INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 16 No. 2 (2024) 182-194
https://publisher.uthm.edu.my/ojs/index.php/ijie

Crashworthiness Performance of Circular Hybrid Crash Box Due to Axial Load

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DOI: https://doi.org/10.30880/ijie.2024.16.02.019

Article Info

Received: 15 January 2024
Accepted: 21 April 2024
Available online: 30 May 2024

Keywords

Energy absorption, deformation mechanism, hybrid, composite-metal

Abstract

In the previous study, hybrid crash box combines low-density and high strength of composite materials with aluminum materials had been developed. In this study, circular hybrid crash box with friction model is investigated. Crash box design is modelled by using computer simulation with ANSYS workbench. Composite carbon toray T300 – epoxy resin (CCE) and metal aluminum alloy 6063 (AA6063) is used as hybrid crash box material. Axial loading with a speed of 10 m/s is applied to circular hybrid crash box model by using impactor with mass of 100 kg. The orientation angle of composite lay-up and hybrid material configuration with two models of friction was running as 16 models. Energy absorption and deformation pattern were observed to determine crashworthiness performance. Based on the results, it can be denoted that the Al-Ko45 with friction model of 0.68 shows largest energy absorption of 7.53 kJ with specific energy absorption of 32.552 kJ/kg. The deformation pattern produces mixed mode with progressive crushing folding that can enhance energy absorption.

1. Introduction

Crash box is the one of passive safety devices which absorb collision energy. It can reduce the kinetic energy of collision which transmitted to passenger [1]. Many researchers did some research to enhance the crashworthiness performance through energy absorption ability and deformation pattern on crash box. Some of them varied the crash box geometry and material selection. In terms of crash box geometry, circular crash boxes can absorb more specific energy compared to other geometrical shapes [2].

More recently, an alternative in achieving a lightweight design of crash box, metal material is replaced by composite. Although most composites showed slightly plastic characteristics, well-designed to absorb more specific energy compared with conventional metals [3]. However, composites easily collapse because of cracking, fracture, debonding and delamination matrix-fiber [4]. As a result of that, composites experience catastrophic failure which causes a reduction in energy absorption capability [5]. Therefore, use of metal, such as aluminum, is still being considered to generate progressive failure through plastic behavior. Further, by using hybrid material, unstable failure of composite can be changed to progressive failure. Composite guided by aluminum through plastic deformation. Composite also deforms into fragments, which has potency as foam filled. This development can improve crashworthiness performance along with energy absorption value enhancement [6]. Besides that, to ensure crash box crashworthiness during loading, stable deformation mode must be guaranteed during the crushing [7]. To predict material behavior, knowing the mechanical properties is necessary. Research related to the mechanical properties of composite showed that fiber orientation angle has more effect on the mechanical properties than the number of layers and resin type [8]. Furthermore, based on previous study, different fiber orientation angles showed different tensile strength values on composites [9].

Material combination as a crash box material, such as composite and aluminum alloy, can be used to enhance crashworthiness performance, along with energy absorption enhancement by progressive failure [10]. Controlled failure by progressive crushing may result in fiber rupture and delamination of the composite material, both of which can influence the stiffness of the absorber during impact. Hybrid structure, which is composed of carbon composite and aluminum, projected as the one of alternative crash box material. Circular hybrid crash box combines low density-high strength material with low cost. Thus, it can absorb more energy. Previous study utilized hibiscus natural fiber and AA6063 as a crash box material. The result showed this combination can enhance crashworthiness performance [11]. Besides that, HOCT configuration (composite tube outside AA6063 tube) has higher energy absorption value than HICT configuration (composite tube inside AA6063 tube). However, another research showed different results. AL-CF configuration (carbon T300/epoxy composite inside AA6061-O tube) crash box has the highest energy absorption value [10] [12]. On hybrid crash box, surface condition between metal tube and composite tube able to affect energy absorption ability. Li did research to find out the effect of aluminum surface, which was treated, to energy absorption ability on hybrid crash box [13]. Surface treatment enhanced interfacial bonding connection. The result showed that there is an increasing energy absorption along with interfacial bonding connection enhancement. Another researcher did research to find out the friction coefficient value on aluminum which has contact with carbon fiber/epoxy composite [14]. The result showed the initial friction coefficient value is estimated at 0.23. After experiencing wear and tear between carbon fiber composite and aluminum, the friction coefficient value reached its peak in 0.68. The epoxy of composite is softened and sticks to the aluminum surface and the friction corresponds to the so-called stick and slip process. The stick-slip behavior occurred when the friction force was high.

According to the explanation, circular hybrid crash box provides good lightweight and crashworthiness performance. For promoting wide application of circular hybrid crash box, the goal of this study is to develop suitable numerical models for exploring energy absorption and deformation mechanisms of hybrid crash box. In this research, AA6063 and T300 carbon/epoxy composites were used as crash box material. Composite made from carbon fibers showed a required degradation mechanism and high specific deformation energy, compared to glass or polypropylene fibers [15]. The effect of fiber orientation angle on composite, hybrid material configuration, and interface connection between composite tube and AA6063, will be analyzed by using computer simulation, to diminish trial and error for prototype production. Besides that, this research was conducted to find out the stress distribution and force vector cause deformation pattern through finite element method (FEM) [16]. FEM was used to predict the causal relation between the geometric and material on the loading [17].

2. Research Method

This research was conducted by using computer simulation based finite element method software. Hybrid crash box designed by using circular cross-section. In this research, the outside diameter of both model configuration of circular hybrid crash box is designed to be 60 mm. The thickness of both tubes, aluminum tube and composite tube, is 2 mm. Circular hybrid crash boxes are 150 mm in length. In this research, crash box material using AA6063 and T300 carbon/epoxy composite, material properties are presented in Table 1.

Crash box models were tested by using axial loading. The simulation domain will be meshed, and the boundary condition is defined. Several boundary conditions such as loading, material properties and geometry as the important aspect should be monitored [18]. In this research, the weight and the velocity impactor are 100 kg and 10 m/s, respectively. Those weight and velocity based on previous study [19]. Figure 1 shows loading models and boundary condition that were used in this research.

The research was conducted to obtain circular hybrid crash box design with the highest specific energy absorption value. The effect of fiber orientation angle on composite, the hybrid material configuration, and interface connection between aluminum tube and composite tube, researched further. The composite fiber angle orientation that used in this research were $[0/90]_5$, $[15/-75]_5$, $[30/-60]_5$, $[45/-45]_5$, as shown at Figure 2. The material configuration hybrid crash box, divided into 2 configurations, namely the metal tube outside (Al-Ko) and the metal tube inside (Ko-Al), as shown in Figure 3. Besides that, the interface connection between AA6063 and composite was varied. Those variations are 0 friction connection and friction connection 0.68. Furthermore, model coding on each variation is shown at Table 2.

Table 1 *Properties material of hybrid crash box*

Data Properties	AA6063	T300 carbon/epoxy composites
Density (kg/m^3)	2700	
UTS (MPa)	189	1490
Yield Stress (MPa)	160	
Modulus of Elasticity (GPa)	58	x 120 y 120 z 8.2
Poisson Ratio	0.33	xy 0.42 yz 0.3 xz 0.3
Shear Modulus (GPa)		xy 4.45 yz 2.91 xz 2.91
Shear Strength (GPa)		xy 0.084 yz 0.032 xz 0.032
Tensile Strength (GPa)		x 1.82 y 1.82 z 0.076
Compressive Strength (GPa)		x -1.47 y-1.47 z -0.2397

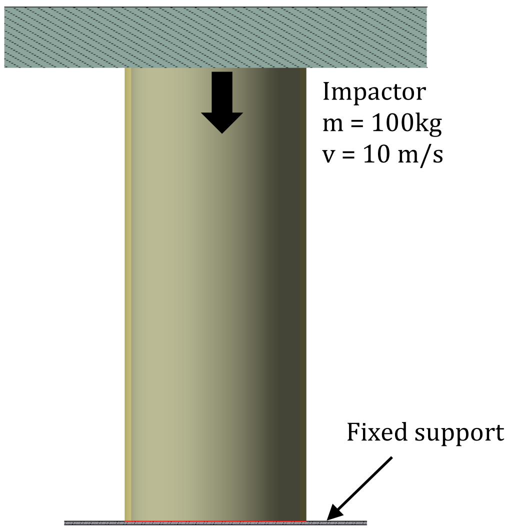


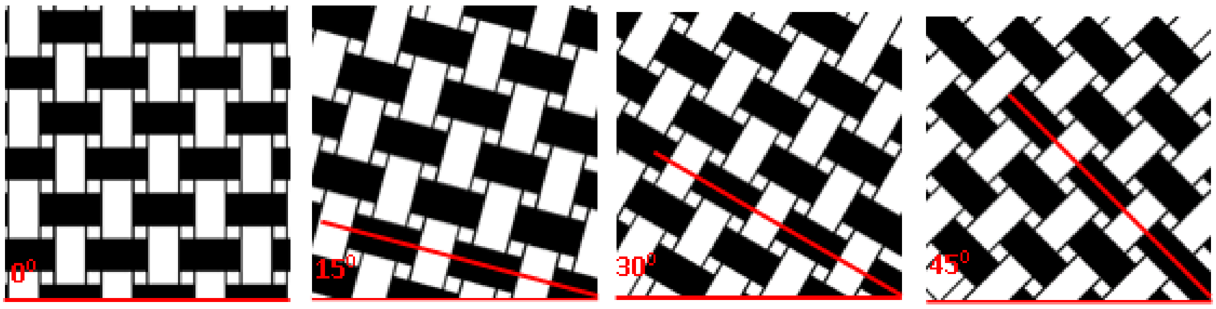
Fig. 1 *Loading and boundary condition*

Variations of interface connection, modelled by using friction coefficient value. Based on previous study, the maximum friction coefficient value between aluminum tube and carbon/epoxy composite is 0.68 [14]. This assumption indicates that there is surface roughness and causes interfacial bonding connection between tube surfaces. The enhancement of interfacial bonding can make the two tubes with different material as a one unity, so the energy absorption enhances [13]. Besides that, the friction coefficient of 0, which means that the surface is bonded without friction, is used for comparation.

Numerical simulations are performed with an explicit finite element LS-Dyna. The element type which is used is quadrilateral with size 2 mm as shown in Figure 4. In common use of crash simulation, the quadrilateral mesh type has advantages in terms of efficiency in manufacturing the number of elements and also reduce connection geometry [20]. This element type has a lumped mass matrix as required by the explicit calculation scheme and is suitable for the large deformations which occur in the folding process. To capture the details of folding process, 2 mm of mesh is chosen after calculation with different element dimensions. This size is obtained with acceptable calculation time and accuracy. Crash boxes absorb collision energy through plastic deformation. Loading response on specific displacement formed force-displacement curve, as shown at Fig 4. Usually, to evaluate the crash box crashworthiness, the amount of total energy which absorbed by crash box during collision, was used. The amount of absorbed energy obtained from the area under the force-displacement curve. Energy absorption can be calculated by using equation 1.

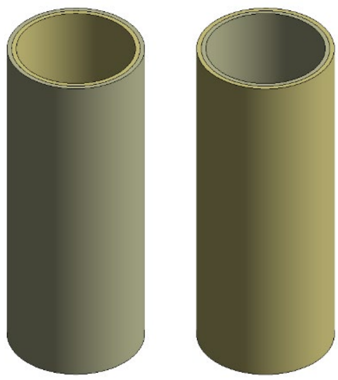
$$EA = \int_0^{\delta_1} P(\delta)\, d\delta \tag{1}$$

where, W is energy (J), EA is energy absorption (kJ), P is load (kN) and δ is deformation length (mm).



(a) (b) (c) (d)

Fig. 2 *Variations in the orientation of woven carbon fiber (a) [0/90]; (b) [15/-75]; (c) [30/-60]; (d) [45/-45]*



(a) (b)

Fig. 3 *Hybrid materials configuration (a) Al-Ko model; (b) Ko-Al model*

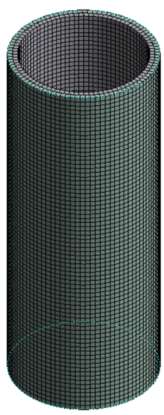


Fig. 4 *Mesh*

Table 2 *Circular hybrid crash box design variation*

No	Model	Interface Connection	Material Configuration	Fiber Orientation Angle
1	Al-Ko0fric0	Friction 0	Al-Ko	$[0/90]_5$
2	Al-Ko15fric0			$[15/-75]_5$
3	Al-Ko30fric0			$[30/-60]_5$
4	Al-Ko45fric0			$[45/-45]_5$
5	Ko-Al0fric0		Ko-Al	$[0/90]_5$
6	Ko-Al15fric0			$[15/-75]_5$
7	Ko-Al30fric0			$[30/-60]_5$
8	Ko-Al45fric0			$[45/-45]_5$
9	Al-Ko0fric0,68	Friction 0,68	Al-Ko	$[0/90]_5$
10	Al-Ko15fric0,68			$[15/-75]_5$
11	Al-Ko30fric0,68			$[30/-60]_5$
12	Al-Ko45fric0,68			$[45/-45]_5$
13	Ko-Al0fric0,68		Ko-Al	$[0/90]_5$
14	Ko-Al15fric0,68			$[15/-75]_5$
15	Ko-Al30fric0,68			$[30/-60]_5$
16	Ko-Al45fric0,68			$[45/-45]_5$

The other important indicator on crashworthiness performance evaluation is specific energy absorption (SEA) [21]. SEA represents the amount of absorbed energy to the weight of the crash box. This determines crashworthiness performance because of changes in the weight of the crash box, specifically in this research, the use of hybrid materials with different configuration. The amount of SEA can be calculated by using equation 2.

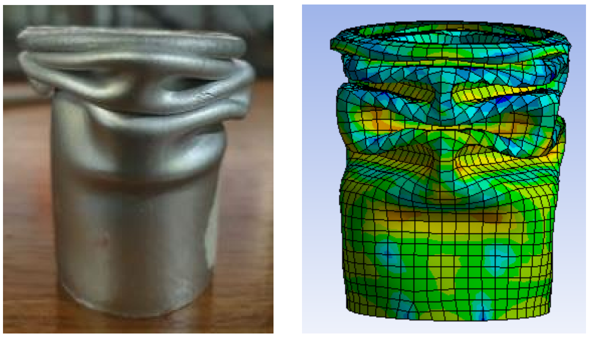
$$SEA=\frac{\int_0^{\delta} P(\delta)\, d\delta}{m}=\frac{EA}{m} \tag{2}$$

where, SEA is specific energy absorption (kJ/kg) and m is crash box mass (kg).

3. Result and Discussion

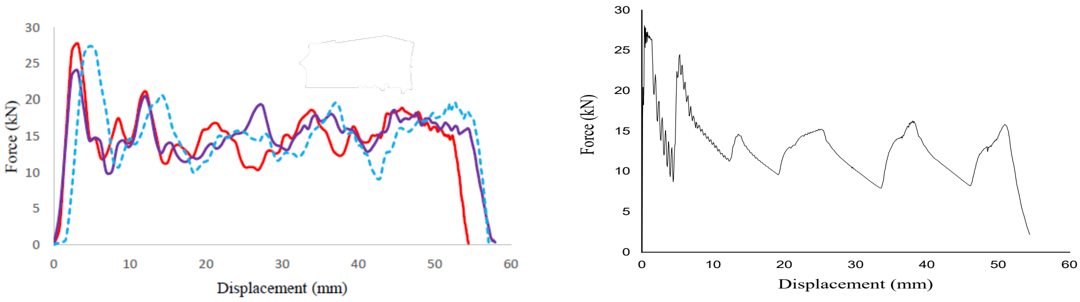
The simulation was performed in numerical simulation using ANSYS Workbench. Verification in research aims to find out the comparison of the results of the FEM software simulation process with the experimental results displayed with error values. Figure 5 shows a comparation of the deformation pattern between experimental and result by the dropped impact testing. The force-displacement curve of comparation is shown in Figure 6. Result of validation is shown in Table 3.

From the result validation obtained a small error value, so the FEM software set-up can apply for the research. The simulation test was carried out to determine the effect of orientation angle of composite lay-up, hybrid material configuration interface connection. The test obtains force-displacement curve as response to loading. Figure 7 and Figure 8 represent the response of reaction force response to loading as shown on force-displacement curve. This response consists of initial phase and secondary phase. The initial phase included the response before failure occurred at the peak load known as initial peak crushing force. Then, it was continued with changes occurring through plastic failure in the crash box wall until the formation of the first folds faced outward and inward in line with the response in the increases and decreases of the force-displacement curve. The following phase consisted of the fold formation with constant wavelength along the length of the model. Meanwhile, there are 2 modes of composite failure that can be evaluated on force-displacement curve, such as catastrophic failure and progressive failure. The force-displacement curve of catastrophic failure was indicated by a sudden increase in load to the peak value, followed by extreme load dropping after failure. On progressive failure, the absorbed energy is constant and greater than catastrophic failure.



(a) (b)

Fig. 5 *The deformation pattern (a) Experimental; (b) Simulation*



(a) (b)

Fig. 6 *The Force-displacement curve (a) Experimental trend; (b) Simulation*

Table 3 *The validation result*

No	Parameters	Experimental	Simulation	Error (%)
1	Peak crushing force (kN)	27.79	28.11	1.15
2	Energy Absorption (J)	804	806	0.25
3	Specific Energy Absorption (J/kg)	25.93	26	0.27

Based on the previous study, the failure behavior of composite tube is dominated by fracture, lay-up delamination and cracking [22] [23]. Meanwhile, progressive folding as a form of plastic deformation, occurs on aluminum tube [12]. Progressive folding generates loading response oscillation around the mean value. Progressive crushing is a controlled process in which energy is absorbed through the gradual collapse of the material or structure, rather than sudden and catastrophic failure. The goal is to dissipate the energy from an impact, such as a collision, in a way that minimizes the risk of injury to occupants or damage to valuable contents. Figure 4 shows the force-displacement curve and deformation pattern for each loading stage in the Al-Ko15fric0 model. It was noted that at the first stage of crushing, load response increased rapidly until the initial peak crushing force. Until the initial peak crushing force, the hybrid crash box only experiences elastic deformation and no damage occurred. When displacement was 2-100 mm, plastic deformation began to occur in the aluminum tube. The aluminum tube was deformed from the top, forming a first fold followed by subsequent folds and it formed concertina deformation pattern. The deformation at the top was caused by stress concentration starting at the top of the crash box. Through computer simulation test, stress concentration and force vector can be observed on every stage. The initial stage of failure in the composite tube with the fiber orientation direction $[15^0, -75^0]$ occurred stress concentration at the top of the composite tube. The stress concentration caused fractures and long cracks. It generated deformation in the form of splaying and fragmentation. Splaying in the form of folds resulted from long cracks which bent towards the inside of the tube, thereby reducing crushing force [10]. Crushing force dropping causes a reduction in energy absorption.

Extremely dropping in force-displacement curve followed by progressive crushing folding on aluminum tube is important indication.

In the Al-Ko45 crash box model, friction 0.68 produced a force-displacement curve with a deformation pattern at each loading stage as shown in Fig. 5. From fig 5, on the initial stage of crushing, stress distribution occurs on the upper and lower tubes until it reaches the initial crushing force point. At this stage, crash box experiences plastic deformation without deformation failure. Once the displacement reaches 5 mm, the crash box collapses causing the crushing force to drop, and the aluminum tube forms the first fold in concertina mode. On the lower tube, followed by failure of the composite tube. There is opposite direction of the impactor load because of the deformation which begins in the lower tube. This phenomenon can be seen in Figure 8 where the load reaction drops below 0, the crash box experiences negative force reaction, after displacement reaches 10 mm. Furthermore, this phenomenon is shown in Figure 9. When the tube reaches 5 mm displacement, the direction of force vector in the same direction as the impactor direction. Otherwise, the direction of force vector opposite to direction of impactor when the tube reaches 10 mm displacement.

The composite tube undergoes local buckling deformation and forms folds which fill the metal folding. In the next stage, the effect of composite tube reinforcement is maintained until the final stage of loading. The reinforcement effect happens because the composite tube was progressively deformed. In the other side, the fragmentation of composite tube, because of composite tube deformation, works like foam-filled which fills the inside of the aluminum tube which can improve energy absorption [6]. The foam filling can be used as a structural reinforcement to provide a high load capacity with minimal axial collapse [4]. Besides that, hybrid model also has similar characteristic with multi-cell model which consists of more than 1 tube. The addition of a multi-cell box has an important effect on increasing energy absorption performance [24]. The amount of energy absorption of each model due to frontal load can be seen in Table 4.

Crash boxes absorb collision energy due to axial load. The collision energy converted into strain energy in the form of deformation. Deformation pattern is the result of strain energy conversion. Energy absorption (EA) and specific energy absorption (SEA) are important parameters to evaluate crashworthiness. Crash boxes are considered to have good crashworthiness performance when the SEA is high [25]. Table 4 showed 16 crash box models test results. The value of energy absorption was calculated based on the area under the force-displacement curve. The energy absorption value increased in the model provided with an interface connection with a friction coefficient value of 0.68. The condition of the tube surface affected the bond between materials, thereby increasing interface interactions which could increase the ability to absorb energy [13].

Table 4 *The result of crash box simulation*

No	Model	Total Mass (kg)	EA (kJ)	SEA (kJ/kg)
1	Al-Ko0fric0	0.231	5.385	23.279
2	Al-Ko15fric0	0.231	5.118	22.125
3	Al-Ko30fric0	0.231	6.052	26.165
4	Al-Ko45fric0	0.231	7.263	31.398
5	Ko-Al0fric0	0.227	6.172	27.220
6	Ko-Al15fric0	0.227	5.659	24.955
7	Ko-Al30fric0	0.227	6.293	27.752
8	Ko-Al45fric0	0.227	6.305	27.803
9	Al-Ko0fric0,68	0.231	6.313	27.293
10	Al-Ko15fric0,68	0.231	5.961	25.769
11	Al-Ko30fric0,68	0.231	5.503	23.791
12	Al-Ko45fric0,68	0.231	7.530	32.552
13	Ko-Al0fric0,68	0.227	5.265	23.218
14	Ko-Al15fric0,68	0.227	5.094	22.462
15	Ko-Al30fric0,68	0.227	5.940	26.198
16	Ko-Al45fric0,68	0.227	5.941	26.200

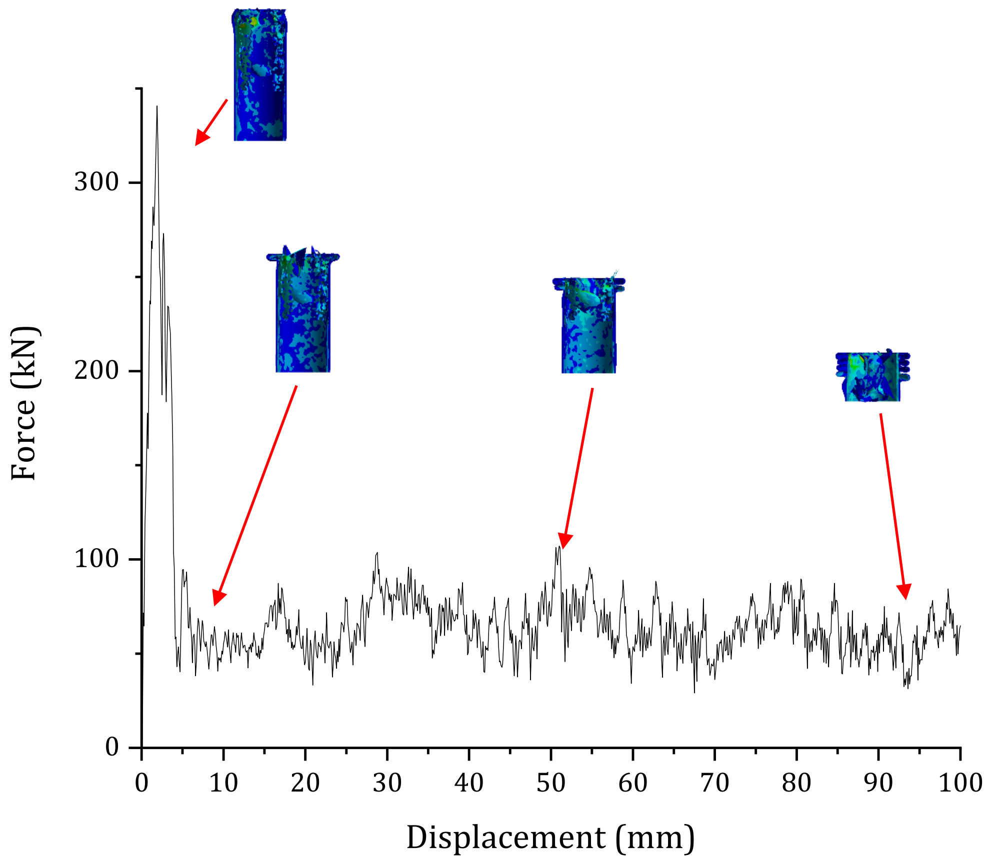


Fig. 7 *Al-Ko15fric0 force-displacement curve and deformation pattern*

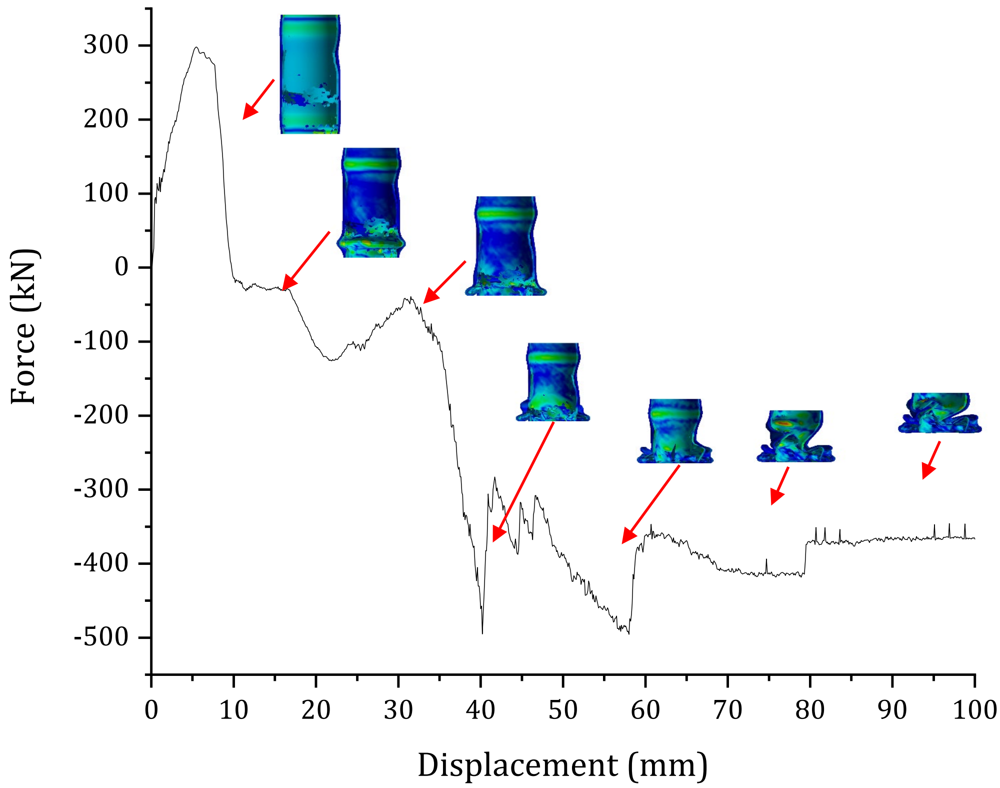
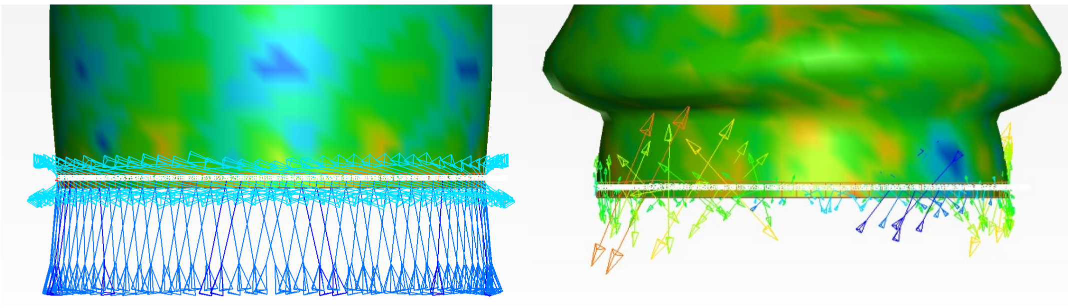


Fig. 8 *Al-Ko45fric0,68 force-displacement curve and deformation pattern*



(a) (b)

Fig. 9 *Force vector direction on Al-Ko45fric0,68 model (a) displacement = 5 mm; (b) displacement = 10 mm*

From Table 1, the energy absorption values of 16 models were obtained. The largest specific energy absorption occurred in the Al-Ko45 friction 0.68 hybrid crash box model with a SEA (specific energy absorption) value of 32.552 kJ/kg. The higher the specific energy absorption value is, the higher the efficiency of material use and the potential for great light weight will be [26]. The energy absorption (EA) value in this model was also the highest compared to other crash box models, namely 7.53 kJ. By observing the force-displacement curve in Figure 7, the AlKo45 friction 0.68 model experienced an increase in the final stage of loading. It increased the energy absorption capacity. The circular hybrid crash box model with interface connection friction 0 absorbed less energy compared to the circular hybrid crash box model with interface connection friction 0.68. The model with the smallest SEA value was Al-Ko15 friction 0 model. The SEA value of this model was 22.125 kJ/kg.

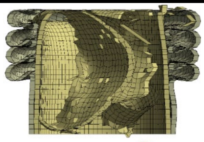
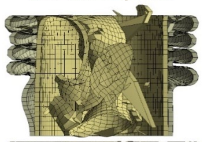
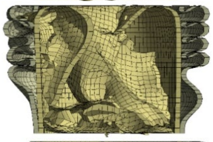
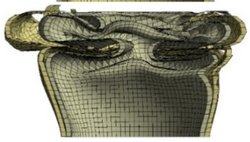
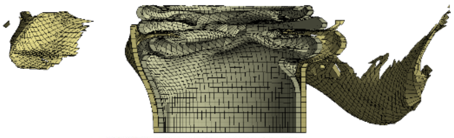
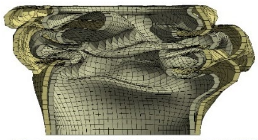
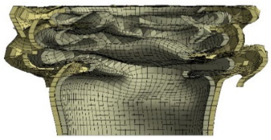
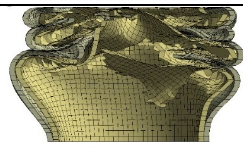
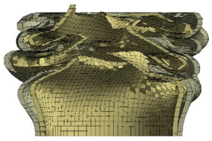
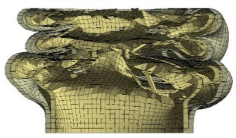
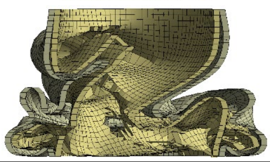
Table 5 showed the deformation pattern on 16 circular hybrid crash box models. In the crash box model with interface friction 0, most of the composite tubes experienced splaying with large fractures. Splaying, known as lamina bending, is deformation pattern with large fragments which bend to inward or outward. Splaying cause catastrophic failure so the force-displacement curve drops extremely [27]. Furthermore, composite tube and aluminum tube on most of the crash box model with interface friction 0, experiences delamination resulting in reduced ability to absorb energy. On the final stage of failure only the aluminum tube experienced the load, while the composite tube no longer contributed to resistance to compressive loads [28]. In addition, the folded condition of the aluminum tube is empty, containing no folds or fragments of composite. This happens because of the lack of interfacial bonding connection between aluminum tube and composite tube. However, Al-Ko45fric0 has the highest energy absorption value, among the model with 0 friction, because both of tubes deformed together to resist the load.

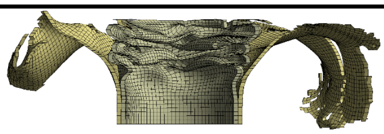
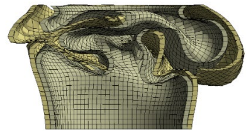
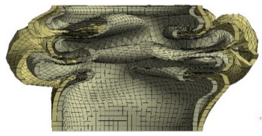
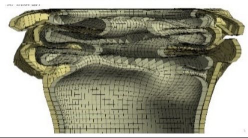
On circular hybrid crash box's model with interface connection friction 0.68, aluminum tube deformed plastically. Most of the models experience progressive crushing folding. This folding formed because of composite deformation filled the aluminum folding. The reinforcement effect by the composite tube is maintained during the failure process. This leads to energy absorption enhancement [29].

4. Conclusion

The effect of adding composite tube inside aluminum circular hybrid crash box denotes the improvement of energy absorption ability. Furthermore, interface connection also enhances the ability to absorb energy on hybrid crash box, because it can make the two tubes with different properties, as one unity. Besides that, by using interface connection, the composite tube inside the aluminum tube gives reinforcement effect. Viewed from the angle of carbon fiber perspective, the fiber orientation angle also affects the ability to absorb energy on hybrid crash box. Carbon fiber angle of $[45/-45]_5$ has the highest energy absorption value for all condition and configuration, along with the enhancement of specific energy absorption value. Furthermore, the majority of Al-Ko configurations have the highest energy absorption values, along with the enhancement of specific energy absorption value. Finally, Al-Ko45 with 0.68 as a friction coefficient between AA6063 tube and composite tube model, has the highest energy absorption and specific energy absorption are 7.530 kJ and 32.552 kJ/kg, respectively. Otherwise, Al-Ko15 with 0 as a friction coefficient between AA6063 tube and composite tube model, has the lowest specific energy absorption of 22.125 kJ/kg, respectively.

Table 3 *Deformation pattern on each model*

No	Interface Connection	Model	Deformation Pattern
1	Friction 0	AlKo0	
2		AlKo15	
3		AlKo30	
4		AlKo45	
5		KoAl0	
6		KoAl15	
7		KoAl30	
8		KoAl45	
9	Friction 0.68	AlKo0	
10		AlKo15	
11		AlKo30	
12		AlKo45	

No	Interface Connection	Model	Deformation Pattern
13		KoAl0	
14		KoAl15	
15		KoAl30	
16		KoAl45	

Acknowledgement

This paper was supported by the research grant of PMDSU program, Ditjen Diktiristek. Many thanks to member of Design and System Engineering Laboratory, Composite Laboratory, Manufacturing Process Laboratory, Brawijaya University, and all related parties who contribute this study.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design****: Delia Hani Wakhidah, Moch. Agus Choiron, Anindito Purnowidodo, Yudy Surya Irawan;* ***data collection****: Delia Hani Wakhidah;* ***analysis and interpretation of results****: Delia Hani Wakhidah, Moch. Agus Choiron;* ***draft manuscript preparation****: Delia Hani Wakhidah, Moch. Agus Choiron,* ***review and supervision****: Moch. Agus Choiron. All authors reviewed the results and approved the final version of the manuscript.*

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