Deformation pattern and energy absorption of polylactic acid (PLA) carbon crash box under quasi static loading

Redyarsa Dharma Bintara¹, Moch. Agus Choiroń²
1 Mechanical Engineering Department, State University of Malang
Semarang 5, Sumbersari, Lowokwaru, Indonesia
Email: reddyarsa.dharma.ft@um.ac.id
2 Mechanical Engineering Department, Brawijaya University
MT Haryono 167, Lowokwaru, Malang, Indonesia

Abstract. The purpose of this study is to investigate the deformation pattern and energy absorption (EA) in Polylactic Acid Carbon Crash Box. The crash box specimen was produced by using 3D printer machine. The quasi static testing method is performed to compress the specimen with a speed of 2 mm min⁻¹ using universal testing machine. It was pressed until it reaches deformation of 80 mm from its original length of 120 mm. The deformation was analyzed in three different variations of wall thickness (Wt), 1.6 mm; 1.8 mm; and 2 mm. The deformation pattern and the maximum EA are analyzed to determine the best design specifications. The results show that the highest EA occurs on Wt 2 mm (357.986 J), whereas the lowest EA occurs on Wt 1.6 mm (224.012 J). The local buckling and discontinue folding consist on three model of crash box. In addition, the fragmentation is also formed on Wt 2 mm of crash box but it is not looked on remain models.

Keywords: crash box, PLA carbon, quasi static

1. Introduction
Over the past several decades, many studies have investigated the performance of energy absorption of crash boxes with metal as well as metal and composite alloys as based material. Crash box is a component that has a function to absorb energy, especially for collision energy. Metallic crash boxes have been widely used for automotive and aerospace applications [1]. In automotive applications, a Crash box structure is applied to absorb impact energy while the vehicle crash with other vehicle. The main purpose of applying this component is to keep the passengers and drivers in their positions without a sudden decrease in deceleration. The crash boxes made of metallic generally form progressive folding while on composite, folding is formed by fractures. Square hollow section beam Aluminum crash box (Al6063T5) with Carbon Fiber Reinforced Plastic (CFRP) has been investigated for dynamic axial loads [2]. The test is performed by varying the low impact speed in accordance with the regulations of the Research Council for Automobile Repairs (RCAR). The test results show the specific energy absorption and collision force efficiency increased from 30% to 38%. The Aluminum crash box with the addition of 1050H14 Al as its filling material has been tested by quasi-static and dynamic crushing methods using experimental and LS-DYNA simulation methods. The results showed a similarity between the...
load and deformation in the two tests. Furthermore, the form of aluminum with full and partial filling shows the energy absorption efficiency when compared with the form of the crash box without the filler [3]. Multi-cell hexagonal crash boxes with the addition of fillers have also been studied to determine the amount of impact energy absorption [4]. The research uses ANSYS 18.1 software as a tool to predict the estimation energy absorption. The results showed that the highest energy absorption occurred in hexagonal multi-cell with the addition of foam to the crash box outer wall. The shape of the crash box profile based on H360 steel and aluminum 6008T7 has been optimized using LS-OPT that is connected to the LS-DYNA software [5]. This test uses a low speed (16 km h\(^{-1}\)) in accordance with ENCAP standards. The results show that the optimal form of a crash box is aluminum filled with PU foam. Whereas the less good shape is rectangular profile shape. The deformation pattern and energy absorption also investigate on initial fold crash box by oblique crash test [6]. Other researchers also applied the impact load on crash boxes component based on GFRP (glass fiber reinforced plastics) with low speed. The test material is varied in viz form square, cylindrical, hexagonal and decagonal when getting axial loads [7]. In this test, the highest energy absorption occurs in the decagonal model. The development of crash box with origami trapezoid model [8] has been studied and manufactured by using traditional investment casting [9]. In addition, quasi static impact testing has also been investigated in the form of origami [10]. Square hybrid carbon of crash boxes has also been carried out using Quasi-static testing [11]. In this study, a compressive speed of 2 \( \text{mm min}^{-1} \) was performed to compress the crash box specimen. The purpose of this study is to determine the folding characteristics and the maximum energy absorption on the crash box with Polyactic acid (PLA) Carbon based.

2. Method and material

Crash box specimen is designed using CAD software. Each 3D model is exported into stereolithography file (.STL). STL files are used as 3D input models in 3D printing software. The 3D printing software used is Creality Slicer for simulating the nozzle movement process before being transferred to the 3D printer machine. The geometry of specimen is appropriate to Figure 1. The wall thickness (Wt) of crash box is varied in three different levels which are 1.6 mm, 1.8 mm and 2 mm. Furthermore, the details of the 3D printing set are in accordance with Table 1. The resulting nozzle movement is sequence coordinates of \( x, y, z \) that are exported into a G-Code file. Furthermore, this G-Code is read by the 3D printer machine as a guidance for moving of the nozzle for creating physical 3D object.

![Figure 1. Geometry of crash box](image)

The specimen was produced with commercial Polyactic acid (PLA) Carbon material (Table 2). This material is used as main material on 3D printer machine to make crash box specimens. The 3D printer machine is Creality Ender 3 which specification details as shown in the Table 3.
Table 1. Parameter set on the 3D printing software

| Parameter          | Value       |
|--------------------|-------------|
| Printing speed     | 50 mm s⁻¹   |
| Layer height       | 0.2 mm      |
| Nozzle temperature | 200 °C      |
| Bed temperature    | 60 °C       |

Table 2. Properties material of filament PLA Carbon

| Diameter (mm) | Melt Temperature (°C) | Color |
|---------------|-----------------------|-------|
| 1.75          | 200                   | Black |

Table 3. Specification of Creality Ender 3 machine

| Work Area (mm) | Diameter of Nozzle (mm) | Maximum Temperature (°C) |
|----------------|-------------------------|-------------------------|
| 230x230x250    | 0.4                     | 300                     |

The crash box material is subjected to compressive test (Figure 2) at a speed of 2 mm min⁻¹. The compressive testing is performed until the crash box deformation reaches 80 mm from its initial dimensions (120 mm). When the compressing performed, the shape of crash box is captured every 10 mm displacement of top fixture while the force reaction and displacement is recorded by computerize system. The both data are two important parameters that recorded for calculating the energy absorption in the system. Furthermore, the shape of crash box is observed and analyzed for looking the crash box pattern while maximum energy is calculated by multiply of force reaction and displacement of top fixture.

![Experimental installation](image)

Figure 2. Experimental installation

3. Result and discussion

3.1 Energy absorption of crash box

A compressive test is conducted to see the deformation pattern of crash box. Moreover, the reaction force and deformation of crash box are two important parameters for calculating the energy absorption. It can calculate using Equation 1 [12].

\[ U = \int F \, dx \]  

\( U \) is strain energy (Nm), \( F \) is load (N) and \( dx \) is deformation of crash box (m). Table 4 depict the compressing test result of 3 crash box models. Figure 3 shows the relationship between load and displacement of crash box while the area under of graph is the maximum energy absorption (EA).
Table 4. Result of compression test

| Wall thickness (mm) | Energy absorption (kgf m) | Energy absorption (Joule) | Deformation model                      |
|--------------------|---------------------------|---------------------------|----------------------------------------|
| 1.6                | 22.8584                   | 224.012                   | Local Buckling, brittle fracturing     |
| 1.8                | 31.6737                   | 310.402                   | Local Buckling, brittle fracturing     |
| 2                  | 36.5292                   | 357.986                   | Local Buckling, brittle fracturing, fragmentation |

Figure 3 shows the force reaction during compressing test. In the beginning test, the reaction force rises until the maximum point that occurs between 0 mm to 10 mm of displacement top fixture. This is due to the model does not have fracture enough, although the folding shape is initial formed (Figure 4). The minimum reaction force is in lowest value on the displacement of top fixture around 20 mm. In this condition, the folding and fracture is start formed on three models (Figure 5). Furthermore, the reaction force tends to rise again for all models until the 80 mm displacement of top fixture. The crash box breaks along during crushing and produce fragments on the crash box wall (Figure 6). The EA is calculated by measuring the area under the line of the graph for each model. The lowest and highest of EA occurs in the Wt 1.6 mm and Wt 2 mm with 224.012 J and 357.986 J respectively.

Figure 3. Curve force reaction and displacement of 3 crash box models due to compressing test

Figure 4. Deformation crash box when 10 mm displacement of top fixture. a) Wt 1.6 mm, b) Wt 1.8 mm, c) Wt 2 mm
Figure 5. Deformation crash box when 20 mm displacement of top fixture. a) Wt 1.6 mm, b) Wt 1.8 mm, c) Wt 2 mm

Figure 6. Deformation crash box when 80 mm displacement of top fixture. a) Wt 1.6 mm, b) Wt 1.8 mm, c) Wt 2 mm

3.2 Deformation pattern

Figure 7. Folding shape of crash box. a) Wt 1.6 mm, b) Wt 1.8 mm, c) Wt 2 mm

Figure 7 shows the final deformation model of 3 variants crash box. The local buckling type dominate on the deformation for all models (Figure 7). During the compressing test, an internal folding occurs on all models, whereas the transversal crack is tend occurring on Wt 1.6 mm, Wt 1.8 mm and Wt 2 mm. Crash box forms folds to discontinue until the compressing test is complete. The deformation patterns that occur on this model is categorized as local buckling that characterized by the formation of these folds. Furthermore, there is a combination of...
fragmentation and local buckling deformation patterns that is found on $Wt_2 \text{ mm}$. The characteristic is marked by the formation of folds and producing fragments during the compressing process, as shown in Figures 7.c.

4. Conclusion

The energy absorption and deformation pattern are two important parameters that is observed in this study. The highest $EA$ occurs on $Wt_2 \text{ mm}$ (357.986 J), whereas the lowest $EA$ occurs on $Wt_1.6 \text{ mm}$ (224.012 J). Furthermore, the local buckling and discontinue folding consist on three model of crash box. The discontinue folding is caused by transversal crack that occurs on the boundary layer of deposited material. In addition, the fragmentation is also formed on $Wt_2 \text{ mm}$ of crash box but it is not looked on remain models.

5. References

[1] Zarei H, Kro M and Albertsen H, 2008 An experimental and numerical crashworthiness investigation of thermoplastic Composite Crash Boxes pp 245–257.
[2] Kim H C, Shin D K, Lee J J and Kwon J B, 2014 Crashworthiness of aluminum/CFRP square hollow section beam under axial impact loading for crash box application Compos. Struct pp 1–10.
[3] Toksoy A K and Guden M, 2010 Partial al foam filling of commercial 1050H14 Al crash boxes: the effect of box column thickness and foam relative density on energy absorption Thin-Walled Structures pp 482–494.
[4] Choiron M A, 2020 J. Phys.: Conf. Ser 1446 pp 1-7.
[5] Jiga G, Stamin Ş, Dinu G, Vlăsceanu D and Popovici D, 2016 Material and shape crash-box influence on the evaluation of the impact energy absorption capacity during a vehicle collision Ciência Tecnol. dos Mater pp 67–72.
[6] Choiron M A, Happy H K Purnowidodo A and Rivai A, 2019 Deformation pattern and energy absorption analysis on initial fold crash box by oblique crash test deformation pattern and energy absorption analysis on initial fold crash box by oblique crash test International Conference on Mechanical Engineering Research and Application pp 1-6.
[7] Hussain N N, Regalla S P and Rao Y V D, 2017 Low velocity impact characterization of glass fiber reinforced plastics for application of crash box Mater. Today Proc. pp 3252–3262.
[8] Zhou C, Zhou Y and Wang B, 2017 Crashworthiness design for trapezoid origami crash boxes Thin Walled Struct pp 257–267.
[9] Kusyairi I, Himawan H M, Choiron M A and Irawan S Y, 2019 Manufacture of origami pattern crash box using traditional investment casting method manufacture of origami pattern crash box using traditional investment casting method International Conference on Mechanical Engineering Research and Application pp 1-10.
[10] Yuan L, Shi H, Ma J and You Z, 2019 Quasi-static impact of origami crash boxes with various profiles Thin Walled Struct pp 435–446.
[11] Quanjin M, Salim M S A, Rejab M R M, Bernhardi O and Nasution A Y, 2019 Quasi-static crushing response of square hybrid carbon/aramid tube for automotive crash box application mater. Today Proc pp 1-8.
[12] Tawaf N and Asroni, 2013 TURBO 2 pp 6-14.