ENERGY ABSORPTION AND DEFORMATION PATTERN OF CIRCULAR HYBRID CRASH BOX SUBJECTED TO FRONTAL LOAD

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Crashworthiness is related to the ability of a structure to reduce the effects of a collision risk of injury to passengers and the risk of damage to vital parts of the vehicle. Geometry design of crash box is one important parameter to increase crashworthiness performance by increasing energy absorption through progressive deformation. In previous studies, circular crash box absorbed higher energy than other geometry design. Besides that, another parameter is material design. In other studies, the hybrid model absorbs more energy with a less increasing mass. Hybrid crash box combine low-density and high-strength of composite materials with aluminium materials are affordable and ductile to increase energy absorption. This study aims to develop circular hybrid crash box by variating fibre orientation angle of composite and hybrid material configuration. Crash box design is investigated by using computer simulation with ANSYS Workbench. The crash box materials used are Carbon Toray T300 – Epoxy Resin (CCE) and Aluminium Alloy 6063 (AA6063). Eight of circular hybrid crash box models subjected to axial loading with a speed of 10 m/s. The frontal loading is modelled by setting impactor with mass of 100 kg. Energy absorption and deformation pattern were observed. The results showed that the Al-Ko45 model with orientation angle $[45/-45,-45/45]_5$ and hybrid material configuration of composite inside has highest energy absorption of 8.24 kJ. The deformation pattern in the aluminium part is mixed of concertina at the first stage then continued by diamond pattern, The deformation composite part is dominated by local buckling with transverse shearing. The fractions or folds of composite is functions like foam-filled filling folds of aluminium deformation to initiate progressive crushing folding that can increase the crashworthiness characteristic as the energy absorption.

KEYWORDS

Deformation pattern, energy absorption, hybrid, metal, composite

INTRODUCTION

Crash box is thin-walled structure placed between the bumper and the frame at the front of the vehicle [1]. As crashworthy system, crash box is expected to deform and absorb kinetic energy generated during a crash to prevent the occupants from serious injury [2]. The factors that affect the energy absorption characteristics include the geometry of the structure, the material used and the loading conditions [3]. The majority of accidents occur in the frontal direction by 70% [4].

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 circular, rectangle, square, triangle, hexagonal, hourglass, and conical crash boxes to increase crashworthiness performance. The result showed the circular cross-sectional shape is considered to have good performance energy absorption capability [5] [6]. In previous study on metal tubes with a circular cross section, the energy absorption in aluminium tube, mild-steel tube and stainless-steel tube were observed. Aluminium alloy material was chosen as the material with optimal energy absorption [7]. Lightweight design has become one of most important means to improve fuel efficiency to reduction of fuel consumption. Composite material is one of material choice due to excellent strength and stiffness to weight ratio [8]. Composite made from carbon fibre showed a required degradation mechanism and high specific deformation energy, compared to glass or polypropylene fibres [9]. Composite materials applied to crashworthy structures with circular cross sections. The results of the study revealed that composites with carbon material had the highest SEA capability [10]. However, composite has several disadvantages, as catastrophic failure and high production cost [11]. Composite yield unstable failure when subjected to impact loading [12]. In order to ensure reliability during crushing, stable deformation mode should be guaranteed. Controlled failure by progressive crushing may result in fibre rupture and delamination of the composite material, both of which can influence the stiffness of the absorber during impact [13]. For effective alternative, hybrid crash box is introduced which combines the low-density and high-strength of composite materials with low cost and high plasticity of aluminium.

In this regard, using the circular cross-sectional shape of the hybrid crash box model, development research is needed to study the failure mechanisms in the crash box structure by selecting materials that have better energy absorption capabilities in previous and engineering composite materials to ensure they affect the mechanical properties leading to on energy absorption. The selected metal materials are AA6063 and CCE. The modelling method is applied to the analysis the effect of composite fibre orientation and hybrid material configuration by computer simulation based on the finite element method. The simulation method is used to determine the stress distribution plot and to find out in more detail the deformation pattern in the structure at stage during loading which causes failure.

METHOD

The research was carried out in a simulation using ANSYS software with the LS-Dyna sub-program. The modelling consists of 3 main structures namely crash box, impactor and fixed support as shown in Fig 1. The crash box is assumed to be a flexible body which can be deformed while the impactor and fixed support is assumed to be a rigid body. AA6063 material designed in the Mechanical Model sub-program and models with CCE material designed in the ACP (Pre) sub-program. The test was carried out with a 100 kg impactor load at a speed of 10 m/s as the previous experimental test [14]. The gravity acceleration is 9.81 m/s2 in a direction parallel to the impactor velocity.

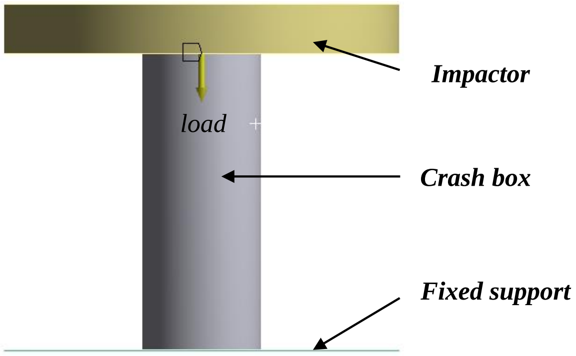


Fig. 1 Crash box load modelling

In the simulation, the deformation experienced by the crash box is set at 100 mm which shows 70% deformations of total length [15]. Deformation changes the crash box shape and crash box will shorten due to structural failure in response to load. The circular hybrid crash box geometry modelling is shown in Fig 2. The test geometry modelling was using the Design Modeler. The tube outside diameter is 60 mm with length is 150 mm.

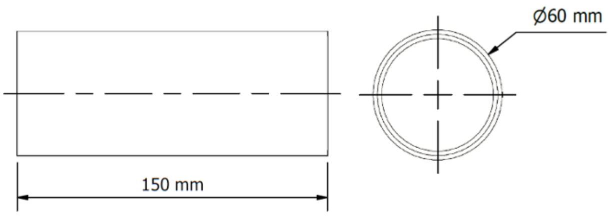


Fig. 2 Crash box geometry modelling

The fibre orientation angle of composite and the configuration of the hybrid material were set as parameter design. The direction of fibre orientation composite affects energy absorption value following the tendency of the material properties such as tensile strength, bending and impact [16]. In another study, the direction of fibre orientation affects the value of the Elastic Modulus and Shear Modulus of composite materials [17]. These mechanical properties produce the stress concentration in the early stages of failure. Variations in the configuration of the hybrid material were chosen as a further development by analysing the deformation patterns. Deformation pattern is relevant to the results of energy absorption. The material configuration chosen was based on considerations from previous studies conducted by Zhu and Wirawan [18] [19]. The crash box material used CCE woven and AA6063. The properties material of CCE refers to the factory material data[20]. Composite laminates consist of 5 paired laminae, each of laminae is 0.2 mm thick.

Computer simulations were carried out on eight models with variations in the orientation angle of composite fibres and the configuration of the hybrid material as shown in Table 1. Notation Al-Ko indicating a hybrid model with an aluminium tube on the outside and composite on the inside, then notation Ko-Al showing a hybrid crash box with an aluminium tube on the inside and composite on the outside. For the notation the number behind the letter represents the angle of the orientation of the composite layups [0/90, 90/0]$_5$, [15/-75,-15/75]$_5$, [30/-60,-30/60]$_5$, [45/-45, -45/45]$_5$. Deformation pattern, energy absorption, total mass, and SEA in each model were observed.

Tabel 1
Variation of hybrid crash box

Model	Code	Orientation angle	Outer diameter (mm)	
			Aluminium	Composite
Single tube	Al		60	
	Ko	[0/90,90/0]$_5$		60
Hybrid tube	Al-Ko090	[0/90,90/0]$_5$	60	56
	Al-Ko15	[15/-75,-15/75]$_5$		
	Al-Ko30	[30/-60,-30/60]$_5$		
	Al-Ko45	[45/-45,-45/45]$_5$		
	Ko-Al090	[0/90,90/0]$_5$	56	60
	Ko-Al15	[15/-75,-15/75]$_5$		
	Ko-Al30	[30/-60,-30/60]$_5$		
	Ko-Al45	[45/-45,-45/45]$_5$		

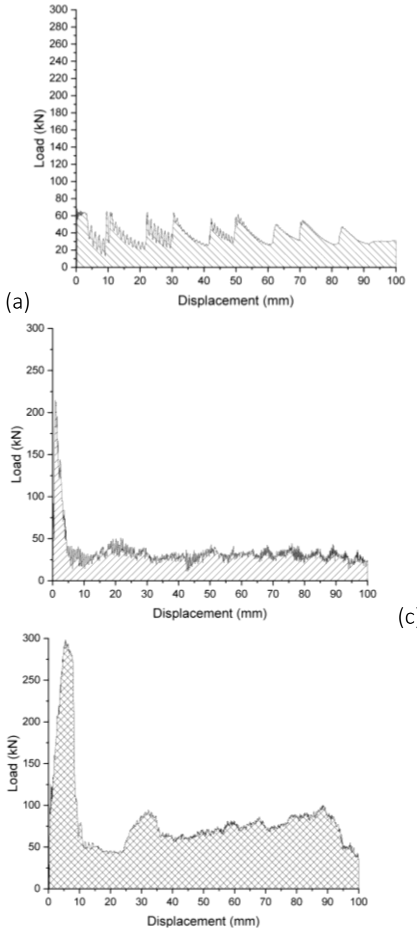
RESEARCH RESUT AND DISCUSSION

3.1 Result of Computer Simulation

3.1.1Energy Absorption of Hybrid Crash Box

Energy absorption shows the ability of a crash box to absorb crash energy into strain energy through plastic deformation. The amount of energy absorption is one of the crashworthiness parameters of crash box structure. Strain energy is obtained through the area under the load-displacement curve as a reaction carried out by the crash box in receiving the load given by the impactor. The load-displacement curves of the circular single tube aluminium crash box, circular single tube composite crash box and circular hybrid crash box (Al-Ko45) models can be seen in Fig 3.

Fig 3 shows a comparison of the curves area of the single tube and hybrid tube. The area of the in the hybrid crash box model is larger compared the load-displacement curve of single tube aluminium tube and single tube composite crash box models. This condition indicates the value of energy absorption is greater in the hybrid crash box model. This condition refers in the previous study [18]



(a) (b) (c)

Fig 3. Area Under Load-Displacement Curve In Crash Box (A) Single Tube Aluminium (B) Single Tube Composite (C) Hybrid Tube (Al-Ko45)

Computer simulations using ANSYS software were carried out on 2 single tubes models and 8 hybrid crash box models with variations in the configuration of the hybrid material arrangement and the fibre orientation of composite. The simulation data obtained as shown in Table 2. Simulation results contains peak crushing force (PCF), mean load (P_{mean}), energy absorption (EA) and specific energy absorption (SEA) on the deformation distance of 100 mm.

Table 2
Simulation result data of *Circular Hybrid Crash Box*

Models	Total Mass (kg)	PCF (kN)	P_{mean} (kN)	EA (kJ)	SEA (kJ/kg)
Al	0.147	68,56	37,11	3,75	25,49
Ko	0.084	166.80	29.20	2,92	34,80
Al-Ko090	0.231	297.62	73.97	7.40	32.04
Al-Ko15		340.50	76.24	7.63	33.02
Al-Ko30		294.70	49.44	4.95	21.41
Al-Ko45		298.88	82.25	8.24	35.68
Ko-Al090	0.227	186.34	64.59	6.46	28.47
Ko-Al15		324.18	49.78	4.98	21.95
Ko-Al30		305.23	23.33	2.34	10.29
Ko-Al45		222.47	64.42	6.45	28.40

From Table 2., the energy absorption values of the 8 models are obtained. The Al-Ko45 hybrid crash box model absorbed the greatest energy with an EA of 8.24 kJ. This condition indicates an increase the energy absorption 2 times greater than single tube aluminium of 3.75 kJ in the previous experiment. Hybrid model made of metal and composite materials increase large energy absorption with less mass. Even the highest energy absorption value in this study was 25% greater when compared to the highest energy absorption value in the previous study on the same hybrid model of 6.05 kJ [18]. The Ko-Al30 hybrid crash box model absorbed the least energy with an EA value of 2.34 kJ.

The greatest energy absorption in the Al-Ko45 model is supported by the highest P_{mean} value in the same model, which is 82.25 kN. This condition was in good agreement with previous study that a higher P_{mean} relate to more energy absorption[21]. Conversely, the smallest P_{mean} in the Ko-Al30 model of 23.33 kJ, means the ability to absorb energy is less.

Specific energy absorption (SEA) is used to evaluate the energy absorption capability of the crash box per unit mass. The higher the SEA value on the crash box, the higher the mass efficiency of energy absorption. The Al-Ko45 hybrid crash box model has highest SEA of 35.68 kJ/kg. The Al-Ko45 model has the highest SEA because the crash box has the largest energy absorption value compared to other models.

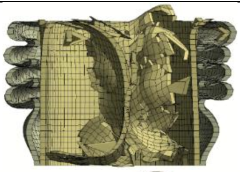
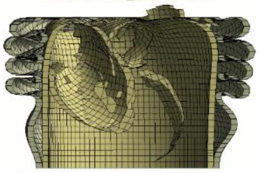
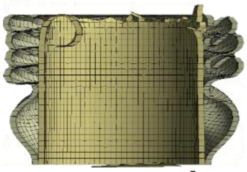
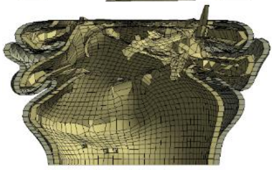
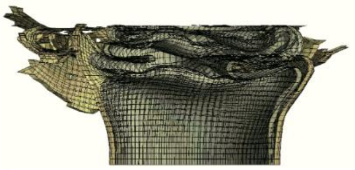
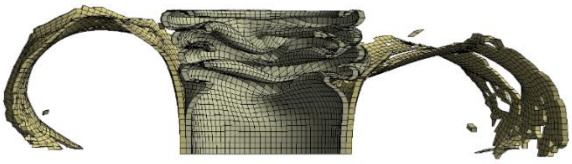
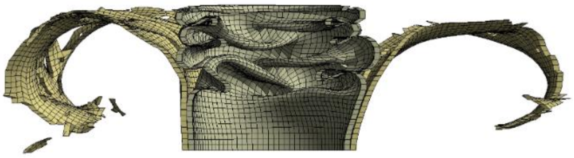
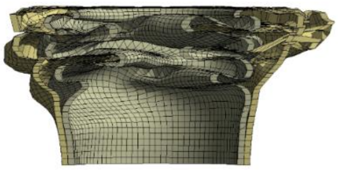
3.1.2 Deformation pattern

In this study, the hybrid crash box made of composite and aluminium has various deformation patterns in each model. Table 3 shows the deformation pattern data for each model. The different deformation pattern of aluminium crash box such as concertina, diamond or mixed. Meanwhile, the deformation pattern of composite crash box including catastrophic failure modes and progressive failure modes. Catastrophic failure will result in a sudden decrease in load which cause decrease the energy absorption value. The catastrophic failure mode forms a crack on either the middle plane or due to a longitudinal crack. In the progressive failure mode, the load tends to be constant as the displacement increases. The deformation patterns include transverse shearing, brittle fracturing, local buckling and lamina bending. The different deformation pattern is because of properties of aluminium and composite. Aluminium is ductile, whereas composites are stiff and brittle.

Most of the deformation patterns Al-Ko model show uniform deformation patterns. The outside tube made from aluminium folds to form concertina deformation pattern. The folds are empty which not filled with composite fragments. The deformation pattern composite tube inside is folded inward and brittle fracturing. The exception is an Al-Ko45 model, the deformation patterns of aluminium tube is diamond with folds are generally filled with fragments of composite.

In the Ko-Al model, most of the inner aluminium tube has a diamond deformation pattern. Meanwhile, the outer composite tube in the Ko-Al090, Ko-Al15 and Ko-Al30 models exhibit longitudinal interlaminar cracks resulting in a bending lamina deformation pattern that folds outwards. The deformation patterns of composite tube for the Ko-Al45 model is local buckling with some transverse shearing filling some folds of the aluminium tube.

Tabel 3
Deformation Pattern

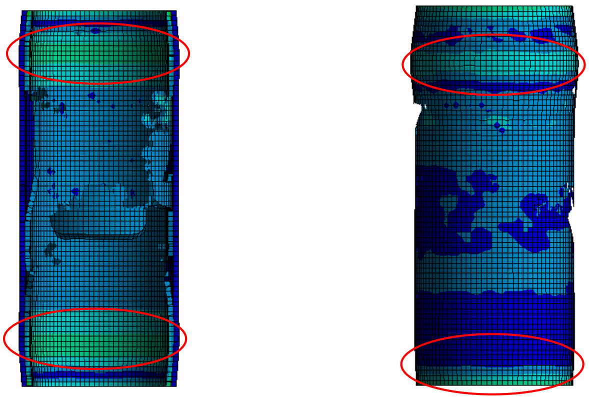
Models	Deformation Pattern	Deformation
Al-Ko090		Composite (inside) : lamina bending and brittle fracturing Aluminium (outside) : concertina
Al-Ko15		Composite (inside) : lamina bending and brittle fracturing Aluminium (outside) : concertina
Al-Ko30		Composite (inside) : brittle fracturing Aluminium (outside) : concertina
Al-Ko45		Composite (inside) : local buckling and transverse shearing Aluminium (outside) : mixed
Ko-Al090		Composite (outside) : lamina bending Aluminium (inside) : diamond
Ko-Al15		Composite (outside) : lamina bending Aluminium (inside) : diamond
Ko-Al30		Composite (outside) : lamina bending Aluminium (inside) : diamond
Ko-Al45		Composite (outside) : local buckling Aluminium (inside) : diamond

3.2 Discussion

3.2.1 The effect of the direction of orientation of the composite fibre on energy absorption and deformation patterns

The variations in the orientation of the composite fibres used in the test were [0/90, 90/0]$_5$, [15/-75, -15/75]$_5$, [30/-60, -30/60]$_5$, [45/-45, -45/45]$_5$ in each configuration of the hybrid crash box material. The direction of fibre orientation in the Al-Ko configuration shows highest energy absorption. The fractions and folds of the composite in the fibre orientation [45/-45, -45/45]$_5$ mostly fill the folds of the aluminium tube as shown in Table 3. The model with fibre orientation [30/-60, -30/60]$_5$ in Al-Ko and Ko-Al configurations has least energy absorption. The compression load is unevenly distributed, causing failure at higher stresses which results in large fragments which lead to the deformation patterns of lamina bending and brittle fracturing [22].

The direction of fibre orientation affects the deformation pattern formed. From Fig 4 it can be seen in the model with the direction of fibre orientation [45/-45, -45/45]$_5$, deformation begins with stress concentrations in the longitudinal direction at the top and bottom of the tube and initiates the formation of folds. Crack propagation was observed during the failure. Most of the composite tubes are folded together with the aluminium tubes to form progressive crushing folding [21]. The energy absorption increased because the load response tends to be constant hence the P_{mean} is larger.



(a) (b)

Fig 4. Stress Concentration of Composite Tubes (a) Al-Ko45 Model (b) Ko-Al45 Model

The highest energy absorption in the model with fibre orientation [45/-45, -45/45]$_5$ in the Al-Ko configuration. The Al-Ko45 form the progressive failure mechanism. In contrast, the deformation of Ko-Al45 was buckling. The buckling occurs because the deformation of aluminium on the inside is disturbed by the deformation of composite. The aluminium tube forms a diamond deformation pattern. The diamond deformation pattern are asymmetrical folds with angles. Part of the angle exerts pressure on the composite tube causing stress concentration in certain areas. As can be seen in Fig 5., at a deformation distance of 20 mm stress concentration in certain areas causing buckling.

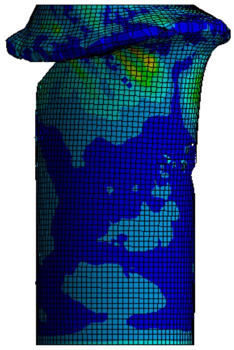
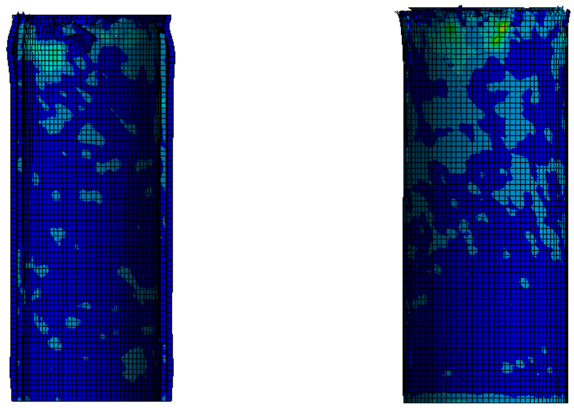


Fig 5. Stress Concentration of Model Ko-Al45 at a deformation distance of 20 mm

The Al-Ko30 and Ko-Al30 models as shown in Fig 6, the stress concentration distribution unevenly in the composite tube resulting in a initiate deformation of a crack at the top then form fragmentation. The unstable failure caused by initiation of fragmentation resulting a drop load suddenly [13]. In the next stage the composite tube delaminates from the aluminium tube. In the Ko-Al model, the composite tube delaminates by folding outward to form a lamina bending deformation pattern as shown in Fig 8. In the Al-Ko model, most of the composite tube is splitting in the form of a brittle fracture deformation pattern, resulting loss of composite fragments. Finally, only the aluminium tube supports the load. As a result, the energy absorption value is decreases.



(a) (b)

Fig 6 Stress Concentration of Composite Tubes (a) Al-Ko30 Model (b) Ko-Al30 Model

3.2.2 The effect of the hybrid material configuration on energy absorption and deformation patterns

Based on the data in Table 2., the greatest energy absorption value in the Al-Ko hybrid crash box model with the orientation direction of the composite fibres [45/-45, -45/45]$_5$ of 8.24 kJ and the lowest in the Ko-Al hybrid crash box model with the orientation direction of the composite fibre [30/-60, -30/60]5 of 2.34 kJ. Fig 7 shows the load-displacement crash box Al-Ko45 curve with deformation captures. It can be seen that the deformation in the Al-Ko45 model begins in the composite tube then uniform stress concentrations in the longitudinal direction at the top and bottom of the tube initiates the formation of folds. After that the aluminium tube starts to deform plastically. Together with the aluminium tube, progressive crushing folding is formed with the folded part being filled by the deformation fragments of the composite. The reinforcement effect by the composite tube is maintained during the crushing process. The load-displacement curve fluctuates around the mean crushing force produce a better P_{mean} value, therefore energy absorption performance is greater [23]. In addition, the then load-displacement curve is decrease significantly compared to the load-displacement curves in other models.

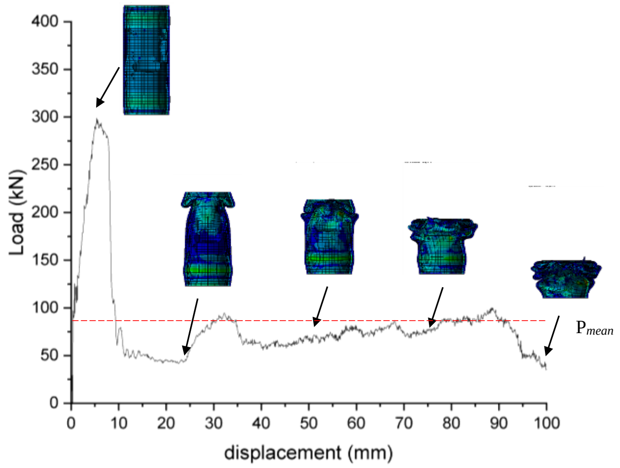


Fig 7. Load-Displacement Curve and Al-Ko45 Crash Box Deformation Pattern

Fig 8 shows the load-displacement crash box Ko-Al30 curve with deformation captures. The deformation in the Ko-Al30 model initiate with the cracking of the top composite tube, at the same time the aluminium tube inside begins to deform plastically in a diamond mode. Furthermore, plastic deformation of the inner aluminium tube causes longitudinal cracks in the outer composite tube, causing a drastic decrease in the load curve. Deformation in the composite is in the form of outward lamina bending because long interlaminate cracks, it reduces the energy absorption [24]. In aluminium tubes, the diamond-shaped folds produce lower energy than the concertina deformation pattern [25]. In addition, in the final stage of failure in the aluminium tube, the composite tube no longer contributes to the resistance to compressive loads [18]

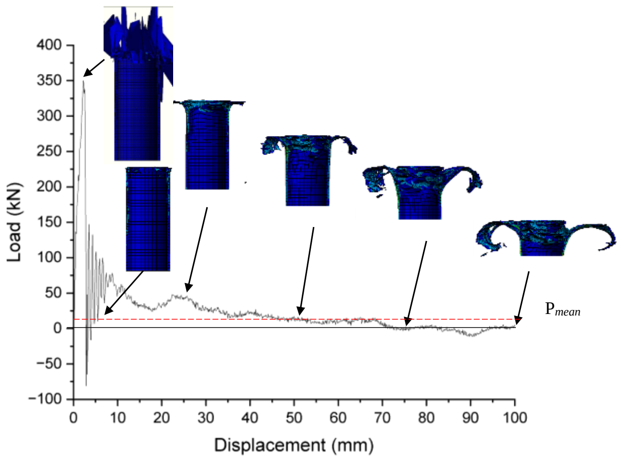


Fig 8 Load-Displacement Curve and Deformation Pattern of Ko-Al30 Crash Box

Fig 9 shows a comparison of the final deformation patterns formed in the Al-Ko45 and Ko-Al30 models in that aluminium tubes both experience diamond deformation patterns. In contrast, the aluminium tube folds of Al-Ko45 are filled with folds and composite fragments, whereas in the Ko-Al30 model all parts of the folds of the aluminium tube are empty. In the Al-Ko45 model, the composite deformation in the form of fractions or folds functions like foam-filled filling folds of aluminium deformation can increase the crashworthiness characteristic as the energy absorption value increases [26]. In the Ko-Al30 model, the composite tube delaminates outwards to form a lamina bending deformation pattern. The deformation pattern of lamina bending has very low crushing efficiency hence the ability to absorb energy is less [27]. The composite separated from aluminium during the first stage of the crushing, and then only the aluminium alloy subjected to the load until crushing is over, which resulted in the reduce of energy absorption capacity [23].

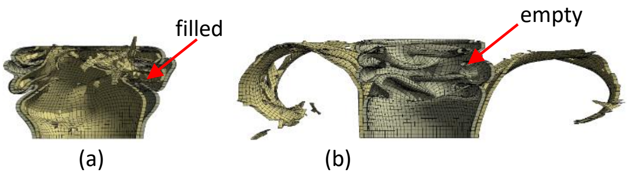


Fig 9. Final deformation pattern (a) Al-Ko45 model (b) Ko-Al30 model

CONCLUSION

The failure characteristics in metal and composite crash box are different. This results in a different load-displacement curve trend. In metal tubes, the failure is indicated by the formation of folds in response to loading, resulting in a load-displacement curve that increases and decreases constantly fluctuation around F_{mean} during failure. Meanwhile, in the composite tube, the failure is indicated by the mechanism of interlaminar and intralaminar crack which continue during the failure then the load-displacement curve formed has a constant trend after the initial peak crushing force.

Differences in the direction of orientation as well as the composition and configuration of the hybrid material affect the energy absorption. The direction of fibre orientation affects the initial stage of failure, the stress concentration of model when loading initiates the formation of folds which affect the next failure. Fractures and folds of the composite in the fibre orientation mostly fill the folds of the aluminium tube. This condition increases energy absorption because the fragments and folds of composite function like foam-filled. The configuration of the material arrangements forms a progressive crushing folding, the reinforcement effect of the inner composite tube is maintained during the failure process. Crash box with the Al-Ko configuration model at the fibre orientation angle $[45/-45, -45/45]_5$ absorbs the greatest energy of 8.24 kJ. The hybrid models absorb 2 times greater than single tube aluminium with a less mass increment. In future research, experimental verification will be necessary to confirm the simulation results. Opportunities to develop design optimizations will provide better crash box design implementation.

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