \sigma_b}{4\lambda} + \frac{5\pi t \lambda \sigma_u^2}{E_z} + \frac{2bt \tau_s^2}{G_{12}} + \frac{2.5\pi t b^2 \sigma_u^2}{E_z \lambda} \right] \quad (14)$$

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A single stroke crush distance for transverse shearing mode can be found from Eq. (15) by setting

$$\lambda = \sqrt{\frac{bt\sigma_b E_z + 10b^2\sigma_u^2}{20\sigma_u^2}} \quad (15)$$

The mean force during the progressive crushing can be found by calculating from Eqs. (11) and (15) substituting in Eq. (10) and (14) (see Table 1). The results were in good agreement with the relevant experimental results and the discrepancy between experimental and theoretical results is less than 1.5% and 5% for brittle fracture and transverse shearing crushing modes, respectively.

Table 1. Comparison of experimental and analytical mean force results of off-axis CFRP composite box.

Off-axis Specimen	**Cushing failure mode**	***F_m (Exp.) kN***	***SEA (Exp.) kJ/kg***	***F_m (Anal.) kN***	***SEA (Anal.) kJ/kg***	***Error (%)***
Stitched	Transverse Shearing (TS)	57	12.5	54	11.8	5
Non-stitched	Brittle Fracture (BF)	118	25.8	116	25.4	1.5

4 Conclusion

In this paper fracture analysis was performed to study the effect of stitching on off-axis crushing behaviour and energy absorption of carbon/epoxy twill-weave composite box composite. The two types of specimens, stitched and non-stitched composite boxes were subjected to quasi-static off-axial compression load.

Two fracture mechanisms of bundle fracture and interlaminar crack propagation in Mixed-Mode-I/II were found for all composite boxes at off-axis crushing process. Owing to crack propagation in Mixed-Mode I/II and more friction and bending resistance at one side of the composite box, which first contacted the crushing platen, the amount of SEA at off-axis loading of 10º was higher than the equivalent value in axial loading. However, the CFE of non-stitched composite boxes at off-axis loading is higher than the CFE of stitched boxes. In off-axial crushing process the scenario was different from what we were expected to observe.

It was observed that in off-axis loading the energy absorption of stitched boxes is less than the energy absorption of non-stitched boxes. The main problem was related to the position of stitched area in the box wall. It is assumed that lower position from top of the box could allow all sides of box firstly get involved in crush process, and then the stitched area increases the load resistance and consequently energy absorption capabilities. Finally it is concluded that the position of stitched area has to be optimised against the crashworthiness criteria to find the highest amount of energy absorption capability in composite tubular structures.

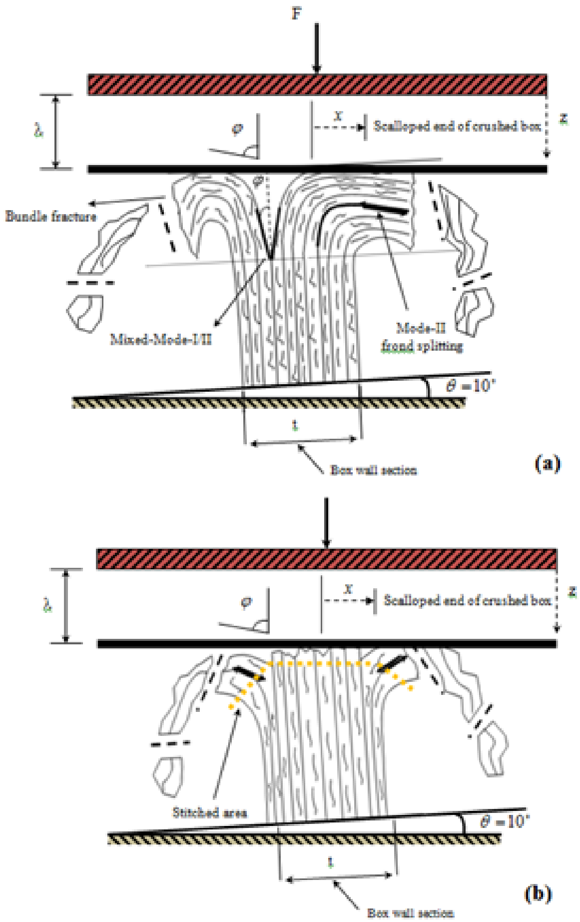

Figure 7. Ideal crush zone, a) non-stitched and b) stitched CFRP composite box in off-axis angle of 10°.

References:

[1] World Health Organisation (WHO), 2009. Road traffic injuries, Available at: http://www.who.int/en.

[2] Farley G, Jones R. 1992. Crushing characteristics of continuous fibre reinforced composite tubes. Journal of Composite Materials, 26:37–50.

[3] Mamalis A.G, Manolakos D.E, Demosthenous G.A and Ioannidis M.B. 1998. Crashworthiness of Composite thin-walled structural components. Publisher CRC; 1st edition.

[4] Jacob G.C, Fellers J.F, Simunovic S, Starbuck M. 2002. Energy absorption in polymer composites for automotive crashworthiness. Journal of Composite Materials, 36:813-50.

[5] Han H, Taheri F, Pegg N, Lu Y, 2007. A numerical study on the axial crushing response of hybrid pultruded and ±45° braided tubes, Composite Structures, 80(2):253-264.

[6] Savona S.C., Hogg P.J. 2006. Effect of fracture toughness properties on the crushing of flat composite plates. Compos Sci Technol, 66:2317-2328.

[7] Ghasemnejad H, Blackman B.R.K, Hadavinia H and Sudall B. 2008. Experimental studies on fracture characterisation and energy absorption of GFRP composite box structure. Composite Structures, 88(2):253-261.

[8] Ghasemnejad H and Hadavinia H. 2010. Off-axis crashworthiness characteristic of woven glass/epoxy composite box structures. J. Reinf Plast Comp. 29(15):2306-2330.

[9] Ghasemnejad H, Hadavinia H, Aboutorabi A. 2010. Effect of delamination failure on the crashworthiness of hybrid composite box structures. Materials and Design, 31:1105-1116.

[10] Ghafari-Namini, N. and Ghasemnejad, H. 2012. Effect of natural stitched composites on the crashworthiness of box structures. Materials & design, 39: 484-494.

[11] Hadavinia H and Ghasemnejad H. 2008. Effects of Mode-I and Mode-II interlaminar fracture toughness on the energy absorption of CFRP twill/weave composite box sections, Composite Structures 89(2):303-314.