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Quasi-static study of the energy absorption of armadillo bio-inspired tubes under axial and oblique loads

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ABSTRACT

Today the implementation of biomimetic elements during the design of thin-walled structures (BTWS) is relevant among engineers and designers since bionic solutions are the result of successful evolution and adaptation processes. The current article presents the design and evaluation of five BTWS based on the nine-banded armadillo armor. The BTWS were designed considering the pectoral and pelvic patterns of the armadillo's carapace. In all cases, the tubes were made of aluminum alloy 6061. The evaluation of the BTWS was through a numerical oblique compression test with loading angles of 0°, 5°, 10° and 15°. Oblique loading conditions are used since in practice most car crashes occur under these conditions. The numerical results revealed a decrease in the Pmax and Pm as the load angle (θ) increased. Likewise, it confirmed the superior performance of BTWS respect to conventional tube regardless of θ value. Specifically, an improvement in crash force efficiency (CFE) and energy absorption (Ea) of 86% and 78% was computed. Despite a decrease in Ea was observed as the loading angle increased, BTWS exhibited an enhancement of this parameter regard to conventional tube named HX-00. Regardless of the load angle, the best energy absorption performance was calculated for BTWS HX-04, where an average of 0.85 kJ was calculated. Lastly, comparing the bionic thin-walled structures for each loading angle, the largest crush force efficiency (CFE) of 0.74 was obtained on a structure with a main circle surrounded by smaller irregular pentagons (HX-04).

Keywords: crashworthiness, finite element analysis, oblique load, armadillo-bioinspired tubes.

INTRODUCTION

Safety of passengers is an important goal in crashworthiness design since every year more than 1.35 million people die around the world due to car crashes [1, 2]. Thus, more safety in transportation systems is necessary. In this way, the use of thin-walled structures (TWS) as energy absorption devices have been widely validated and implemented [3–5]. Although car crashes occur in different forms, oblique crashes present a high risk to passenger safety, since head and neck injuries can occur [6]. In this form, the car suffers a load impact at an angle condition. This condition is relevant since the energy absorption mechanism of TWS, which relies on plastic deformation, may be only partially carried out [7]. To counter the harmful effects during frontal or oblique car crashes, automobile industry implements a frontal collision system formed by a from bumper supported by two crash boxes at the ends, which are then joined to the front rails (see Figure1). While all of these components are designed to absorb energy, the bulk of the energy absorption is done by the crash boxes. Commercially the crash boxes usually have rectangular, square or circular cross-section shapes. Although his behavior is acceptable, nowadays researchers have warned on the optimization of geometric shape to improve the crashworthiness performance. Although new configurations of crash boxes involve complex geometries, which could be a challenge for massive implementation, its superior crashworthiness performance than conventional crash boxes increase the chances of survival of passengers. Likewise considering the versatility of extrusion process and the tendency of cost reduction of emerging manufacturing technologies (e.g. additive manufacturing), the feasibility to manufactured complex thin-walled structure is a reality.

Taking this in mind Li et al. [8] presented a numerical analysis to evaluate the energy absorption characteristics of triangular, quadrangular and hexagonal side hierarchical TWS. The structures were subjected to axial and oblique load conditions. A better performance was observed on the 7th order hierarchical triangular structure than on the conventional column under axial load. Likewise, the influence of hierarchical order and loading angle on energy the absorption characteristics was confirmed. As a conclusion, in general terms, a better performance was obtained on 4th order side hierarchical structures. On the other hand, Zhang et al. [9] performed a numerical study of the energy absorption capacity of hybrid cross-section beams subjected to oblique loads. The hybrid cross-section was obtained by adding ribs at the top and bottom ends of the tubes. During the study, conventional single and double square tubes and its hybrid analogue were evaluated by a quasistatic oblique compression test. Parameters such as number of cells, height, and load angles were studied. At the end, the effectiveness of the structure with hybrid cross-section was confirmed, considering both energy absorption and structural stability. Khorasani et al. [10] evaluated the energy absorption performance of tapered multi-cell structures by a theoretical and numerical analysis when subjected to oblique loads. In the analysis, the effect of parameters such as number of cells, wall thickness, impact loading angle condition and taper angle on the crashworthiness performance was studied. The structures were evaluated at 0°, 15° and 30° load angle condition. As a result, a formula to predict the mean crushing force of tapered multi-cell structure was established. Additionally, it was determined that high-cell-number tubes with larger taper angles present better performance than low-cell-number tubes or conventional tapered structures. On the other hand, Tran [11] carried out a numerical study of crashworthiness performance of windowed multi-cell square tubes subjected to axial and oblique loads with loading angle of 15°. A combination of multicell square tubes with geometrical imperfections (rectangle holes) was studied. It was found that the use of windowed imperfections decreases the peak load of the structures; however, it also led to a decrease of energy absorption performance. In the same way, Estrada et al. [12] conducted a numerical study to evaluate the crashworthiness performance of multicell tubes under oblique loads. During the study five aluminum structures based on square cross-section were compressed at 0, 5, 10 and 15°. As main finding, the study revealed the importance of multi-cell cross-section since allowed increased the crashworthiness performance. At the end the superiority of structure with a cross-section formed by a main central square with smaller squares at the corners was determined. As can be seen, several efforts have been carried out to improve the crashworthiness performance of structures under oblique loads. The performance of structures is mainly determined by their cross-section. Taking this in mind, nowadays the use of natural geometric patterns as inspiration for the design of TWS is increasing [13–16]. With this objective, Tasdemirci et al. [17] performed an energy absorption study of bionic structures inspired in the balanus creature. The study was carried out experimentally and numerically in both quasi-static and dynamic conditions. The thin-walled structure was formed by a conical core with an outer shell in frusto-conical shape. The effectiveness of the outer shell was confirmed since this component had a higher energy absorption than the conical core. In the same direction, Samsolbahar et al. [18] conducted a numerical analysis to evaluate the crashworthiness performance of BTWS based on the micro-architecture of the vascular bundle of the bamboo structure. As a result of this study, and considering conventional tubes as baseline, a better energy absorption was computed for the BTWS proposed. On another investigation, Estrada et al [19] conducted a numerical study of BTWS bioinspired on the shrimp tail. The structures were designed with segmented sections as in the shrimp tail and evaluated by a three-point bending test. The study confirmed the effectiveness of BTWS over circular profiles.

Finally, as indicated in the above introduction, the study of TWS under oblique load is an important topic among engineers and researchers. However, the use of biomimetics for the design of TWS under oblique loads is barely reported compared to the axial, bending or lateral compression conditions. Then, this article presents the design and numerical evaluation of five BTWS bioinspired in the shell of the nine-banded armadillo. The importance and novelty of this work lies in exploring the effectiveness of the geometric shape of the armadillo shell tiles when they are considered as the cross sections of aluminum tubes, viewed from the macroscopic point of view. In all cases the BTWS were made of aluminum alloy 6061 and were evaluated by a quasi-static oblique compression test with 0°, 5°, 10°, and 15° load angles. At the end of the study bioinspired tubes showed a better crashworthiness performance respect to a conventional profile. In this sense, regardless the angle loading structure HX-04 exhibited the best crush force efficiency equal to 0.74.

CRASHWORTHINESS METRICS

Many quantitative and qualitative parameters have been proposed to evaluate the crashworthiness performance of structures. However, the most important are the peak load (Pmax), mean force (Pm), Energy absorbed (Ea), specific energy absorption (SEA) and the crush force efficiency (CFE). Regarding the latter, a structure has the optimal behavior when CFE has a value close to unity. A description of these indicators is presented in Table 1.

DESIGN OF BTWS CONSIDERING THE CARAPACE OF THE NINE-BANDED ARMADILLO AS BASELINE

The nine-banded armadillo is mammal native to the Americas [21]; many characteristics can be associated to them. However, its survival over millions of years is the result of a successful evolutionary adaptation to its environment. In this sense, an important factor has been the armor provided by its carapace. The shell of the armadillo is made mainly of keratin and is divided in three regions; the pectoral, banded and pelvic regions. Depending on the region, two kinds of geometric patterns can be observed. Hexagonal tiles are disposed in the pectoral and pelvic regions while triangular patterns are observed in the banded region. During the attack of a predator, the carapace is subjected to compression forces. Taking this into account, the current paper proposes five bionic thin-walled structures based on the pectoral and pelvic regions of the armadillo (HX-01-05). The tiles of these regions are formed mostly by a main polygonal shape surrounded by smaller forms (Table 2). Thus, the BTWS follows this natural pattern. All BTWS have the same mass and length, thus an adjustment of the thickness was made accordingly. The structures were made of aluminum alloy 6061 and evaluated by an oblique compression test with loading angles (θ) of 0°, 5°, 10°, and 15°. Geometric characteristics of the evaluated specimens are shown in Table 2. Since the current work is for academic purposes, the images related to the armadillo and its carapace were taken from literature [22].

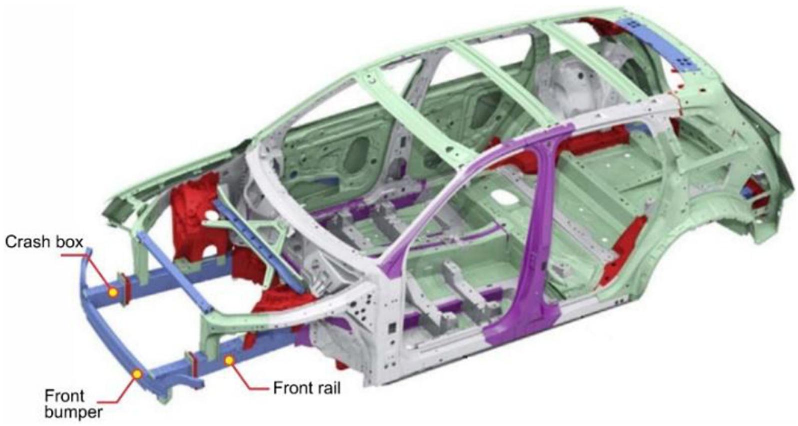
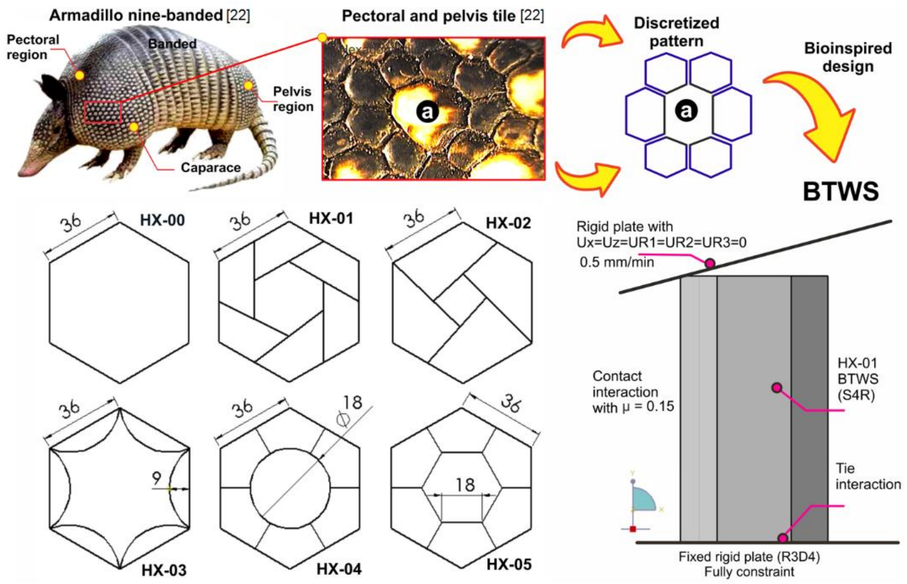


Figure 1. Body in white and frontal collision system of an automobile, adapted from [20]

Table 1. Typical crashworthiness parameters, where is the displacement and F the crushing force

Peak load [Pmax] kN	Mean Force [P_m] kN	Energy absorbed [Ea] kJ	Crush force efficiency [CFE]
Obtained from curve	$P_m = \frac{E_a}{\delta}$	$E_a = \int_0^\delta F.d\delta$	$CFE = \frac{P_m}{P_{max}}$

Table 2. Characteristics of the conventional (HX-00) and bio-inspired tubes based on the armadillo carapace



Specimen code	Length (mm)	Thickness (mm)	Mass (gr)
Hx-00	130	1.20	91
Hx-01	130	0.60	91
Hx-02	130	0.68	91
Hx-03	130	0.55	91
Hx-04	130	0.63	91
Hx-05	130	0.64	91

FIRST DISCRETE MODEL AND EXPERIMENTAL VALIDATION

The current article is performed by finite element method analysis. Thus, a first discrete model is development and experimentally validated [23]. The discrete model consists of the compression test of a conventional hexagonal profile (HX-00) with loading angle θ equal to 0°. In this way, a hexagonal profile is useful for our purposes since the pectoral region of the armadillo shell is mostly formed by hexagonal tiles, while the oblique load condition are special cases of the compression test. The profile was modelled using S4R elements with isotropic linear elastic and plastic properties for aluminum alloy AA6061 with young modulus of 68 GPa, Poisson ratio of 0.33, density of 2700 kg/m^3 and yield stress of 71 MPa [23]. The compression of the profile was carried out by two rigid plates, which were modeled with R3D4 elements. The test was performed at a 0.5mm/min loading rate. Since the aluminum alloy is insensitive to strain rate effects [24] its effects were neglected. With respect to boundary conditions, the bottom end of the profile was tied to the bottom plate, which was fully fixed. On the other hand, the top rigid plate was only unconstrained in the y-direction to allow the crushing process. A friction coefficient of 0.15 was used. Lasty, as a result of a mesh convergence analysis, an element size of 2 mm was determined. From this, acceptable values within a reasonable computational time. Geometric characteristics of the profile and discrete model are shown in Figure 2.

The validation of the model was carried out by direct comparison of numerical results against experimental data presented in the literature [23]. In this sense, Figure 3a presents a comparison of the crush force efficiency of both experimental and numerical results. Both models initially reached a maximum peak load (Pmax) close to 21 kN. Later, a sudden decrease in the force is obtained (i.e. loss of load carrying capacity) and a repetitive folding process is observed. The energy absorbed (Ea) for both models are presented in Figure 3b. At the end of the compression test an Ea value of 0.7 kJ was computed. For this case a difference close to 2% was calculated.

The final deformation mode is presented in Figure 4. As can be seen, a good agreement between experimental and numerical models is observed. Progressive and symmetric plastic folds were obtained in both cases. In this sense, the surfaces were fully deformed plastically, minimizing the apparition of buckling phenomena. At this point, the experimental deformation mode shows only the formation of plastic folds without any signs of progressive damage such as crack initiation or growth. This confirms the effectiveness of the linear elastic-plastic model used in the present study to capture the quasi-static behavior of the structure.

Thus, we confirm that the discrete model correctly captured the quantitative and qualitative behavior of structure HX-00. Only maximum differences of less than 3% for the compression force, Pmax and Ea were calculated. Likewise, the final deformation mode revealed the accuracy of the model to capture correctly the qualitative behavior of the structure. Thus, the numerical techniques are validated, which allow us to continue with our numerical analysis of BTWS.

RESULTS AND DISCUSSION

The above mentioned numerical results of crashworthiness and energy absorption of armadillo-bioinspired tubes are presented in this section. Additionally, for comparison purposes, the results for a conventional hexagonal tube are also presented. The mechanical behavior of the structures was obtained by studying the crash force vs displacement curves (see Figures 5–6). At this point we remark that it is possible to do a direct comparison among structures, since all structures have the same mass of 91 gr. Regardless of the structure, as the loading angle θ increases, the Pmax decreases. The maximum values of Pmax were obtained when the structures were subjected to axial loading (θ = 0°), in this case a Pmax value close to ~20 kN was computed. Regardless of θ, once failure occurred, the BTWS presented better stability of the crushing load compared to the conventional tube (HX-00). A mean force in a range of 8 to 10 kN was computed for the BTWS. Likewise, the natural pattern allowed for a better control of the deformation process, which contributed to avoid the drop in force during the folding process as it was observed in the HX-00 tube. Focusing on the armadillo-bioinspired tubes and

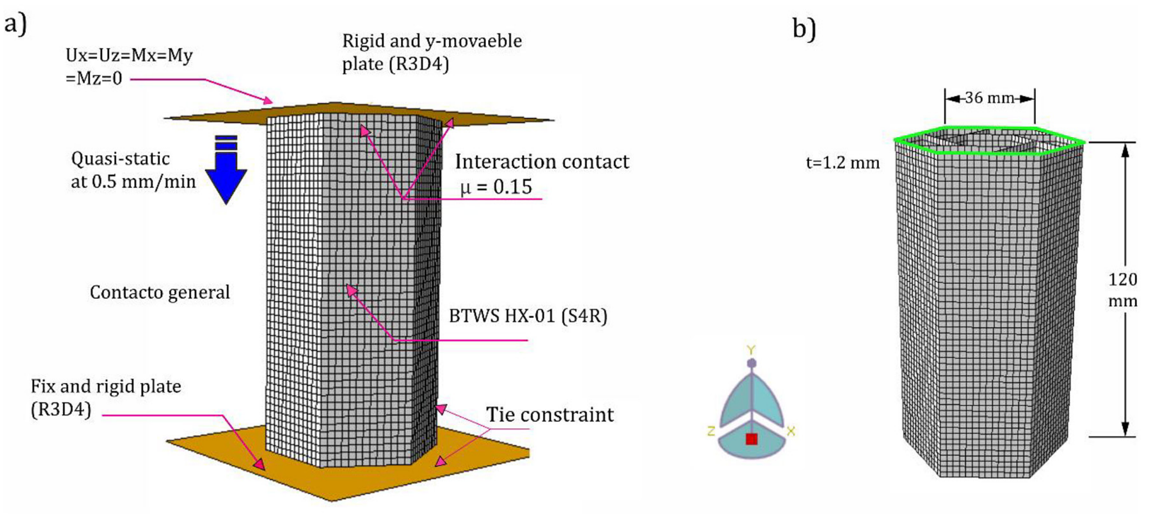


Figure 2. a) Discrete model of the axial compression test with = 0 and b) geometric characteristics of HX-00

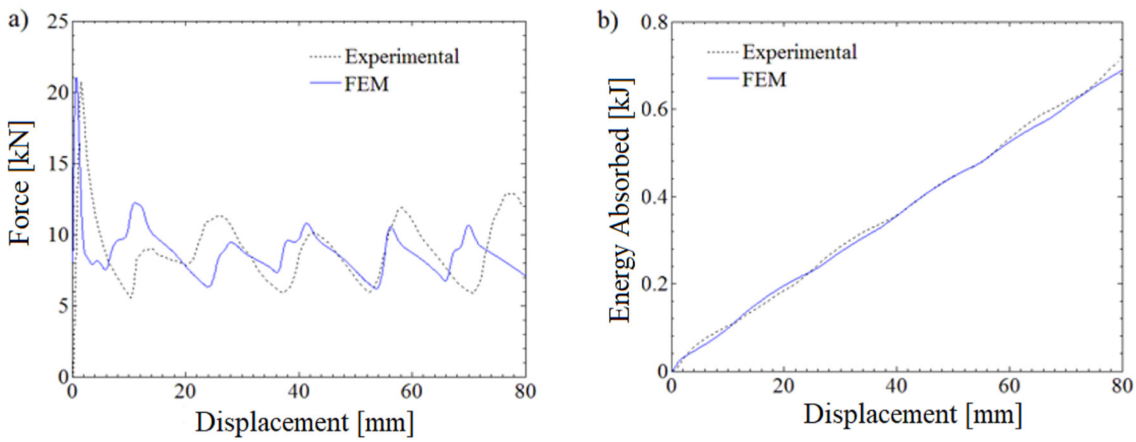


Figure 3. Comparison of numerical and experimental results [23]: a) force vs displacement curves, b) energy absorbed (Ea) for structure HX-00

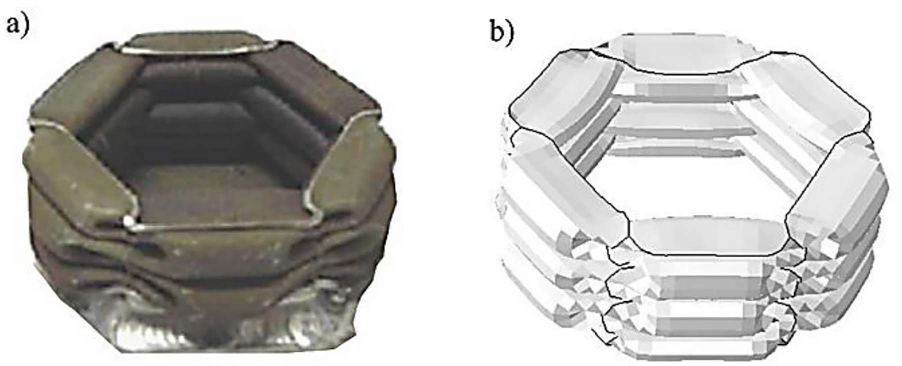


Figure 4. Final deformation mode of structure HX-00: a) experimental [23], b) numerical

regardless of the loading angle, the best load carrying capacity was observed on structures HX-04 and HX-05.

The stability of the structures depends on the deformation mode, which determines the fully plastic formation of wrinkles or the occurrence of buckling phenomena. To understand the progressive collapse of the BTWS, Figures 7–9 are presented. Regardless of the type of structure, as the loading angle increases, a buckling phenomenon is observed in all structures. From this, a partial formation of plastic folds is obtained. However, the effectiveness of the BTWS cross-sections respect to structure HX-00 was observed. Focusing on the conventional tube, this presented a symmetric deformation mode at 0°, however as θ increases, partial and smooth wrinkles form. Meanwhile, the BTWS based on the pectoral pattern of the armadillo's shell, exhibited greater interaction between the tube walls, which allowed for better stability of the structures, contributing to the full formation of wrinkles during the crushing process. Although the BTWS presented a non-symmetric deformation mode, this condition allowed for greater formation of static and traveling hinge lines. Then, greater work was required to form the plastic wrinkles, consequently this contributed to obtain a better load carrying capacity of the bionic thin-walled structures.

The quantification of the crashworthiness performance of both conventional and BTWS was performed by the calculation of the crashworthiness indicators presented in Table 1. Figure 10a presents the behavior of Pmax for all structures as the loading angle varies. In all cases, as θ increased, a decrease of Pmax was computed. This decrease was mostly smooth from 5° onwards. Considering the axial condition (θ = 0), all structures presented similar values of Pmax close to 20 kN. Then, the structures experienced a decrease in Pmax of approximately 30% when they were loaded at 5°. For the subsequent loading angles (10° and 15°), Pmax decreased at a rate of 4%. Regardless of

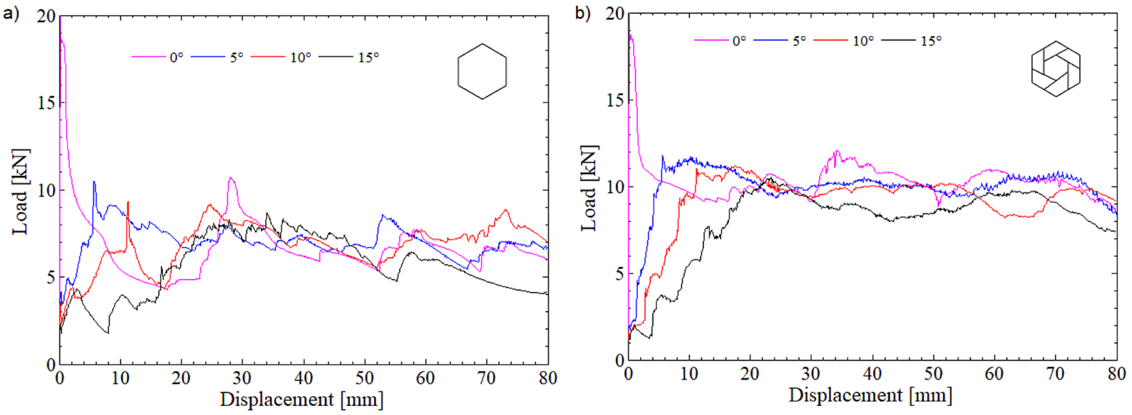


Figure 5. Force vs displacement curves for evaluated structures, where a) HX-00, b) HX-01

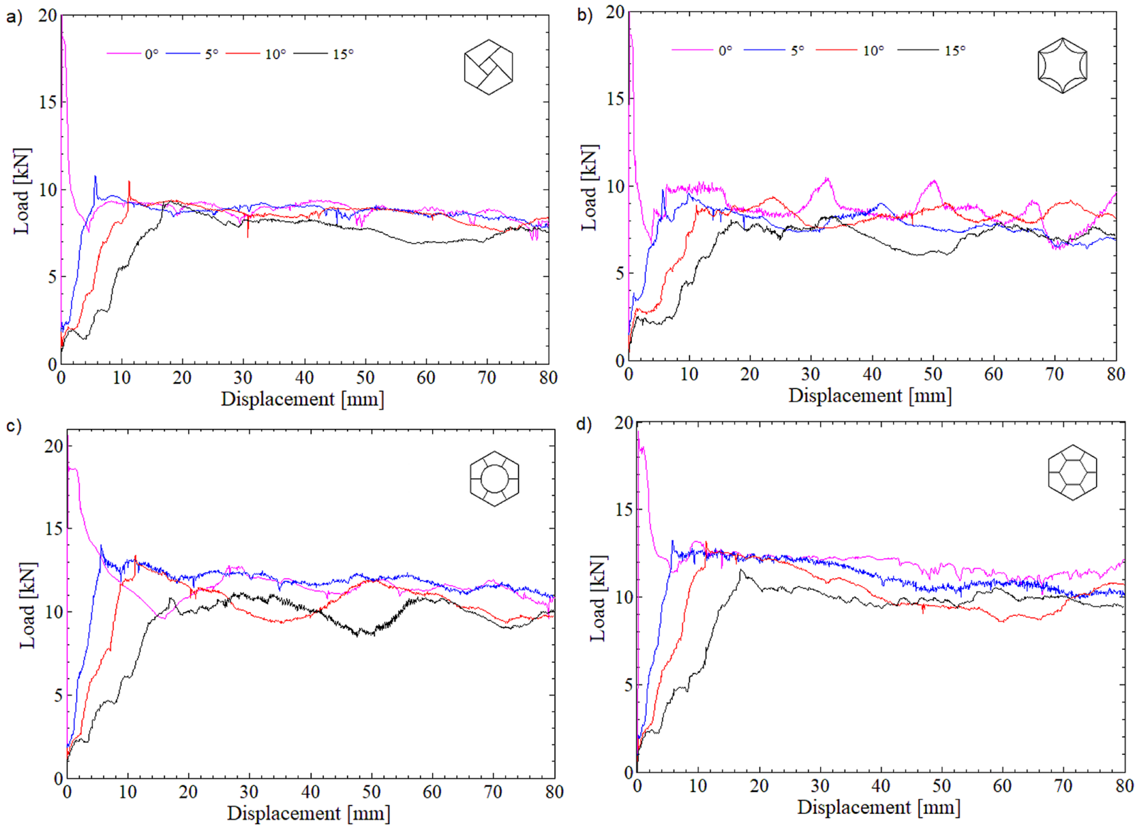


Figure 6. Force vs displacement curves under different load angles (θ), for armadillo-bioinspired tubes a) HX-02, b) HX-03, c) HX-04 and d) HX-05

the BTWS type and θ values, all BTWS presented a larger initial resistance to compression than structure HX-00, being most visible from 5° onwards. Figure 10b presents a comparison of the mean force (Pm) among structures. The Pm refers to the force achieved after the failure of the structures was reached. In the same way as Pmax, Pm showed a downward trend as the loading angle increased. The Pm values obtained were confined in a range from 5.6 kN to 12.02 kN. In most cases, the Pm decreased at a rate of~ 8% with every 5° increase in the loading angle. From the Pmax and Pm curves we determine the improved effectiveness of the armadillo-bioinspired tubes in a range from 2% to 78% respect to the conventional hexagonal profile. Likewise, among the BTWS, the best load carrying capacity at the beginning and during the compression test was for structure HX-04 with a cross-section composed of a main circular shape surrounded

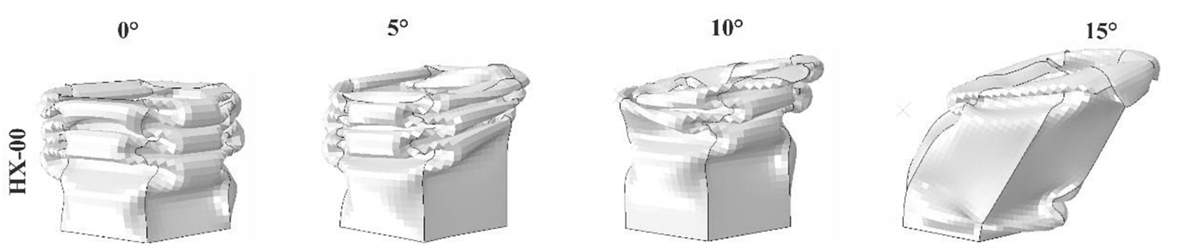


Figure 7. Final deformation state of the conventional hexagonal tube (HX-00) at different loading angles

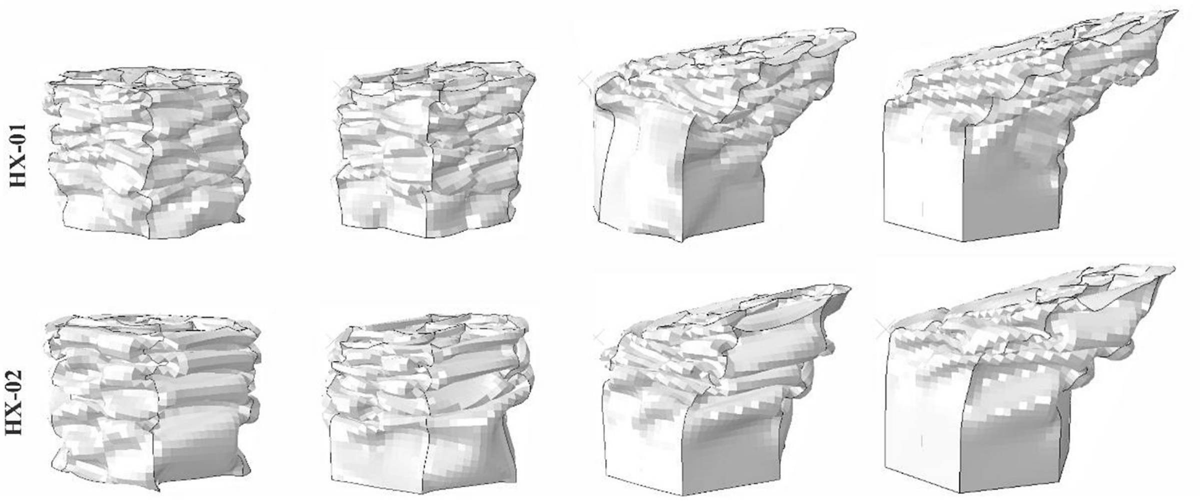


Figure 8. Final deformation state of the armadillo-bioinspired tubes at different loading angles, I

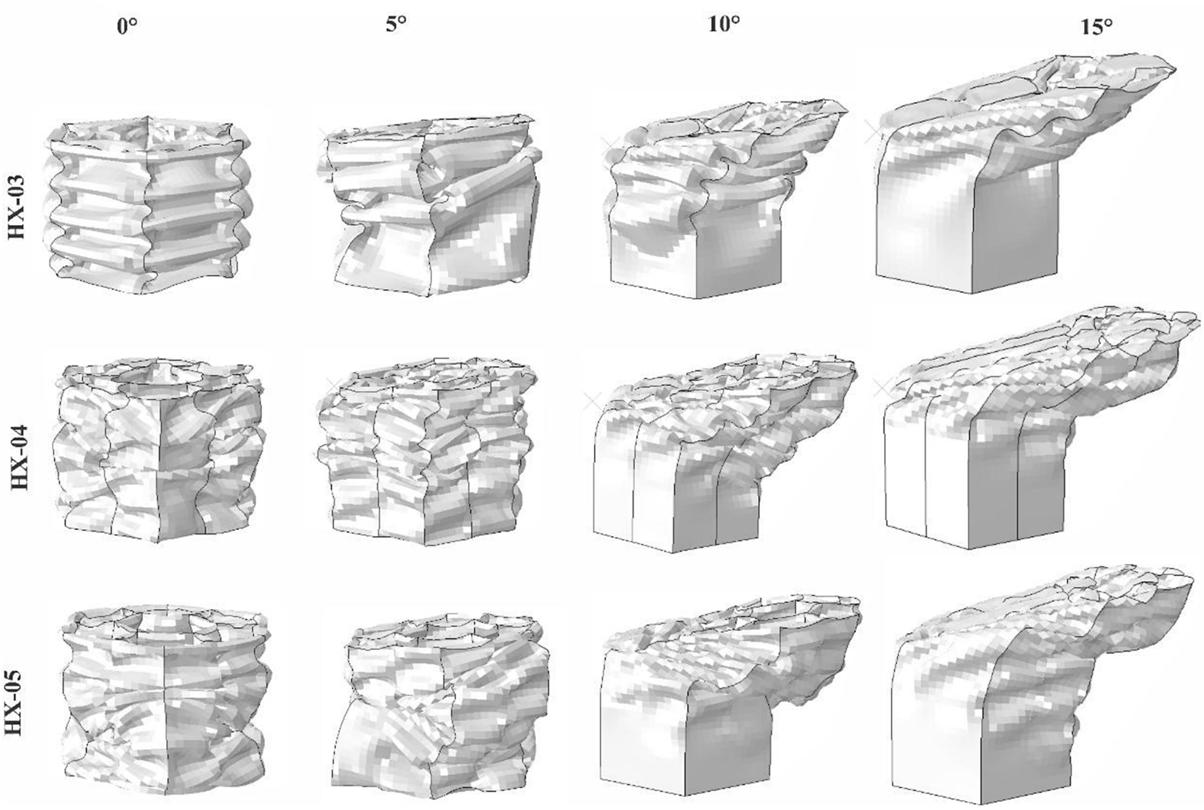


Figure 9. Final deformation state of the armadillo-bioinspired tubes at different loading angles, II

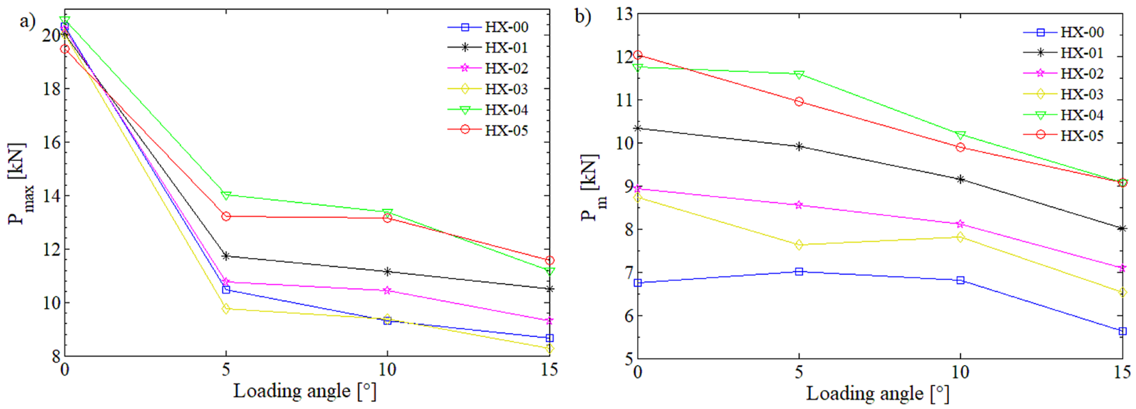


Figure 10. a) Pmax and b) mean force (Pm) for conventional and BTWS structures at different θ values

by smaller irregular pentagons. Meanwhile, the BTWS with the worst performance, was HX-03.

The energy absorbed (Ea) by plastic deformation is presented in Figure 11. It shows, the loading angle has a direct influence on the energy absorbed. In this sense, a reduction of this parameter in a range from 4% to 12% was calculated as θ increases. This behavior is in agreement with the expected mechanical behavior, since as increases a lesser quantity of material is plastically deformed. However, all BTWS exhibited a better Ea performance when compared to the convectional structure HX-00. Regardless of the loading angle, the best Ea performance was obtained for structure HX-04, which achieved values of 0.94 kJ, 0.93 kJ, 0.81 kJ and 0.73 kJ for 0°, 5°, 10° and 15°, respectively. In this sense, this bionic cross-section improved the Ea performance in the order of 61–74.19% relative to the conventional tube (HX-00).

The explanation to high Ea performance for bioinspired profiles, particularly of structure HX-04 lies in stability and stiffness provided for the cross-section (main circle surrounded by smaller pentagons). In this sense, regardless of the loading angle, a fully plastic deformation of the surfaces always is performed. Physically, at the time that the oblique load is applied, the pentagon's sides act as increaser or stiffness. In this sense, by being positioned at different angles to the main circle, it contributes to distributed in better way the oblique load toward middle circle, minimizing the apparition of buckling phenomena. From this as the oblique crushing process is performed, always there is surfaces to be deformed both progressively as fully chaotic, which increases the quantity of energy absorption (Figure 12).

On the other hand, Figure 13 presents the crush force efficiency (CFE). This dimensionless indicator accounts for the effectiveness of the crushing force during the compression test. A CFE value close to unity means optimal behavior for the structure. In general, considering both conventional and BTWS, as the loading angle increases to 5°, an improvement in CFE in a range from 34.13% to 102% is observed. For larger loading angles (θ) the CFE values can be considered almost equal. Using structure HX-00 (conventional tube) as reference, and regardless of the value, all BTWS showed an improvement in the CFE parameter from 2.85% to 86%.

The highest CFE value of 0.84 was computed for structure HX-01 at θ = 5°. However, this structure did not have the highest CFE performance for the other loading angles. Thus, since it is important to get a functional structure no matter the loading angle, structure HX-04 exhibited an acceptable CFE behavior for all θ values. This structure achieved an average CFE of 0.75. Compared with the average CFE for the conventional tube (HX-00), this represented an improvement of 25% in CFE. Thus, the effectiveness of the armadillo-bioinspired tube (HX-04) is confirmed. This BTWS, which is characterized by a main circular shape surrounded by irregular pentagons, is highly recommended for the control of axial and oblique loads up to 15°. Given the importance of quasi-static analysis in the field of crashworthiness – since it allows capturing the main collapsing behavior of the structures [25] – the bioinspired structure HX-04 could serve as a valuable tool for engineers and designers in the initial crashworthiness design of passive energy absorption systems in the automobile industry, such as crash boxes.

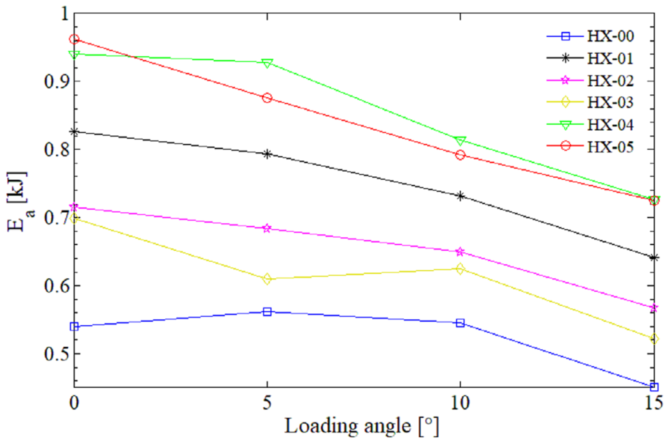


Figure 11. Energy absorption for HX-00 and BTWS at different θ values

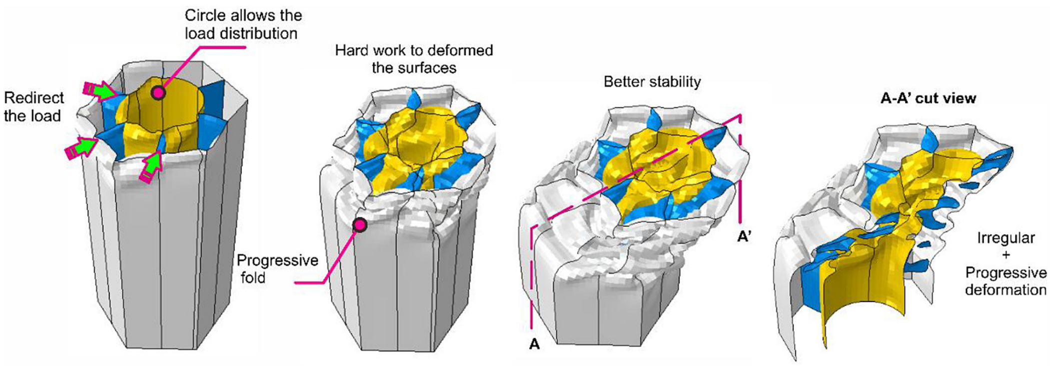


Figure 12. Mechanism of energy absorption of structure HX-04, case of θ = 10°

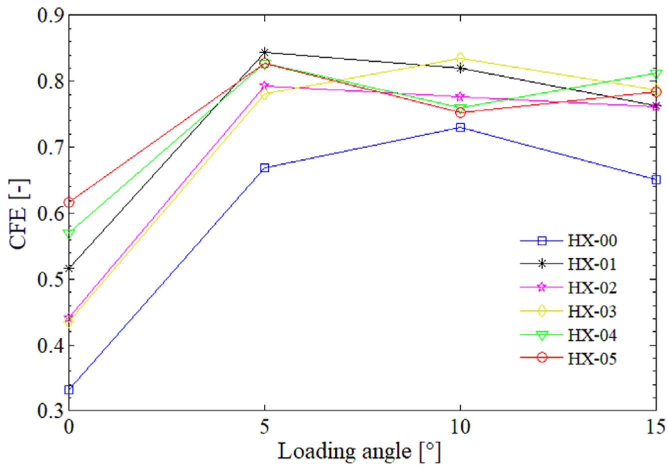


Figure 13. Crush force efficiency for HX-00 and BTWS at different θ values

CONCLUSIONS

In this article, a successful numerical analysis to evaluate the crashworthiness performance of armadillo-bioinspired tubes (BTWS) under axial and oblique loads was performed. For this purpose, five BTWS based on the pectoral tiles patten of the armadillo's shell were proposed. The structures were evaluated and loaded at angles θ of 0°, 5°, 10° and 15°. Finalizing the analysis, we list the following findings.

1. Quasi-static analysis provides valuable insights for evaluating and characterizing the energy absorption mechanism and

deformation modes of structures, since they are performed under controlled conditions. This type of analysis is particularly useful in the early stages of crashworthiness design, as it enables the prediction of structural response trends under crashing scenarios (i.e. the preliminary response).
2. Regardless of the type of structure and considering that all structures have the same mass, both the conventional and bioinspired structures exhibited a decrease in peak load (Pmax) as the loading angle increased. In this sense, comparing the axial condition with the highest oblique load condition (15°), the Pmax decreased, in an range from 40.66% to 58.65%.
3. The effectiveness of the armadillos-bioinspired tubes respect to the conventional structure (HX-00) was confirmed. In this sense, regardless of the loading angle, the BTWS presented better load carrying capacity at the beginning (Pmax) and during the crushing process (Pm). An improvement within a range of 2% to 78% was obtained for the BTWS.
4. Respect to energy absorption (Ea), a downward trend in this parameter was observed as the loading angle (θ) increases. In this case, a reduction from 4% to 12% was computed. However, the bioinspired tubes presented an enhancement of this parameter of up to 78% respect to the HX-00 structure. The highest Ea performance was computed for BTWS HX-05 with 0.96 kJ when loaded at 0°.
5. Considering all load angle conditions, the best energy absorption performance was obtained for BTWS HX-04, where an average of 0.85 kJ was calculated.
6. Respect to the CFE indicator, as θ increased, an improvement of CFE was computed for both conventional and BTWS. Significant changes of CFE were visible when transitioning from 0° to 5°. With respect to HX-00, BTWS exhibited an improvement of CFE from 2.85% to 86%. Considering all load angle conditions, structure HX-04 presented the best CFE performance with an average of 0.74.
7. The best CFE average performance was computed for BTWS HX-04, which has a cross-section formed by a central circle surrounded by irregular pentagons. In this way, this BTWS is highly recommended to counter the harmful effects of axial and oblique loads up to 15°. Thus, this cross-section could be used as a starting point for engineers and designers when designing automobile components with high crashworthy properties, e.g. crash boxes.
8. Finally, although HX-04 presents a complex geometry is possible to obtaining it by an extrusion process, considering cost profitability for mass production and quality in the surface finish respect to others manufacturing process. In this sense, from the manufacturing point of view the bioinspired tube (HX-04) is feasible and reliable.

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