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CHARACTERISTICS OF DEFORMATION PATTERN AND ENERGY ABSORPTION IN HONEYCOMB FILLER CRASH BOX DUE TO FRONTAL LOAD AND OBLIQUE LOAD TEST

Moch. Agus Choiron
Associate Professor, Head of Design and System Engineering Laboratory
Department of Mechanical Engineering
Brawijaya University
Jl. Mayjen Haryono, 167, Malang, Indonesia, 65145
E-mail: agus_choiron@ub.ac.id

Розроблено конструкцію краш-боксу, що дозволяє підвищити здатність краш-боксу поглинати енергію удару. У попередніх дослідженнях розроблений краш-бокс з додаванням наповнювача. Додавання наповнювача в краш-бокс дозволяє збільшити поглинання енергії. Алюмінієві стільникові наповнювачі володіють поєднанням легкої маси і здатності поглинати енергію удару. Додавання наповнювача в краш-бокс також дозволяє зменшити можливість глобального вигину в краш-боксі. Методом дослідження є комп'ютерне моделювання з використанням програмного забезпечення ANSYS Academic ver 18.1. В даному дослідженні використовувалися круглі, квадратні і шестикутні варіації поперечного перерізу, які досягали однакової площі поперечного перерізу конструкції. Геометрична модель краш-боксу і стільникового наповнювача визначається як товщина краш-боксу (tc) 1,6 мм, товщина стільникового наповнювача (m) 0,5 мм для одношарового і 1 мм для двошарового і довжина краш-боксу (l) 120 мм. Використовувані матеріали були AA6063-T6 для краш-боксів і AA3003 для стільникових наповнювачів. Модель випробувань складалася з двох типів, а саме, випробування на лобове навантаження і випробування на похиле навантаження. Швидкість ударного елементу (v) встановлена на 15 м/с. Ударний елемент і нерухома опора моделюються у вигляді жорсткого тіла, а краш-бокс розглядається як пружне тіло. Спостереження проводилися з використанням таких характеристик як картина деформації і величина поглинання виробленої енергії відповідно до даної моделі навантаження. Виходячи з результатів картини деформації, можна встановити, що в моделі краш-боксу з квадратним і шестикутним стільниковим наповнювачем картиною виниклої деформації було складання гармошкою, а у краш-боксу з круглим стільниковим наповнювачем був змішаний режим при випробуванні на лобове навантаження. Що стосується похилих навантажень, то краш-бокс знижує глобальний вигин на всіх моделях. Результати моделювання з використанням моделі випробування на лобове навантаження показали, що краш-бокс з колоподібним стільниковим наповнювачем має найбільше поглинання енергії, а краш-бокс з шестикутним стільниковим наповнювачем – найвище питоме поглинання енергії (ППЕ). В ході випробування на похиле навантаження було виявлено, що краш-бокс з шестикутним стільниковим наповнювачем володіє найбільшим поглинанням енергії і ППЕ. Порівнюючи модель шестикутного краш-боксу зі стільниковим наповнювачем і без нього, слід зазначити, що шестикутний краш-бокс з стільниковим наповнювачем має більш високу ефективність при зіткненні

Ключові слова: краш-бокс, стільниковий наповнювач, випробування на лобове і похиле навантаження

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1. Introduction

The number of vehicles in Indonesia increases every year. Unfortunately, there is an increase in the number of accidents, which cause fatalities [1]. Accidents on vehicles usually occur in three types of crash, namely the frontal, oblique and roll over where 64 % of the average accidents occur in the frontal direction [2]. Based on these conditions, a safety system on the vehicle is required in order to minimize the impact caused by the collision. Crashworthiness performance had been developed on the structure ability for vehicle passengers protecting in a crash accident. One of passive safety systems is a crash box. The crash box is designed to reduce the energy absorption to an acceptable level.

Crash box is used as an energy absorption device. A lot of research has been done in different cross-sectional shapes to achieve high specific energy absorption. Comparison of the behavior of the crash box as energy absorption devices demonstrates the strong correlation between deformation pattern (collapse mode) and energy absorption capability. The vehicle product requires guaranteed safety to meet the requirements of safety standards created by government firms. Safety standard for front impact used is FMVSS 208 in the USA [3], in Canada the standard is CMVSS 208 [4] and in Europe it is ECE R-12 [5]. In another test type, the energy absorption response of the crash box under oblique loads becomes a challenge due to bending mode occurring rather than progressive axial crushing. This condition produces a lower energy absorption capability on oblique test rather than frontal test. The crash box design is explored to find better energy absorbers in both loading conditions. In the past decade, a lot of researches have been done in developing the filler crash box. The energy absorption capacity can be increased by adding stiffness with the addition of filler materials in the crash box. Therefore, studies are devoted to improving the energy absorption of the crash box without increasing volume and lightweight, cellular materials such as honeycombs are developed as fillers for the crash box design.

2. Literature review and problem statement

Crash box is a passive safety system on vehicles in the form of thin-walled structures, which are generally tubular located between the main structure and the bumper of the vehicle [6]. The aim of crash box design is to minimize the residual crash energy getting transferred to passenger safety. Impact energy due to collisions absorbed by the crash box will cause deformation on the crash box itself so that it is expected to prevent greater deformation in the entire front frame of the vehicle. At the time of collision, the crash box is used to absorb some or all of the energy intended to minimize the damage impact, which occurs in the main car frame.

The shape of the developed crash box consists of several types, namely circle, rectangle, square, hexagonal, octagonal, and ellipse. Static and dynamic testing on crash boxes with variations in the shape of circular, rectangular and square sections has been carried out through experiments to find the cross-section shape, which produces the greatest energy absorption [7]. Crash box design subjected to both axial and oblique loads is proposed, and it is found that the hexagonal profile was a better choice for energy absorption value [8]. Crash behavior of the tapered tube subjected to axial and oblique loading was studied [9, 10]. It can be noted that in both loading conditions there was lower initial buckling resistance. Addition of foam filled on the multi-cell hexagonal crash box has an important effect to improve energy absorption performance [11, 12].

Honeycomb structure is a structure that can be used as the main body of the crash box or as a filler in the crash box. The crash behavior of aluminum columns filled with aluminum honeycomb has been experimentally investigated in order to demonstrate the advantage of honeycombs as a filler in the crash box. This study observed a dramatic decrease in the first peak load during the oblique impact test [13]. Honeycomb filling was also shown to increase the specific energy absorption of filled tubes over that of Al tube [14]. The axial crushing behavior of hollow CFRP tubes and aluminum honeycomb-filled CFRP tubes was studied and the result shows that specific energy absoprtion of the hollow CFRP square tubes was observed to be greater than the SEA of either aluminum honeycomb-filled CFRP tubes [15].

However, the use of filler as the honeycomb structure in the crash box has not yet obtained an appropriate comparison value in the cross-section variation. Therefore, it is necessary to investigate the crash box with honeycomb filler at different cross-sectional shapes with the similar cross-sectional area to denote the best cross-section shape conditions on the crash box with honeycomb filler. The benefit of the study is to develop a crash box design with honeycomb filler and get a design, which results in an increase in energy absorption through computer simulations with reducing the time required in the trial and error setting of the crash box design process.

3. The aim and objectives of the study

The aim of the study is to investigate the crash box with honeycomb filler at different cross-sectional shapes with the similar cross-sectional area to denote the best cross-section shape conditions on the crash box with honeycomb filler.

To achieve this aim, the following objectives are accomplished:

– to observe deformation patterns and energy absorption in a crash box with honeycomb filler and various cross-sectional forms by using the frontal test models;

– to observe deformation patterns and energy absorption in a crash box with honeycomb filler and various cross-sectional forms by using the oblique test models;

– to prove that the addition of aluminum honeycomb as a filler for the crash box will affect the crash force efficiency.

4. Research method

The modeling method is applied to the analysis of the crash box design by a software based on the finite element method. The test model was carried out with the frontal and oblique test models. The crash box design is modeled with circular, square, and hexagonal honeycomb fillers (Fig. 1). The deformation pattern and the energy absorption in the crash box with the honeycomb filler were obtained by calculating the area under the graph curve of the relationship between force reaction and displacement obtained from the simulation. The impactor velocity (v) 15 m/s is set with two test models, namely frontal and oblique load test (Fig. 2).

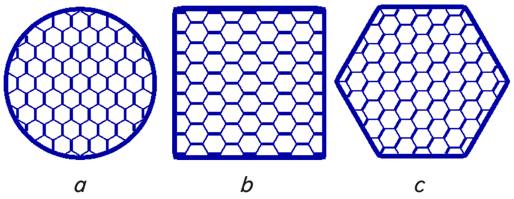

Fig. 1. Variations in the filler crash box shape: *a* – circle; *b* – square; *c* – hexagon

Geometry data input on the crash box and honeycomb filler; crash box thickness (tc) 1.6 mm, honeycomb filler thickness (t) 0.5 mm for single layer and 1 mm for double layer and crash box length (l) 120 mm.

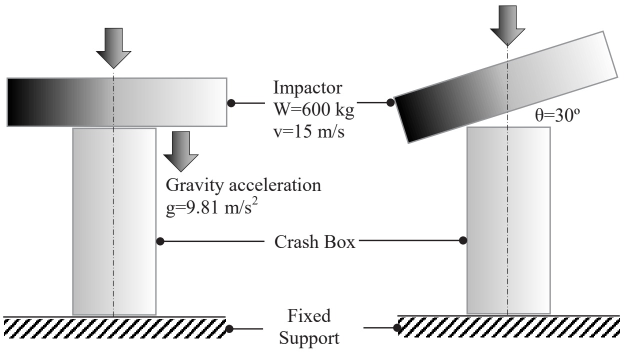

Fig. 2. Frontal and oblique load test

Data of crash box material using AA6063-T6 and honeycomb using AA3003 can be seen in Table 1.

Table 1

Material of the crash box and honeycomb

Data Properties	AA6063-T6	AA3003
Density (kg/m^3)	2,700	2,730
Modulus of Elasticity (GPa)	68.2	69
Poisson Ratio	0.3	0.33
Yield Strength (MPa)	171	40
Tangent Modulus (MPa)	500	200
Ultimate Tensile Strength (MPa)	241	110

The impactor and the fixed support are modeled as a rigid body, while the crash box is assumed as an elastic body.

5. Research results of deformation pattern and energy absorption

5. 1. Deformation patterns and energy absorption due to frontal load

The amount of energy absorption from each model due to frontal load can be seen in Table 2 and the occurred deformation patterns are shown in Fig. 3–5.

Table 2

Energy absorption and specific energy absorption due to frontal load

Crash Box model with honeycomb filler	Energy Absorption (kJ)	Specific Energy Absorption (kJ/kg)
Circular	5.109	22.960
Square	5.689	23.956
Hexagonal	5.611	24.626

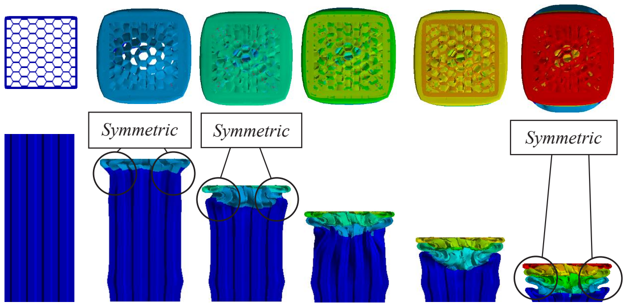

Fig. 3. Crash box deformation pattern with square-shaped honeycomb filler due to frontal load

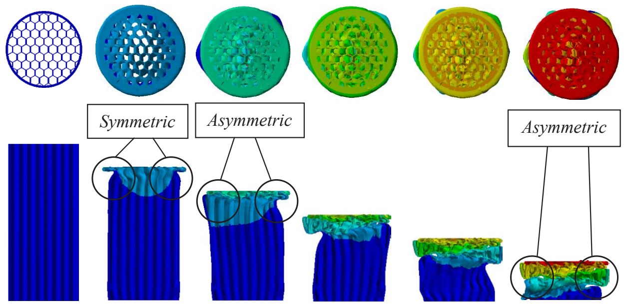

Fig. 4. Crash box deformation patterns with circular honeycomb filler due to frontal load

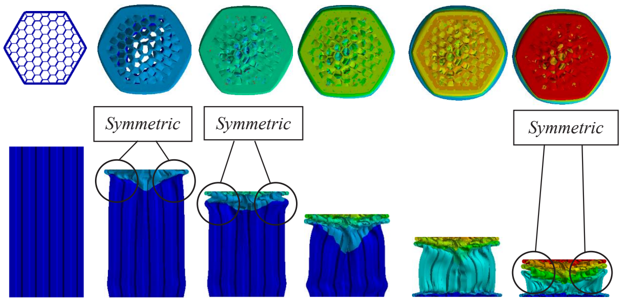

Fig. 5. Crash box deformation pattern with hexagonal honeycomb filler due to frontal load

Deformation patterns, which occur in the crash box due to frontal loading have three forms, namely concertina (axisymmetric), diamond and mixed mode (axisymmetric-diamond). Deformation patterns in each model were analyzed based on visual observations on the simulation results. Deformation patterns for each simulated crash box variation were taken up to the final displacement of 90 mm. In the crash box model with square and hexagon honeycomb filler, the deformation pattern was concertina, while the deformation pattern of the crash box with circular honeycomb filler was mixed mode (concertina – diamond).

5. 2. Deformation patterns and energy absorption due to oblique load

The amount of energy absorption from each model due to oblique load can be seen in Table 3 and the deformation patterns are shown in Fig. 6–8.

Table 3

Energy absorption and specific energy absorption due to oblique load

Crash box model with honeycomb filler	Energy (kJ)	Specific Energy Absorption (kJ/kg)
Circular	3.798	17.069
Square	3.542	14.915
Hexagonal	4.063	17.832

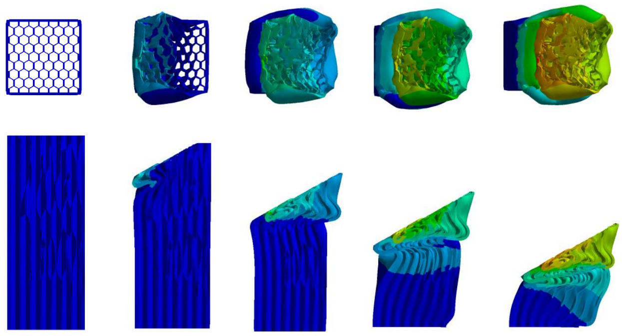

Fig. 6. Crash box deformation pattern with square-shaped honeycomb filler due to oblique load

Regarding the oblique loads, the crash box remains to collapse the global bending on all models [8], which leads to the reduction of load-carrying and energy absorption [16]. As can be seen from Table 3 and Fig. 6–8, the correlation between the deformation pattern and energy absorption capability shows that the crash box with hexagonal honeycomb filler has the highest energy absorption and SEA.

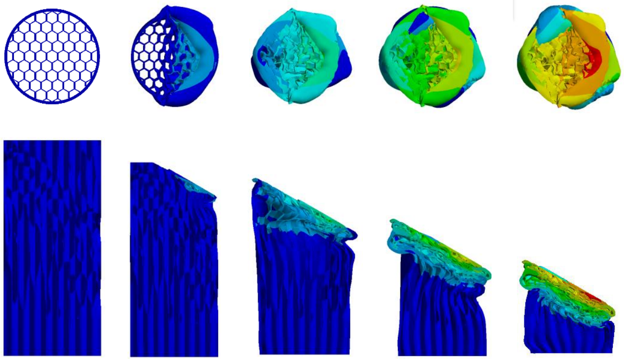

Fig. 7. Crash box deformation pattern with circle-shaped honeycomb filler due to oblique load

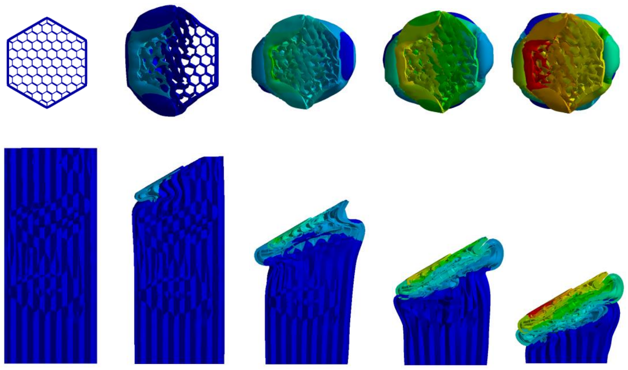

Fig. 8. Crash box deformation pattern with hexagon honeycomb filler due to oblique load

6. Discussion of research results of deformation pattern and energy absorption

The amount of energy absorption was calculated from the area under the Force curve of reaction-displacement as shown in Fig. 9, 10. In accordance with Table 2, circular crash boxes with honeycomb fillers had the highest energy absorption while hexagonal crash boxes with honeycomb fillers had the highest SEA.

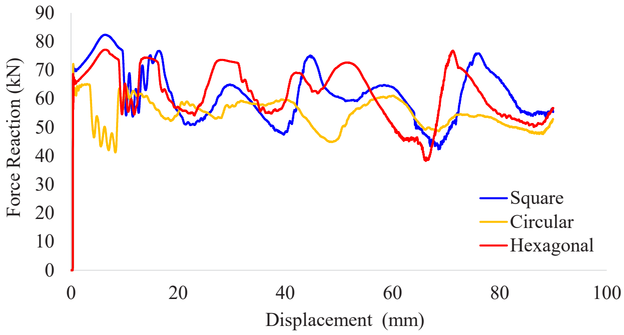

Fig. 9. Force reaction curve – displacement in 3 crash box models due to frontal load

The difference in the shape of the crash box section with the same cross-sectional area is intended to find out the comparison between variations of the crash box section. Fig. 11 showed the folding process in the hexagonal crash box as an example of the folding process in the crash box. The beginning experience of crash box folding started from the top and bottom of the crash box, where the part was the one closest to the impactor when the collision occurred (top) and the part closest to the pedestal, where the reaction force occurred (bottom). Regarding the beginning of folding, the graph of the relationship between force reaction and displacement showed the first peak, which indicated the emergence of a peak on the graph, then folding would occur in the crash box. Furthermore, folding would continue to form along with the load given to the crash box.

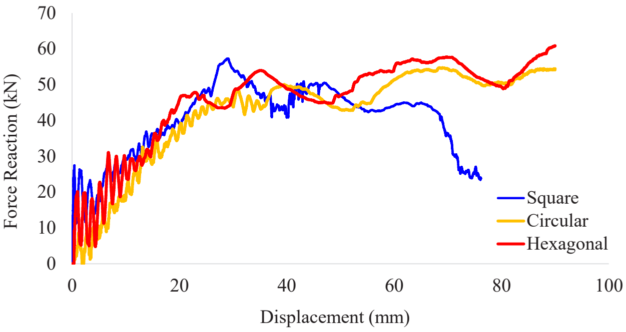

Fig. 10. Force reaction curve – displacement in 3 crash box models due to oblique load

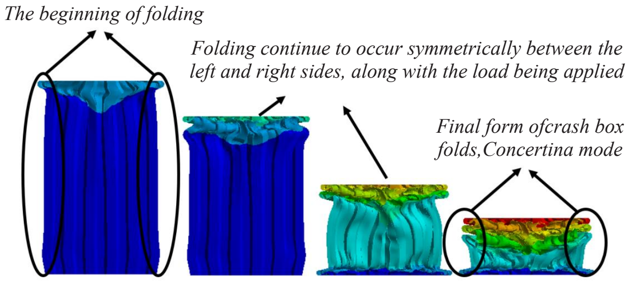

Fig. 11. Folding process in the crash box

Crash box with a circular cross-section had a different deformation pattern from other cross-sections. The occurred deformation in a crash box with a circular cross section was mixed mode. The deformation process in this crash box can be seen in Fig. 12.

At the start of loading, the crash box experienced a folding at its top with a concertina mode pattern, in accordance with the symmetrical folding between its right and left sides. Furthermore, the crash box experiences an asymmetrical folding between its right and left sides (diamond mode). Then, the crash box wall formed asymmetrical folds with increasing loading time. At the end of loading, the deformation, which occurred in the crash box showed two different patterns, concertina mode and diamond mode, so the occurred deformation pattern was a mixed mode.

The analysis of deformation pattern in the crash box with honeycomb filler can be seen through the vector of stress direction, which showed the force symbolized by arrows in different colors. The differences in colors were: red color indicated areas with high stress intensity, green color indicated areas with moderate stress intensity, and blue color indicated areas with low stress intensity. The analysis shown by the front view geometry (partial cut) and by the top view was visually observed on the vector of stress. Fig. 13 showed the stress vector in a crash box with a circular cross-section, where the spread of the occurred stress vector was indicated by an arrow with the direction at each geometry point. The deformation pattern of the crash box with a circular cross-section is marked with points A, B, C and D showing the sides of each geometry with uniform distribution of vector directions at each point symmetrically. Thus, the concertina mode deformation pattern occurred. Points E, F, G, and H were the continuation of the deformation pattern, which showed each geometry side with a non-uniform distribution of vector directions at each point, so the occurred deformation pattern was diamond mode.

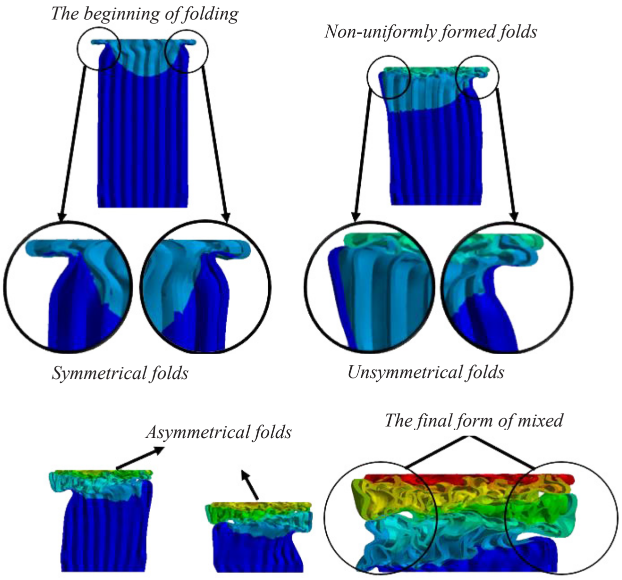

Fig. 12. Crash box deformation process with circular honeycomb filler

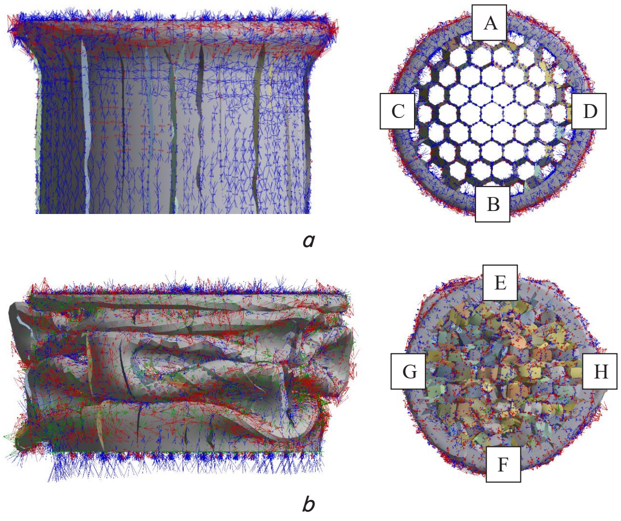

Fig. 13. Distribution of principle stress in the crash box with circular honeycomb filler: *a* – at the beginning of deformation; *b* – until the final deformation

Crash box with hexagon-shaped honeycomb filler had the highest energy absorption and specific energy absorption of 5611.89 Joule and 24.626 kJ/kg, respectively with concertina mode deformation patterns. Fig. 14, 15 showed deformation patterns and force reaction-displacement graphs of hexagon-shaped crash boxes with honeycomb fillers and without honeycomb fillers.

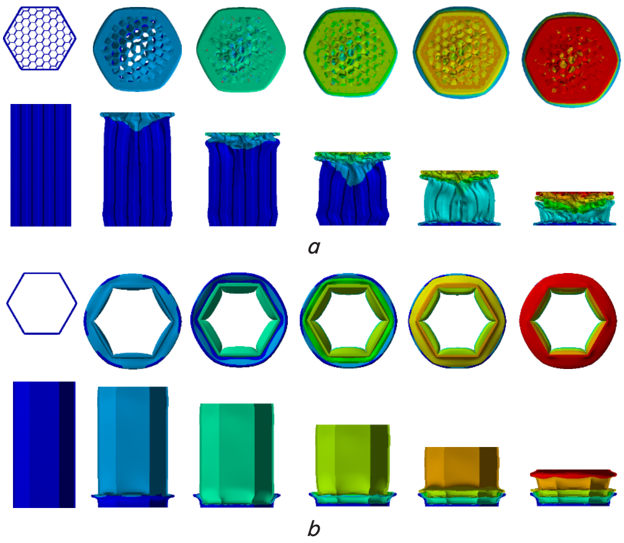

Fig. 14. Deformation pattern of hexagonal crash box: *a* – with honeycomb filler; *b* – without honeycomb filler

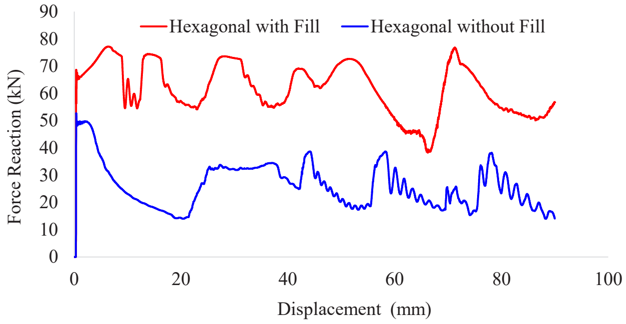

Fig. 15. Graph of force reaction-displacement of the hexagonal crash box

The Ea value of the hexagonal crash box with filler and without filler was 5611.89 Joule and 2245.85 Joule, respectively. From these results, it appeared that a crash box with the addition of aluminum honeycomb as a filler would increase energy absorption significantly. Hexagonal crash box without filler experienced a very high first peak compared to the peak afterwards. This showed that there is a decrease in the critical load received by the crash box as the loading time increases, which causes the next peak to be lower than the first peak.

Crash Force Efficiency (CFE) is a percentage, which states the ability of structures to experience buckling. The lower the CFE value means the more difficult the crash box experiences the first folding. Based on the obtained data, the CFE value of the hexagonal crash box with honeycomb filler and hexagonal crash box without filler can be seen in Table 4.

Table 4

Large CFE crash box in hexagonal shape with and without honeycomb filler

Hexagonal Crash box	Pmean (kN)	Pmax (kN)	CFE
With Filler	61.29281215	68.63262	0.893
Without Filler	25.65416493	52.34441	0.490

From Table 4, it can be seen that the hexagonal crash box with honeycomb filler has the largest CFE value. This showed that the addition of aluminum honeycomb as a filler for the crash box will increase the amount of CFE.

7. Conclusions

1. In the frontal load test, it is found that the crash box with circle-shaped honeycomb has the highest energy absorption while the crash box with hexagon-shaped honeycomb filler has the highest SEA.
2. Based on the oblique load test, it can be denoted that the crash box with hexagonal honeycomb filler has the highest energy absorption and SEA. The percentage of energy absorption decrease varied between 26 % and 38 % for all models.
3. Hexagonal crash box with honeycomb filler has a greater CFE value than hexagonal crash box without honeycomb filler with a significantly different value (CFE=0.893 and CFE=0.490). This shows that the addition of aluminum honeycomb as a filler for the crash box will increase the amount of CFE.

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