MULTI-OBJECTIVE DESIGN OF HONEYCOMB HYBRID CRASH BOX UNDER FRONTAL LOADING

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DOI: 10.17973/MMSJ.2023_03_2022162

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This research aims to obtain the optimal honeycomb hybrid crash box design. Finite elements, parametric studies, and multi-objective optimization are carried out sequentially. Parametric studies are carried out to obtain important parameters to increase energy absorption and minimize mass. The effect of structure angle, honeycomb side length, and structure thickness are selected as the design parameter. Energy absorption and crash box mass are observed as design responses. Based on the results, it can be determined the optimal design from multi-objective optimization is angle structure of 21.131^0, side length of 8.006 mm, and thickness of 1.2 mm. The model validation results for the optimal solution are appropriate; it is characterized by a honeycomb-filled structure that supports the folding of the outer wall of the crash box.

KEYWORDS

hybrid crash box, honeycomb, multi-objective design, energy absorption, mass.

1 INTRODUCTION

The vehicle structure is required to be capable of protecting passengers. The front rails, bumper system, and crash box absorb about 70% of the total impact force in a frontal crash [Ahmad Baroutaji 2017]. Crashworthiness is the ability of a structure to absorb the force from an impact and reduce the risk of injury to all occupants. In addition demands to protect passengers, vehicle design is also required to reduce mass. This is to increase fuel economy without compromising vehicle safety and performance. One of the lightweight materials used in modern automotive structures is the honeycomb structure [G and K 2019].

Research using analytical [Zhang 2018], experimental [Usta 2019], and numerical [Altin 2021] methods on honeycomb structures have been investigated. The results showed that the use of a honeycomb increased energy absorption. Significant increase due to honeycomb having relative density [Q. Zhang 2015], material properties and topology configuration [Wu 2021]. The crash box initially used metal material. Current developments use composite materials [Dou 2022][Maqsood 2021] and filaments [Fu 2021] for lightweight concepts.

Research on filament material using 3D printing techniques is interesting to develop (Bohara 2023)(Wang 2022). 3D printing technology has the ability to create complex structures (Rice 2019). Research on complex thin-walled structures with lightweight performance is developed by 3D printing. For example, (Ghazlan 2020) investigated thin-walled cellular structures. The bioinspired structure produced by 3D printing has increased performance. This is related to the collaps and buckling mechanism. (Townsend 2020) observed energy absorption in 3D printed origami honeycomb. It was found that the absorption profile was affected by the overall structural stiffness and the number of folds. The development of filaments followed the development of 3D printing. A comparison of several filaments was observed to determine mechanical properties. It was found that PLA carbon fiber has low tensile strength but good ductility. The mechanical properties of PLA carbon are suitable for the development of a hybrid crash box design. The hybrid structure has been widely developed because it can optimize different material properties.

Hybrid design means combining existing cell configurations to form new configurations. Hybrid honeycombs mostly retain the characteristics of the classic honeycomb in achieving maximum performance. The performance of the hybrid honeycomb can reach a maximum that cannot be reached by the classic configuration [Qi 2021]. The hybrid structure is also defined as a combination of two materials. The result showed that the hybrid structure (aluminum and ABS multi-cell insert) increased energy absorption (EA) [Tabacu 2018]. An indicator in designing thin-walled structures is energy absorption (EA). Excellent energy absorption can reduce passenger injuries.

To better understand the crushing behavior of the hybrid structure, the energy absorption performance of aluminum and PLA carbon hybrid structures is investigated in this study. The aluminum tube is commercial extrusion, and the PLA carbon honeycomb is made by 3D printing. Aluminum is used as the outer tube because it has a higher tensile strength compared to PLA Carbon filament. PLA carbon filament is used as the inner crash box material because it has excellent ductility. Increased energy absorption of hybrid structures is influenced by internal crash box materials, external crash box materials, and interaction effects (Fu 2021). Multi-objective optimization is carried out to obtain an optimal design with high energy absorption and lightweight.

2 MATERIAL AND METHODS

2.1 Finite element model

The three-dimensional (3D) model using ANSYS Workbench explicit dynamic was employed to simulate the energy absorption and deformation pattern of crash box. The crash box folding shape and the force-displacement curve can be estimated by simulation. A finite element model simulation was created for modeling crash box compression (Fig.1). The hybrid crash box were modelled using shell element. Impactor and base were modelled using solid element. Set up meshing for the crash box is set at 2 mm. For impactor and base setup, meshing is set as default. The impactor and base are modeled as rigid bodies. The impactor is constrained to move vertically along the x-axis with a velocity of 7.67 m/s [Velmurugan 2009]. Fixed translation and rotation are constrained for the base.

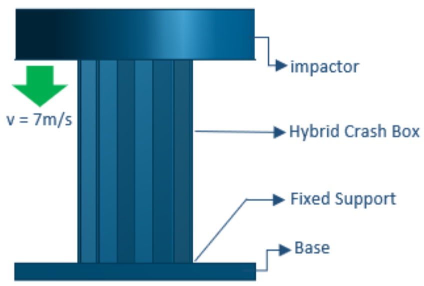


Figure 1. Modeling crash box compression

Honeycomb hybrid crash box is prepared by assembling the outer tube dan filled. The outer tube and filled material are AL6063 and PLA carbon filament, respectively. Material properties AL6063 and PLA carbon filament is shown in Tab. 1. These results were obtained from tensile testing and used in the finite element model. The hybrid crash box material is modeled as linear elastic and plasticity. Isotropic elasticity was chosen as the linear elastic model while for modeling plasticity using bilinear isotropic hardening.

Property	AL6063	PLA Carbon
Density	2380 Kg/m^3	1190 Kg/m^3
Young's modulus	64 GPa	29 GPa
Poisson's ratio	0.33	0.38
Yield strenght	70 Mpa	30 Mpa
Ultimate tensile Strength	107,86 Mpa	32,64 Mpa
Tangent Modulus	450 Mpa	380 Mpa

Table 1. *Material of hybrid crash box*

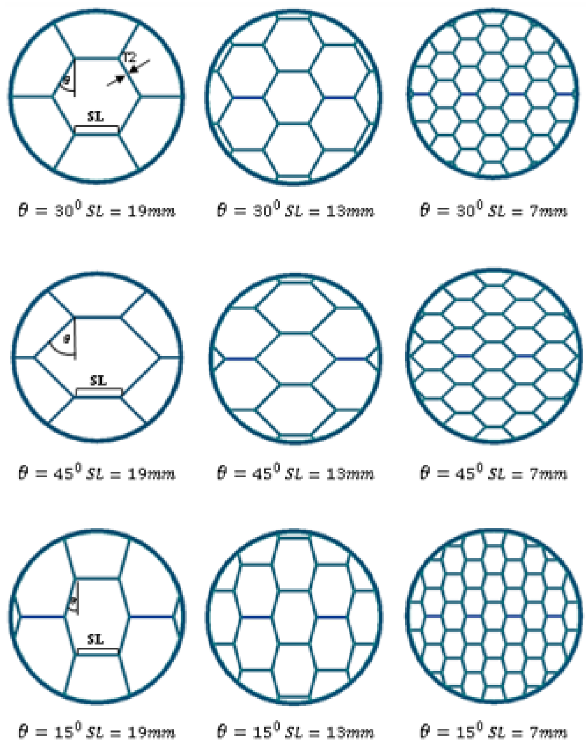


Figure 2. Geometric design parameters

2.2 *Design Parameters*

The design parameters in this study were structure angle (θ), honeycomb side length (SL), and structure thickness (T2). The design parameters were based on the Box-Behnken design with three levels and full replications [A. Baroutaji 2014]. The design parameter level is shown in Tab.2. The selection of this parameter level is based on the ranges commonly used in the crashworthiness. Fig.2 shows the geometric design parameters in this study. The energy absorption (EA) and mass (m) were selected as design responses.

Parameters	Low Level	Middle Level	Upper Level
Structure angle	15^0	30^0	45^0
Honeycomb side length	7 mm	13 mm	19 mm
Structure thickness	0,8 mm	1 mm	1,2 mm

Table 2. **The design parameter levels**

3 RESULT

3.1 *Development of Response Surface Models*

The response surface methodology was applied to obtain the determined effect of the studied parameters. Design matrix models with the result of design responses are tabulated in Tab. 3. The result of the mass and energy absorption of each model are obtained from simulation ANSYS.

Model	θ	SL (mm)	T2 (mm)	EA (kJ)	Mass (kg)
1	30^0	19	0.8	1.135	0.161
2	15^0	7	1	3.337	0.247
3	45^0	13	1.2	2.151	0.206
4	30^0	13	1	2.242	0.2
5	30^0	13	1	2.242	0.2
6	45^0	13	0.8	1.246	0.176
7	30^0	13	1	2.242	0.2
8	15^0	19	1	1.489	0.177
9	30^0	7	0.8	2.274	0.208
10	15^0	13	1.2	2.763	0.219
11	30^0	13	1	2.242	0.2
12	15^0	13	0.8	1.812	0.184
13	30^0	19	1.2	1.685	0.185
14	30^0	13	1	2.242	0.2
15	45^0	7	1	2.491	0.227
16	30^0	7	1.2	3.755	0.253
17	45^0	19	1	1.489	0.174

Table 3. The design matrix models

3.1.1 Analysis of variance for energy absorption (EA) response

Summary ANOVA tables show adequacy measures and model significance. Tab.4 shows the result of the variance analysis generated for the EA response model. The F-value for the EA response model is 174.12. These results indicate that the model is significant. There is only a 0.01% chance the F value occurs due to the noise. Analysis of variance shows that all parameters affect the EA for the hybrid crash box. The most significant models for EA response are:

1. The first-order effect of structure angles (A), honeycomb side length (B), and structure thickness (C).
2. The second-order effect of structure angle (A^2), honeycomb side length (B^2), and structure thickness (C^2).

3. The two levels of interaction between structure angle and honeycomb side length (AB), and interaction between side length and structure thickness (BC).

The final response equation for energy absorption (EA) is described as follows:

$$EA\ (kJ) = -2.83841 - 0.008950A - 0.067319B + 11.02208C - 0.193958B.C - 0.000577A2 + 0.002483B2 - 2.97812C2 \quad (1)$$

Source	Sum of square	Mean square	F-value	p-value
Model	7.55	0.8387	174.12	< 0.0001
A- θ	0.5121	0.5121	106.31	< 0.0001
B-SL	4.59	4.59	952.73	< 0.0001
C-T2	1.89	1.89	392.10	< 0.0001
AB	0.1789	0.1789	37.15	0.0005
AC	0.0005	0.0005	0.1098	0.7500
BC	0.2167	0.2167	44.99	0.0003
A^2	0.0710	0.0710	14.75	0.0064
B^2	0.0336	0.0336	6.98	0.0333
C^2	0.0598	0.0598	12.41	0.0097
Residual	0.0337	0.0048		
Lack of Fit	0.0337	0.0112		
Pure Error	0.0000	0.0000		
Cor Total	7.58			
R^2=0.9956, Adjusted R^2 = 0.9898 Predicted R^2= 0.9288, Adeq Precision = 46.7135				

Table 4. Analysis of variance table for EA – Quadratic model.

3.1.2 Analysis of variance for mass (m) response

The result of the variance analysis generated for the EA response model is shown in Tab. 5.

Source	Sum of square	Mean square	F-value	p-value
Model	0.0100	0.0011	738.04	< 0.0001
A- θ	0.0002	0.0002	161.33	< 0.0001
B-SL	0.0071	0.0071	4720.33	< 0.0001
C-T2	0.0022	0.0022	1496.33	< 0.0001
AB	0.0001	0.0001	48.17	0.0002
AC	6.250E-06	6.250E-06	4.17	0.0806
BC	0.0001	0.0001	73.50	< 0.0001
A^2	5.921E-07	5.921E-07	0.3947	0.5498
B^2	0.0001	0.0001	96.89	< 0.0001
C^2	0.0001	0.0001	47.76	0.0002
Residual	0.0000	1.500E-06		
Lack of Fit	0.0000	3.500E-06		
Pure Error	0.0000	0.0000		
Cor Total	0.0100			
R^2=0.9989, Adjusted R^2=0.9976 Predicted R^2= 0.9832, Adeq Precision =99.0061				

Table 5. **Analysis of variance table for mass – Quadratic model.**

The F-value for the EA response model is 738.04 implies the model is significant. P- Value less than 0.0500 indicates model terms are significant. The most significant models for mass response are:

1. The first-order effect of structure angles (A), honeycomb side length (B), and structure thickness (C).
2. The second-order effect of honeycomb side length (B^2), and structure thickness (C^2).
3. The two levels of interaction between structure angle and honeycomb side length (AB), and interaction between side length and structure thickness (BC).

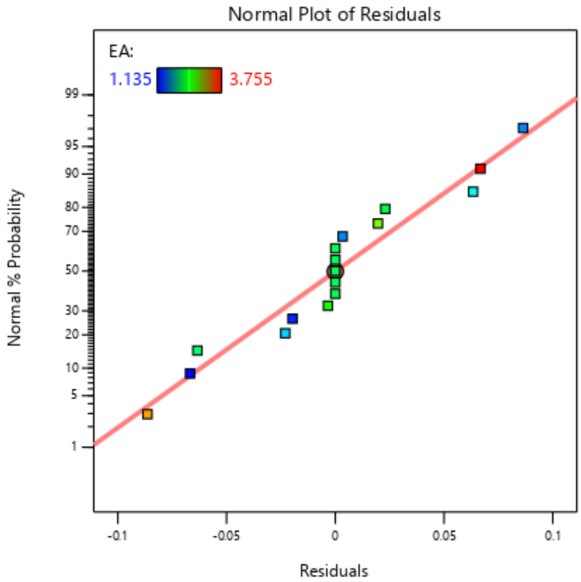
The final response equation for mass (m) is described as follows:

$$Mass\ (kg) = +0.066705 - 0.000664A - 0.006243B + 0.359375C + 0.000047A.B - 0.000417A.C - 0.004375B.C + 1.66667E\text{-}06A^2 + 0.000163B^2 - 0.103125C^2 \quad (2)$$

3.2 Validation of Response Surface Models

Diagnostic plots are shown to validate response surface models. A normal plot of the studentized residual is used to check the normality residual. Predictive accuracy can be observed by comparing the predicted value with the actual value [Yang 2018]. In Fig. 3 it can be seen that the residues are in a straight line. This indicates a normally distributed error rate. Fig. 4 shows the predicted value of the model is randomly distributed with a constant across the graph. This model is reasonable with an observed value.

(a)



(b)

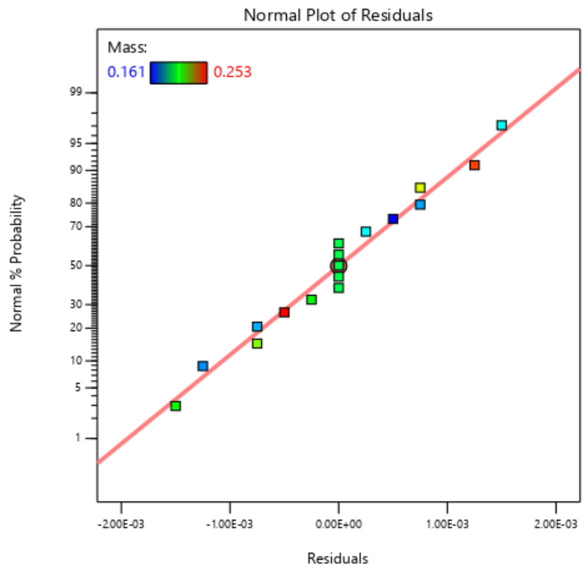


Figure 3. Normal plot of residual (a) EA, (b) mass

(a)

(b)

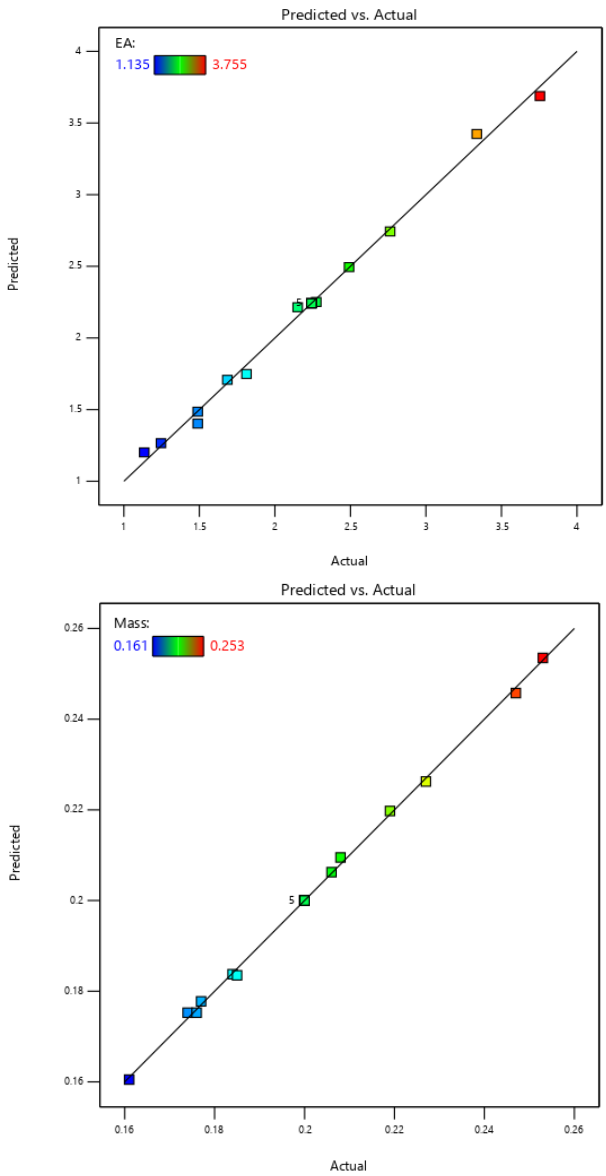


Figure 4. Predicted value vs actual value (a) EA, (b) mass

4 DISCUSSION

4.1 *Parametric Study*

The parametric study was carried out to obtain important parameters for the energy absorption design. The result from the design matrix model was used to study the effect of geometrical on energy absorption and mass response.

4.1.1 The Effect of geometrical on energy absorption response

Fig. 5 shows the side length of the honeycomb (B) have played a dominant role in increasing EA and then thickness (C), and angle (A). The effect of angle on EA is shown in Fig. 6. It is seen that EA decreases as the structure angle increase. Fig. 7 displays the effect of side length on the EA. The energy absorption decreases as the side length increase. The effect of the thickness on the energy absorption is shown in Fig. 8. The EA increases with increasing thickness. Fig. 9 shows the variation of EA with side length and thickness. The energy absorption can be increased if smaller side lengths and large thicknesses are used.

4.1.2 The Effect of geometrical on mass response

The side length of the honeycomb (B) was found to the major effect on the increasing mass, subsequent thickness(C), and angle (A) shown in Fig. 10. The effect of angle on mass is shown in Fig. 11. It is seen that mass decreases as structure angle increase. Fig. 12 displays the effect of side length on the mass. The mass decreases as the side length increase. The effect of the thickness on the mass is shown in Fig. 13. The mass increases with increasing thickness. Fig. 14 shows the variation of mass with side length and thickness. The mass can be increased if smaller side lengths and large thicknesses are used.

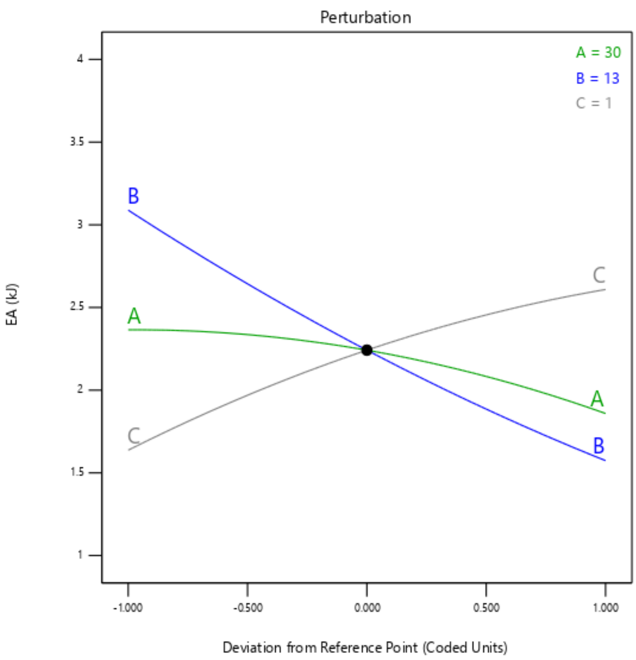


Figure 5. Perturbation plot of EA

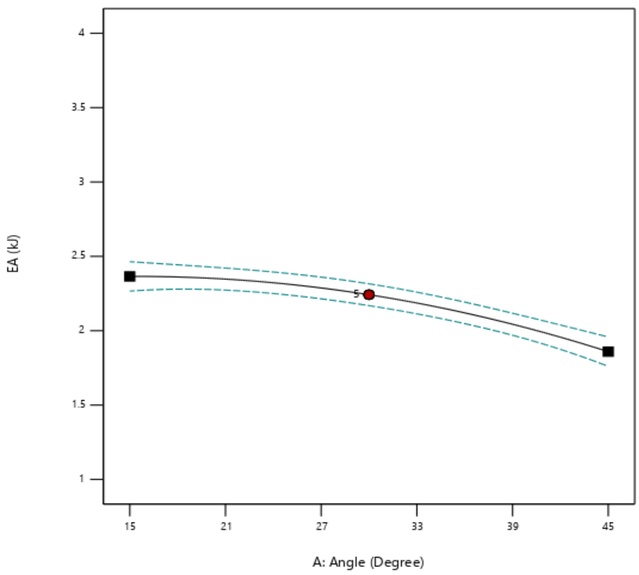


Figure 6. Angle effect on EA

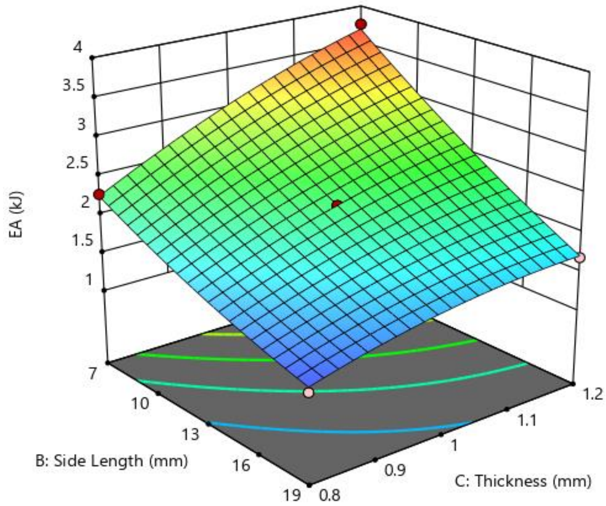


Figure 9. Variation of EA with side length and thicknes

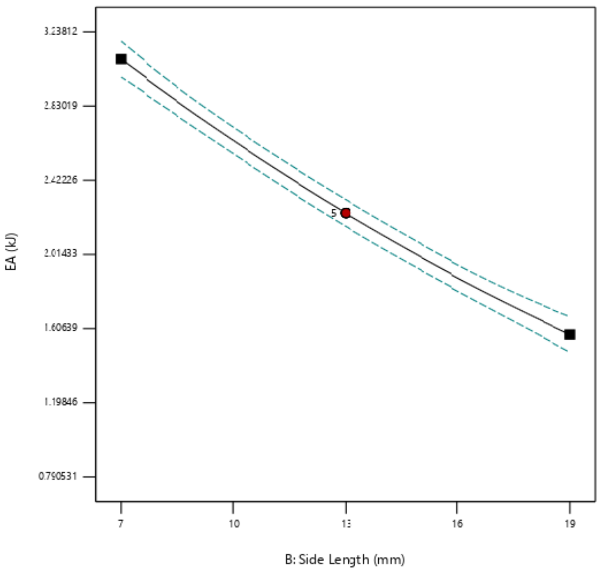


Figure 7. Side length effect on EA

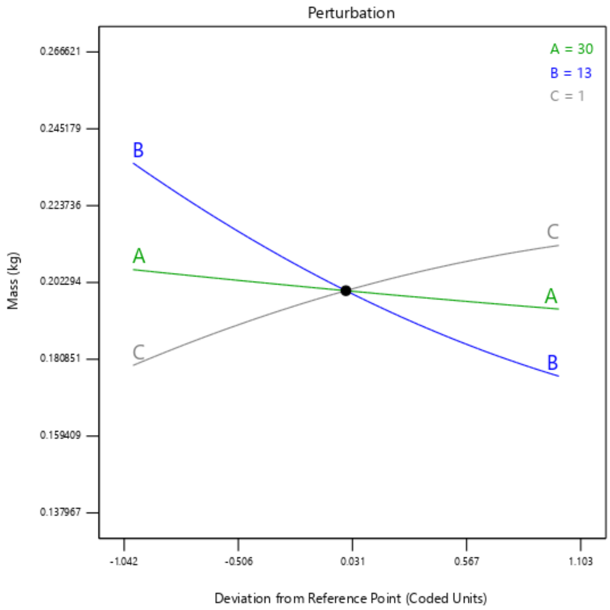


Figure 10. Perturbation plot of mass

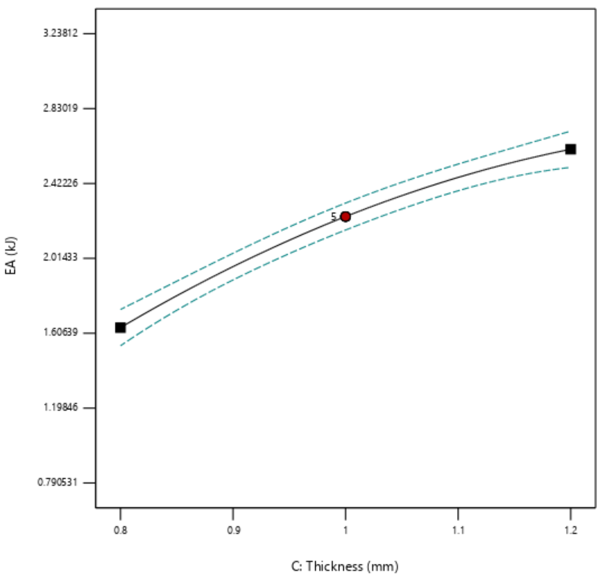


Figure 8. Thickness effect on EA

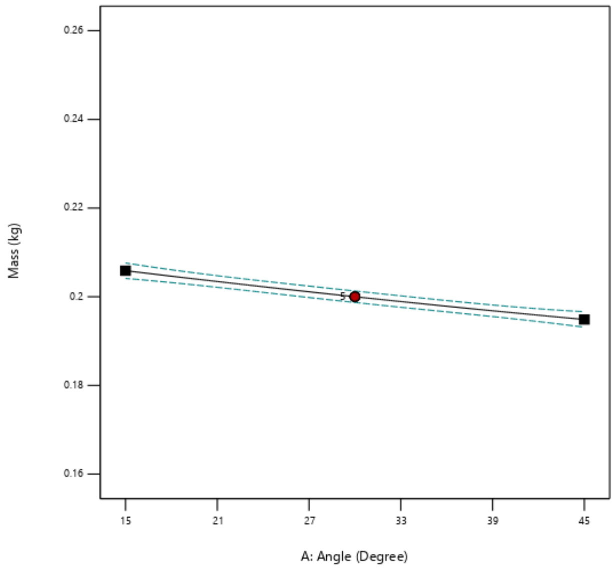


Figure 11. Angle effect on mass

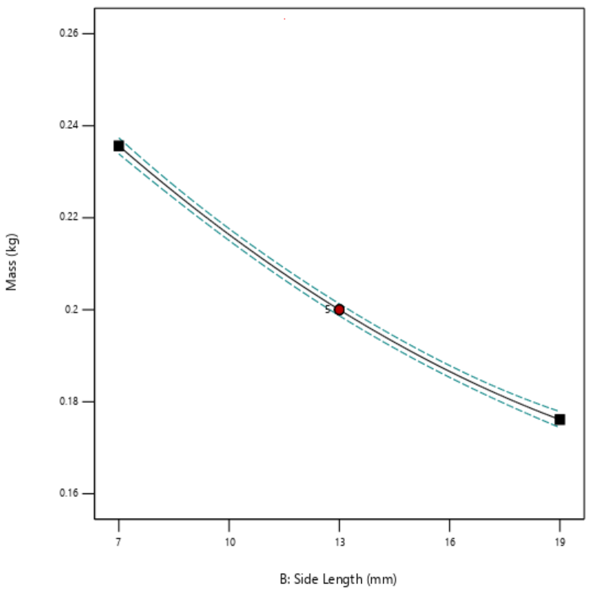


Figure 12. Side length effect on mass

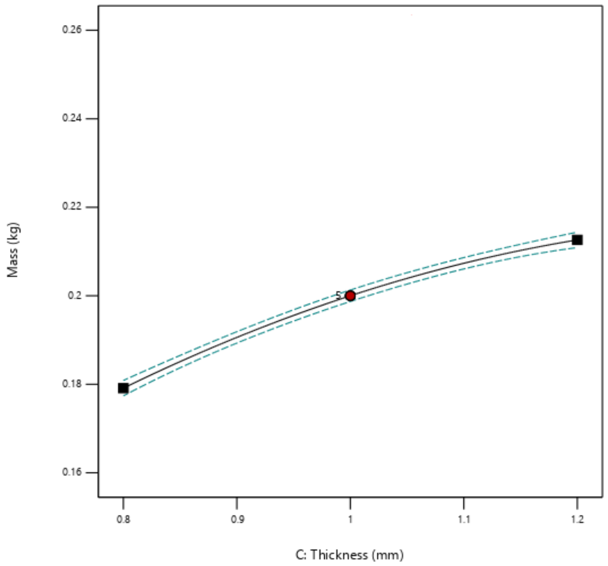


Figure 13. Thickness effect on mass

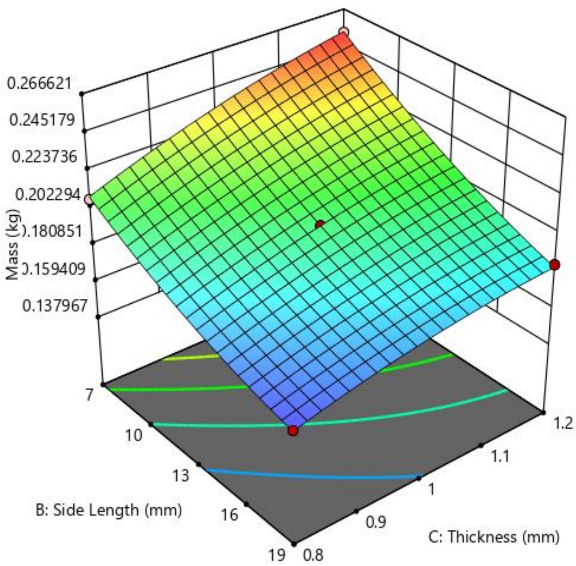


Figure 14. Variation of mass with side length and thickness

From the discussion of the geometrical effect on energy absorption and mass responses, it is still not known what the best design for a honeycomb hybrid crash box. The design response that has been investigated needs to be optimized. Multi-objective design has advantages in understanding the interaction of different crashworthiness criteria [Baroutaji et al. 2015].

4.2 The Optimization problem

The energy absorption capacity of the hybrid crash box is evaluated by the whole structure. Outer wall and honeycomb filled are observed in the design process. The design crash box must absorb impact energy with a collision speed of 7m/s. Crash box design must also have a lighter mass. This leads to the concept of a lightweight structure that saves fuel. The aims of multi-objective design are to maximize energy absorption and minimize mass. The design limit and response objective of multi-objective optimization design are presented in Tab. 6.

Name	Goal	Lower Limit	Upper Limit	Weight
A- θ	is in range	15	45	1
B-SL	is in range	7	19	1
C-T2	is in range	0.8	1.2	1
EA	maximize	1.135	3.755	10
Mass	minimize	0.161	0.253	1

Table 6. **Numerical optimization criteria**

4.3 Design optimization

The geometric factors that cause an increase in EA and decrease in mass are presented in Tab. 7. The best desirability was achieved when the angle structure and side length were set at (21.131^0 and 8.006 mm), and the maximum structure thickness is (1.2 mm).

No	θ	SL (mm)	T2 (mm)	EA (kJ)	Mass (kg)
1	21.131^0	8.006	1.200	3.710	0.252
2	21.249^0	7.995	1.200	3.710	0.252

Table 7. Optimal solution

The optimum design validation process is carried out by numerical simulation. The geometry model for the optimal solution is shown in Fig. 15. Energy absorption and mass prediction results obtained from RS are compared with numerical simulation results.

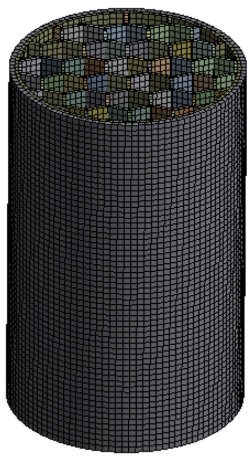


Figure 15. The geometry of the optimal solution

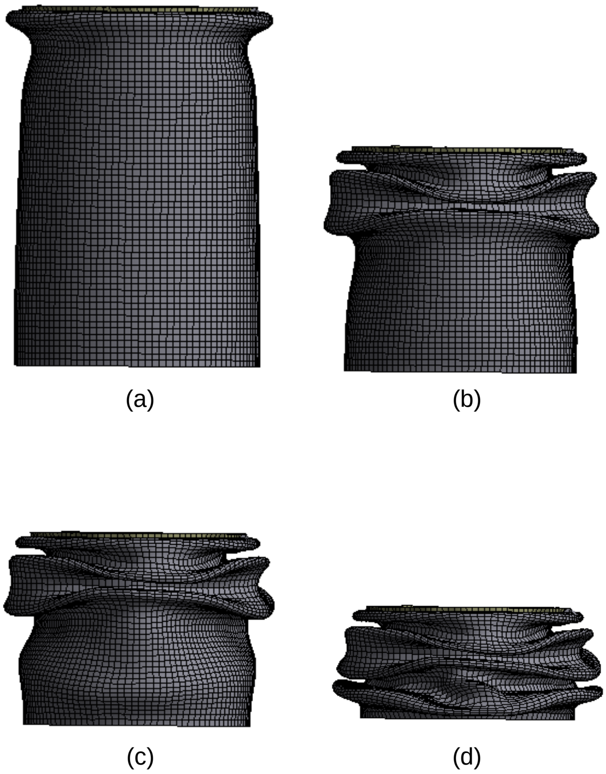


Figure 16. Deformation pattern of the optimal solution

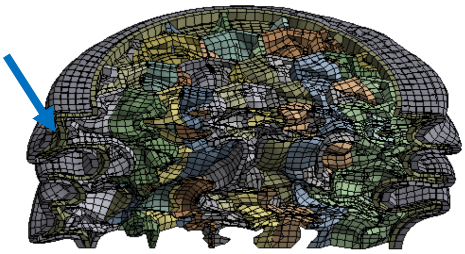


Figure 17. Section geometry of the optimal design

The deformation pattern of the optimal model is shown in Figure 16. The initial fold occurs at the top of the crash box as shown in (a) and is followed by symmetrical folds on the sides of the crash box (b). Near the final crushing force occur, fold at the bottom crash box (c). The final crushing force produces a symmetrical folding pattern on both sides of the crash box (d). Section geometry of the optimal design is shown in Fig. 17. Based on the Design for Manufacturability (DFM), it will be difficult when this optimization results are manufactured. This value is rounded off with angle structure 21^0, side length 8 mm, and thickness 1.2 mm and re-simulated for validation. The simulation results show that there is a decrease in EA of 8.12% than the model number 16 as the higher EA in RSM table.

The effect of the honeycomb-filled structure on energy absorption can be studied by section geometry. From the geometry section, the filled structure helps the crash box folding process. The honeycomb-filled structure becomes the outer wall fold filler. The filled structure improves energy absorption while not damaging the outer wall.

5 CONCLUSION

Finite element model was developed to study the crash box deformation pattern. Parametric studies were carried out to obtain the important parameters to increase energy absorption and minimize mass. The crash box geometry is selected as the design variable. Energy absorption and mass are formulated as a design response. The main points concluded from this study are:

1. The side length of the honeycomb was found to the major effect on the increasing energy absorption compared to angle and thickness parameters. The energy absorption increases as side length decrease.
2. The major effect of increasing the mass of the crash box is the side length of the honeycomb. The mass decreases as the side length increase.
3. Optimal design results from multi-objective optimization are angle structure 21.131^0, side length 8.006 mm, and thickness 1.2 mm.
4. The finite element model validation results for the optimal solution are appropriate; it is characterized by a honeycomb-filled structure that supports the folding of the outer wall of the crash box.

ACKNOWLEDMENTS

The authors would like to acknowledge the support of Design and System Engineering Laboratory, Brawijaya University for ANSYS Research license facilities. This research was funded by Professor's Scheme Grant of Engineering Faculty, Brawijaya University, Indonesia.

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