Crash box design had been developed to increase crashwortiness performance. The crash box cross section is one important parameter to increase the energy absorption as crashwortiness performance. In the previous study, hexagonal cross section provide the higher energy absorption than other cross section. One of strategy to increase cross section is using two cross section put together in one component of crash box design. Bi-tubular crash box shows higher energy absorption with easy manufacture opportunity. In other study, hybrid crash box is investigated to reduce crash box mass. In this study, development of bi-hexagonal hybrid crash box subjected to axial loading to enhance crashworthiness were investigated. Analysis of crash box design is developed by using computer simulation with ANSYS Workbench 19.2. The crash box materials used are Aluminum Alloy and carbon-epoxy woven. The material modeling in the crash box is assumed as deformable body while the impactor is a rigid body. The axial loading is modelled by setting impactor impact the crash box with a speed of 7.67 m/s. Fixed support is set on the bottom of crash box. Nine of frontal test models were simulated for the bi-hexagonal hybrid crash box with different layups orientation angle and composite hexagonal tube diameter. Energy absorption and deformation patterns were observed. The results indicated that the highest energy absorption and specific energy absorption is occured on the A60 model with layups orientation angle of [0/60/0/60] and composite hexagonal tube diameter of 41 mm are 3693.8 J and 19.121 kJ/kg. The deformation pattern in the aluminum part is diamond mode, while in the composite part, the deformation pattern produce transverse shearing, lamina bending, brittle fracturing and local buckling mode

Keywords: Bi-hexagonal hybrid crash box, energy absorption, deformation pattern, axial loading

UDC 331
DOI: 10.15587/1729-4061.2023.273847

DEVELOPMENT OF BI-HEXAGONAL HYBRID CRASH BOX SUBJECTED TO AXIAL LOADING FOR ENHANCEMENT OF CRASHWORTHINESS

Moch Agus Choiron
Corresponding author
Doctor of Engineering, Professor
Department of Mechanical Engineering*
E-mail: agus_choiron@ub.ac.id
Delia Hani Wakhidah
Graduate Student
Department of Mechanical Engineering*
Nurchajat
Associate Professor
Department of Mechanical Engineering
State Polytechnic of Malang
Soekarno Hatta str., 9, Kota Malang, Indonesia, 65141
*Brawijaya University
MT Haryono str., 167, Malang, Indonesia, 65145

*Received date 15.12.2022
Accepted date 17.02.2023
Published date 28.02.2023*

How to Cite: *Choiron, M. A., Wakhidah, D. H., Nurchajat (2023). Development of Bi-hexagonal hybrid crash box subjected to axial loading for enhancement of crashworthiness. Eastern-European Journal of Enterprise Technologies, 1 (1 (121)), 51–57. doi: https://doi.org/10.15587/1729-4061.2023.273847*

1. Introduction

The crash box is a thin-wall structure that is mounted at the frontal area of the vehicle. As a passive safety system in a vehicle, this crash box structure is expected to be capable of absorbing kinetic energy in frontal crash, in maintaining the vehicle deceleration in safe limit, and for minimizing the chance of injury on the vehicle's passenger during collision. The study area of crash box structure involves several aspects and approaches, but mostly focuses on the crashworthiness performance. For lightweight vehicle purpose, many lightweight alternatives to metal have been studied to fulfill mass reduction of vehicle component.

Vehicle accidents can be classified into 3 types of collisions, namely frontal, oblique and roll over directions where 64 % of the average accidents occur in the frontal direction [1]. To reduce the effects of accidents, especially on the safety of drivers, various designs of safety devices have been developed, both passive and active models. One of the passive safety system designs for vehicles is the crash box, which is a thin-walled structure that is placed between the main structure and the bumper of the vehicle [2]. The impact energy due to the collision absorbed by the crash box serves to absorb the impact energy due to the collision by converting it into deformation thus to prevent greater deformation of the entire front frame of the vehicle [3]. The study area of crash box structure involves several aspects and approaches, but mostly focus on the crashworthiness performance. Various crash box designs that have been developed include circle, rectangle, square, hexagonal, octagonal, and elliptical crash boxes to increase crashworthiness performance [4]. It was found that the hexagonal profile was a better design for energy absorption application. The hexagonal crash box has a high SEA and can be encouraged as further research by adding foam [5], multi-cell configuration design [6] and honeycomb filler [7]. For lightweight vehicle purpose, many lightweight alternatives to metal have been studied to fulfill mass reduction of vehicle component. Composites are one of material choice for crash box design due to strength to weight ratio advantage. Research on crash box made of composites due to frontal loading showed that the energy absorption of carbon fiber reinforced plastic was 3327.93 J and the specific energy absorption rate was 37.82 J/g. These values are higher than the aluminum crash box with 1797.65 J of energy absorption and 15.5 of specific energy absorption [8]. Based on these studies, it can be concluded that carbon fiber as a crash box material has promising prospects as a crash absorber structure in the future. The next trend is the use of metal and composite materials in a crash box design, also known as a hybrid crash box. The combination of metal and composite material can provide good alternative solution with different crushing behaviour mechanism. To increase cross section, it can be design by using two cross sections put together in one component of crash box design. Study on bi-tubular crash box shows higher energy absorption and the design can be produced with easy manufacture. Therefore, study on development of bi-hexagonal hybrid crash box is important as one design choice to increase crashworthiness.

2. Literature review and problem statement

The objective of crash box design is to maximize the energy absorption and minimize the mass. The initial crash box designs are circle, rectangle, square, and hexagonal cross section. Due it excellent of crashworthiness performance, hexagonal cross section had been developed [9]. The hexagonal section can absorb more energy than a triangular or square section with the same mass and may be a better choice for an energy absorber. Hexagonal multi-cell crash box have been developed to improve the crashworthiness [10]. This experimental, theoretical, and computational study on the mean crushing strength of hexagonal multi-cell crash box shows folding pattern have a regular shape and random folding pattern may occur. In other study, simple and multi-cell thin-walled tubes with various geometrics were investigated [11]. The hexagonal multi-cell crash box proved to be the best design for higher specific energy absorption. However, there are still many problems to be solved, it is not clear that how the crush mechanism of crash box design when it transforms from a single-cell to a multi-cell crash box.

Quasi static and drop test testing has been carried out through experiments to find the cross-section shape which produces the greatest energy absorption [12]. From the experimental results, it can be denoted that crash box absorb more energy in drop test testing than quasi static testing. The specific energy absorption for circular tube is higher than square and rectangular tubes. Another load model with axial and oblique loadings is applied on several CFRP tapered tubes with various cross-sectional profiles and various tapered angles [13]. This study shows that energy absorption of all models decreased with increasing impact angle in various degree due to their changes in overall deformation mode. Bi-tubular crash box has been investigated by using quasi static loading [14]. The result showed that bi-tubular corrugated tube structure produces 71 % energy absorption capacity increment compared to ordinary corrugated tube structure. The bi-tubular crash box design makes a substantial contribution to the energy absorption increment with easy to manufacture advantages. The axial crushing characteristics of double circular composite tubes exposed to drop mass impact loading conditions was investigated [15]. All the tested tube samples produce a constant and progressive crushing process. The 4-layer carbon fabric tube has superior energy absorption features than the traditional single circular sections. However, bi-hexagonal crash box with different material has not yet obtained. Hybrid crash box have been developed with light mass and optimum energy absorption capability by using different material. Study on hybrid tubes had more energy absorption capability in comparison with the aluminum tubes on the similar cross section [16]. The challenge of this study was value of SEA not too far between hybrid structures and the aluminum tubes. Therefore, it is necessary to investigate bi-hexagonal hybrid crash box to find the best design. All previous research points to the fact that it is important to continue the study of hybrid crash box design development. In order to fully understand crashworthiness performance, observing deformation patterns and energy absorption values will be carried out.

3. The aim and objectives of the study

The aim of the study is to investigate bi-hexagonal hybrid crash box to find the best design through computer simulations.

To achieve this aim, the following objectives are accomplished:

– to find the highest energy absorption on bi-hexagonal hybrid crash with variations on the composite tube diameter and layups orientation angle;

– to observe deformation patterns on bi-hexagonal hybrid crash with variations on the composite tube diameter and layups orientation angle.

4. Materials and methods

The object of this study is hybrid crash box design development with geometry modeling was carrying out using Design Modeler and for composite modeling using ANSYS Composite PrePost (ACP). The test geometry modeling consists of impactor and bi-hexagonal hybrid crash box as shown in Fig. 1.

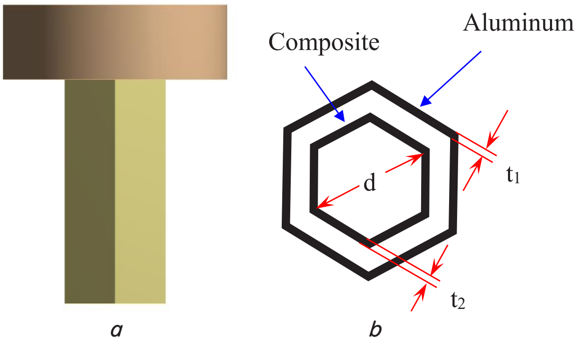


Fig. 1. Bi-hexagonal hybrid crash box geometry modelling: *a* — isometric view; *b* — cross section and geometry size

The method used to solve the problem in this study is to perform an computer simulation of bi-hexagonal hybrid crash box using ANSYS Workbench Release 19.2. The fiber orientation angle and composite tube diameter were set as parameter design with varied by 3 levels for each design parameter. Computer simulations were carried out on nine models with variations in the diameter of the composite tube and the angle of layups orientation as shown in Table 1. Notation A indicating a crash box with a composite tube diameter of 41 mm, then notation B showing a crash box with a composite tube diameter of 50 mm, and the notation C indicating a crash box with a composite tube diameter of 59 mm. For the notation the number behind the letter represents the angle of the orientation of the composite layups. Deformation pattern, energy absorption, total mass, and SEA in each model were observed.

Table 1

Variation of bi-hexagonal hybrid crash box model

Model	Model Symbol	Composite Tube Diameter (mm)	Layups orientation angle
1	A45	41	[0/45/0/45]
2	A60	41	[0/60/0/60]
3	A90	41	[0/90/0/90]
4	B45	50	[0/45/0/45]
5	B60	50	[0/60/0/60]
6	B90	50	[0/90/0/90]
7	C45	59	[0/45/0/45]
8	C60	59	[0/60/0/60]
9	C90	59	[0/90/0/90]

The controlled variables in this research are:

a) the impactor speed is 7.67 m/s;

b) the crash box materials used are Aluminum Alloy and carbon-epoxy woven;

c) crash box height is 150 mm.

This study uses the drop testing modeling method. The material modeling in the crash box is assumed as flexible or deformable body while the impactor is assumed as rigid body. The impactor impact the crash box with a speed of 7.67 m/s in the negative y-direction. The bottom of the crash box is defined as fixed support. The gravity acceleration is 9.81 m/s^2 in a direction parallel to the impactor velocity. The boundary conditions and loading model is shown in Fig. 2.

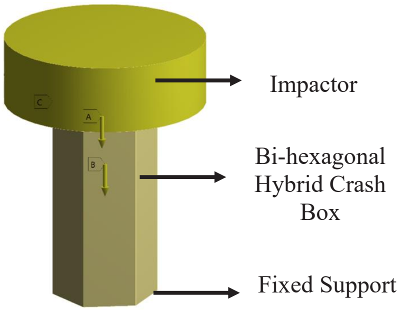


Fig. 2. Modeling of boundary conditions and loading composite crash box

The crash box material used Composite GG200 carbon-epoxy woven refers to the previous study [17]. This type of material is Prepegs (Pre-Impregnated Layers). Each laminate consists of 4 laminae, each of which is 0.2 mm thick.

5. Result of Computer Simulation

5. 1. Energy absorption on bi-hexagonal hybrid crash

From computer simulations that have been carried out on nine bi-hexagonal hybrid crash box models with variations in the diameter of the composite tube and the angle of orientation of the layups, it is shown in Table 2.

Table 2

Simulation result data

Model	Total Deformation	$EA_{composite}$	$EA_{Aluminum}$	EA_{total}	Total Mass	SEA
	mm	J	J	J	kg	J/kg
A45	96.332	282.38	3222.9	3505.3	0.193177	18.146
A60	96.324	283.63	3410.2	3693.8	0.193177	19.121
A90	96.319	238.85	2749.8	2988.7	0.193177	15.471
B45	96.325	297.04	2707.1	3004.1	0.198153	15.161
B60	96.321	298.07	2816.7	3114.8	0.198153	15.719
B90	96.299	311.68	2974.7	3286.4	0.198153	16.585
C45	96.291	361.88	3261.9	3623.8	0.203128	17.840
C60	96.3	377.69	2823.8	3201.5	0.203128	15.761
C90	96.288	395.59	3073.5	3469.1	0.203128	17.078

The simulation results of total deformation, energy absorption (EA), total mass and specific energy absorption (SEA) on each model. From Table 2, the highest energy absorption is found in the A60 model with a total energy absorption value of 3693.8 J and the lowest is in the A90 model with a total energy absorption value of 2988.7 J. The highest SEA value is found in the A60 model with 19.121 J/kg and the lowest SEA value is found in the B45 model with 15.161 kJ/kg. The SEA value is influenced by the energy absorption value and the total mass of the crash box based on the equation:

$$SEA = \frac{E_{abs}}{m},$$

where SEA is specific energy absorption (J/kg), E_{abs} is energy absorption (J) and m is mass (kg). The A60 model has the highest SEA because the crash box has the largest energy absorption value with the smallest mass compared to other models.

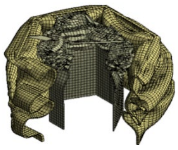
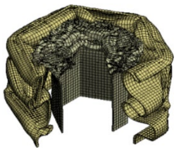
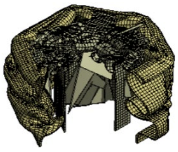
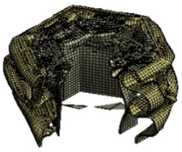
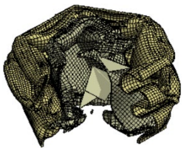
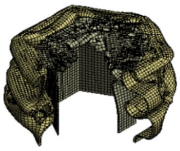
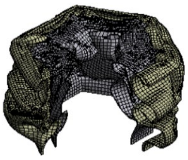
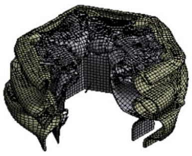
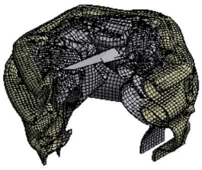
5. 2. Deformation patterns on bi-hexagonal hybrid crash

In this research, the crash box made of hybrid which is composed of composite and aluminium turns out to have different deformation patterns in each model. The deformation pattern data for each model is shown in Table 3. In Aluminum crash box, the deformation pattern can be concertina, diamond or mixed. Meanwhile, in the crash box made from composites, the deformation patterns can be transverse shearing, lamina bending, brittle fracturing and local buckling. The difference in the deformation pattern due to the characteristics of the Aluminum and composite are different. The Aluminum characteristic is ductile, while composites have characteristics stiff and brittle.

For crash box with hybrid materials, the total energy absorption connected with the deformation pattern in the form of folds or fractures. From Table 3, it can be seen that the tendency of the folds formed on the outer tube made of Aluminum is diamond mode which is characterized by the formation of asymmetrical folds with angles. The deformation pattern in the inner tube made of composite can affect the value of energy absorption in the hybrid crash box.

Table 3

Deformation Pattern of Models

Model	Deformation Pattern	Aluminum Deformation	Composite Deformation
A45		Diamond	Local buckling, Brittle fracturing
A60		Diamond	Transverse shearing, Local buckling
A90		Diamond	Brittle fracturing
B45		Diamond	Local buckling, Brittle fracturing
B60		Diamond	Lamina bending, Brittle fracturing
B90		Diamond	Transverse shearing, Local buckling
C45		Diamond	Lamina bending, Local buckling, Transverse shearing
C60		Diamond	Lamina bending, Local buckling
C90		Diamond	Lamina bending, Brittle fracturing

From the nine tested models, all of them have different failure modes with their own characteristics. The deformation pattern on the crash box with an inner tube diameter of 41 mm tends to have local buckling which does not affect the outer tube folding. The crash box with an inner tube diameter of 50 mm tends to experience local buckling accompanied by lamina bending. The composite fragments fill the outer tube fold therefore it can interfere with the folding pattern on the Aluminum side. The crash box with an inner tube diameter of 59 mm tends to experience lamina bending due to deformation disturbed by the folding of the outer tube. Comparative study is done for A60 and A90 models with higher and lower of energy absorption value. Fig. 3, 4 shows the different deformation patterns of the A60 and A90 models.

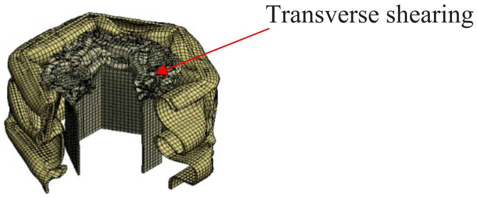


Fig. 3. Deformation patterns on A60 model

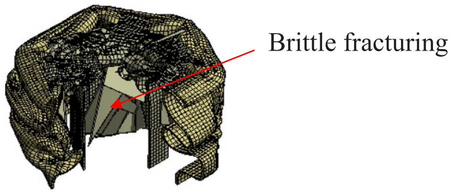


Fig. 4. Deformation patterns on A90 model

Fig. 5, 6 show the normal stress distribution on the A60 (highest EA) and A90 (lowest EA) models.

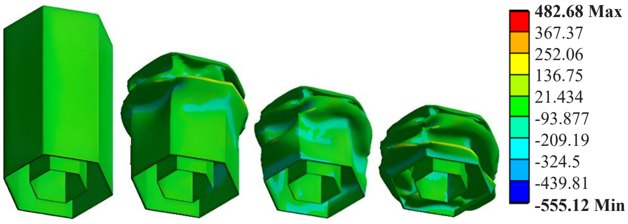


Fig. 5. Normal stress distribution of A60 model during deformation

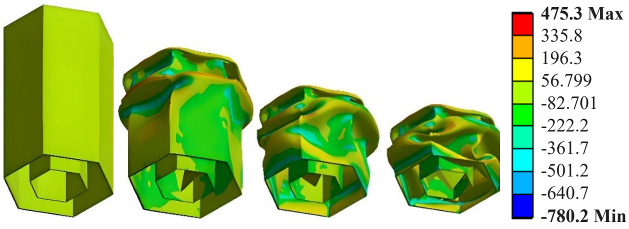


Fig. 6. Normal stress distribution of A90 model during deformation

Fig. 7, 8 show a graphic diagram of the force-displacement on A60 and A90 model.

Moreover, the ability to absorb energy depends on the distribution of the effective stress during deformation process of the crash box. Fig. 9 shows the value of effective stress on the A60 and A90 models.

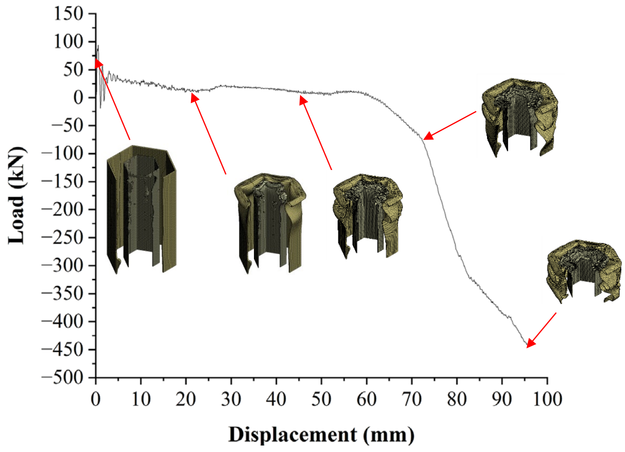


Fig. 7. Force-displacement diagram on the A60 model

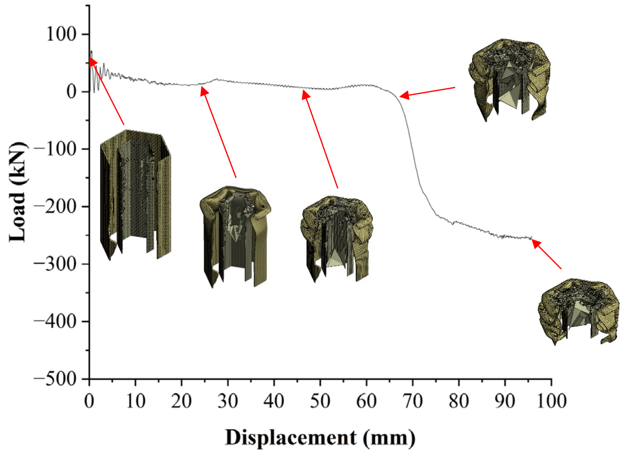
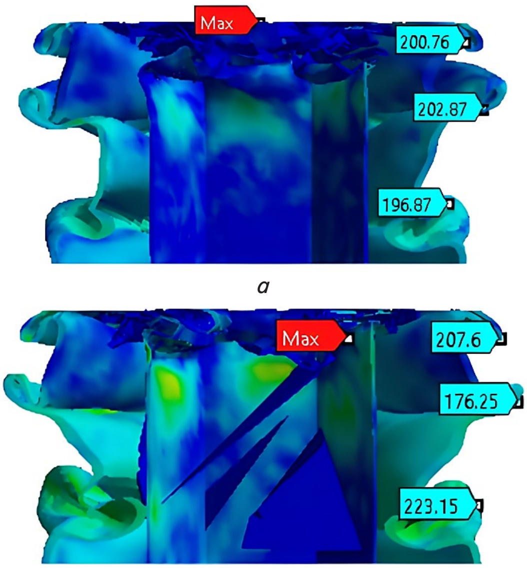


Fig. 8. Force-displacement diagram on the A90 model



a

b

Fig. 9. Effective stress distribution on cross section: *a* — A60 model; *b* — A90 model

The value of effective stress is captured using the probe utilities menu at several observation points in the area around folding on both models.

6. Discussion of computer simulation

Crash box absorbs impact energy into plastic deformation at the time of collision. The energy in the crash box is converted from kinetic energy into strain energy by the occurrence of plastic deformation. It indicates that when a collision occurs, the crash box will receive kinetic energy then it is converted into strain energy in the form of energy absorption. The amount of energy absorption is a parameter that is used to determine the crashworthiness of a crash box. Energy absorption is expressed as area under load-displacement diagrams. The larger the area under the load-displacement diagram, then the value of energy absorption is also getting bigger.

Based on Fig. 3, the A60 model is deformed with neat folding conditions with transverse shearing, and local buckling deformation, in which the transverse shearing mode has the high efficiency. While in the A90 model (Fig. 4), the deformation pattern tends to be brittle fracturing with the composite is broken into large pieces. This is due to the fact that the brittle fracturing mode led to lower energy absorption capacity. The largest energy absorption occurs in the crash box with an inner tube diameter of 41 mm. This condition is occurred due to the inner tube made of composite deforms without being affected by the deformation of the outer tube. There is no contact yet and both tubes are getting deformed separately. This condition refers in the previous study that interaction between the two tubes effect on absorbed energy [18].

Normal stress distribution in the direction of loading can affect the final condition of the deformed crash box, whether it is symmetrical or not. Symmetry conditions are certainly expected, therefore it is necessary to know the stress distribution in the deformed model. Based on Fig. 5, 6, it is seen that the normal stress distribution in the A60 model is still fairly even, therefore final deformation is symmetrical which is marked by the formation of folds in one line. The A90 model shows that there is a random stress distribution, therefore the final deformation formed is not symmetrical. In addition, the maximum normal stress on the A60 model is much higher than the A90 model. This can affect the amount of energy absorbed by the crash box.

The deformation pattern in the crash box is also influenced by the reaction force during deformation. In the Fig. 7, 8, the force reaction graph decreases on the A60 model which is steeper because the failure pattern is larger than the previous displacement range in the A90 model. There is significant reduction in load carrying capacity can be observed in A90 model, which is due to the changes in the failure patterns. This is also related to the normal stress distribution, which displacement of 75 mm there is a random normal stress distribution that affects the value of the force reaction. From Fig. 9, it can be shown that the effective stress in the A60 model has more evenly distributed about 200 MPa if compared to the effective stress in the A90 model. The effective stress distribution on the A90 model is not evenly, causing the reaction force be lower than the A60 model which has an effective stress distribution on a wider area.

It can be stated that the A60 model has shown to be of good potential as an energy absorber candidate for crashworthiness application to reduce serious injuries to the passenger of the vehicle. To further investigate the deformation pattern at different impact velocities, comparative analysis is carried out under different impact velocities and wall thickness to fulfill the crashworthiness requirements. In the next study, the results of computer simulations must be verified with experimental results to ensure that the developed model can be used as a design reference for further model development such as design optimization. Limitation of this model did not represent the delamination mechanisms due to the interlaminar damage initiation properties of the composite material were not defined yet. The interlaminar damage evolution properties can be defined based on a power law fracture criterion [19].

7. Conclusions

1. The highest energy absorption and the specific energy absorption occurs in the bi-hexagonal hybrid crash box model is the A60 model (layups orientation angle of [0/60/0/60] and composite hexagonal tube diameter of 41 mm) with EA of 3693.8 J and 19.121 kJ/kg.
2. The deformation pattern in the bi-hexagonal hybrid crash box due to the frontal test method, the deformation pattern on the aluminum section is only diamond, while in the composite section, the deformation pattern produce transverse shearing, lamina bending, brittle fracturing and local buckling.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed with financial support from Engineering Faculty, Brawijaya University, Malang, Indonesia.

Data availability

All data are available in the main text of the manuscript.

Acknowledgements (upon request)

This study was supported by Professor Accelerated Grant from Engineering Faculty, Brawijaya University, Malang, Indonesia. We also thank Design and System Engineering laboratory, Mechanical Engineering Department, Brawijaya University for providing ANSYS Research license.

References

1. Kokkula, S., Langseth, M., Hopperstad, O. S., Lademo, O. G. (2006). Behaviour of an automotive bumper beam-longitudinal system at 40 % offset impact: An experimental and numerical study. Latin American Journal of Solids and Structures, 3, 59–73. Available at: https://www.lajss.org/index.php/LAJSS/article/view/90/84
2. Ma, J. (2011). Thin-walled Tubes with Pre-folded Origami Patterns as Energy Absorption Devices. University of Oxford, 212. Available at: https://eng.ox.ac.uk/media/8615/ma.pdf
3. Jandaghi Shahi, V., Marzbanrad, J. (2012). Analytical and experimental studies on quasi-static axial crush behavior of thin-walled tailor-made aluminum tubes. Thin-Walled Structures, 60, 24–37. doi: https://doi.org/10.1016/j.tws.2012.05.015
4. Tarlochan, F., Samer, F., Hamouda, A. M. S., Ramesh, S., Khalid, K. (2013). Design of thin wall structures for energy absorption applications: Enhancement of crashworthiness due to axial and oblique impact forces. Thin-Walled Structures, 71, 7–17. doi: https://doi.org/10.1016/j.tws.2013.04.003
5. Choiron, M. A. (2020). Analysis of multi-cell hexagonal crash box design with foam filled under frontal load model. Journal of Physics: Conference Series, 1446 (1), 012022. doi: https://doi.org/10.1088/1742-6596/1446/1/012022
6. Qiu, N., Gao, Y., Fang, J., Feng, Z., Sun, G., Li, Q. (2016). Theoretical prediction and optimization of multi-cell hexagonal tubes under axial crashing. Thin-Walled Structures, 102, 111–121. doi: https://doi.org/10.1016/j.tws.2016.01.023
7. Choiron, M. A. (2020). Characteristics of deformation pattern and energy absorption in honeycomb filler crash box due to frontal load and oblique load test. Eastern-European Journal of Enterprise Technologies, 2 (7 (104)), 6–11. doi: https://doi.org/10.15587/1729-4061.2020.200020
8. Zhu, G., Sun, G., Yu, H., Li, S., Li, Q. (2018). Energy absorption of metal, composite and metal/composite hybrid structures under oblique crushing loading. International Journal of Mechanical Sciences, 135, 458–483. doi: https://doi.org/10.1016/j.ijmecsci.2017.11.017
9. Alavi Nia, A., Parsapour, M. (2014). Comparative analysis of energy absorption capacity of simple and multi-cell thin-walled tubes with triangular, square, hexagonal and octagonal sections. Thin-Walled Structures, 74, 155–165. doi: https://doi.org/10.1016/j.tws.2013.10.005
10. Bai, Z., Guo, H., Jiang, B., Zhu, F., Cao, L. (2014). A study on the mean crushing strength of hexagonal multi-cell thin-walled structures. Thin-Walled Structures, 80, 38–45. doi: https://doi.org/10.1016/j.tws.2014.02.024
11. Vimal Kannan, I., Rajkumar, R. (2019). Deformation and energy absorption analysis of simple and multi-cell thin-walled tubes under quasi-static axial crushing. International Journal of Crashworthiness, 25 (2), 121–130. doi: https://doi.org/10.1080/13588265.2018.1542956
12. Velmurugan, R., Muralikannan, R. (2009). Energy Absorption Characteristics of Annealed Steel Tubes of Various Cross Sections in Static and Dynamic Loading. Latin American Journal of Solid and Structures, 6 (4), 385–412. Available at: https://www.lajss.org/index.php/LAJSS/article/view/232/202

13. Zhao, X., Zhu, G., Zhou, C., Yu, Q. (2019). Crashworthiness analysis and design of composite tapered tubes under multiple load cases. Composite Structures, 222, 110920. doi: https://doi.org/10.1016/j.compstruct.2019.110920
14. Choirotin, I., Choiron, M. A., Purnowidodo, A., Darmadi, D. B. (2021). Deformation Mode and Energy Absorption Analysis of Bi-Tubular Corrugated Crash Box Structure. International Journal of Integrated Engineering, 13 (7), 274–280. Available at: https://publisher.uthm.edu.my/ojs/index.php/ijie/article/view/7928
15. Praveen Kumar, A., Nageswara Rao, D. (2021). Crushing characteristics of double circular composite tube structures subjected to axial impact loading. Materials Today: Proceedings, 47, 5923–5927. doi: https://doi.org/10.1016/j.matpr.2021.04.465
16. Boria, S., Scattina, A., Belingardi, G. (2018). Axial Crushing of Metal-Composite Hybrid Tubes: Experimental Analysis. Procedia Structural Integrity, 8, 102–117. doi: https://doi.org/10.1016/j.prostr.2017.12.012
17. Obradovic, J., Boria, S., Belingardi, G. (2012). Lightweight design and crash analysis of composite frontal impact energy absorbing structures. Composite Structures, 94 (2), 423–430. doi: https://doi.org/10.1016/j.compstruct.2011.08.005
18. Sharifi, S., Shakeri, M., Fakhari, H. E., Bodaghi, M. (2015). Experimental investigation of bitubal circular energy absorbers under quasi-static axial load. Thin-Walled Structures, 89, 42–53. doi: https://doi.org/10.1016/j.tws.2014.12.008
19. Esnaola, A., Elguezabal, B., Aurrekoetxea, J., Gallego, I., Ulacia, I. (2016). Optimization of the semi-hexagonal geometry of a composite crush structure by finite element analysis. Composites Part B: Engineering, 93, 56–66. doi: https://doi.org/10.1016/j.compositesb.2016.03.002