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Effect of Cross-Sectional Shape on Energy Absorption in Crash Boxes

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Keywords : Finite Element Analysis, Crash Box, Energy Absorption

ABSTRACT

Vehicle accidents are a growing concern in today's society. To address this issue, extensive research has been conducted to determine the most effective design for the crash box, a passive safety element. In this study, the performance of cylindrical, square and hexagonal crash boxes has been extensively investigated to determine the optimal choice for a given area. To evaluate the crash boxes, specific energy absorption and crush reaction force were considered as evaluation criteria. Energy absorption of the cylinder design, it provides less energy absorption than the square and hexagonal design. It produces much less peak reaction force than the square and hexagonal crash box. The amount of compression is also much less than square and hexagonal.

INTRODUCTION

Since the invention of the wheel, technology has developed rapidly and people have produced vehicles to meet the need for transportation. In the world report on the prevention of traffic accidents prepared by the World Health Organization, approximately 1.2 million people lose their lives every year in road traffic accidents and approximately 20 to 50 million people are injured and disabled every year. Traffic accidents account for 2.1% of all deaths in the world (Security, 2023). In the early days, human beings took care to develop vehicles with high strength to ensure their safety (Lee et al., 2022). In the following process, it was observed that the force generated in the collision would increase with increasing mass and would be fatal for many more passengers.

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With the developing technology, passive safety measures have been developed that are much lighter and can absorb mechanical energy in the event of a collision. As we know from the principle of conservation of energy, the high energy generated during a collision does not disappear but is transformed. In order to protect the passengers in the event of an impact, elements that will absorb the collision energy and deform plastically have started to be used.

In order to protect the passengers in the event of an impact, elements that will absorb the collision energy and deform plastically have started to be used. These elements are called crash boxes. Crash boxes are designed in possible areas that may cause fatal accidents in the collision of vehicles. These crash boxes convert the mechanical energy that occurs during the collision into plastic energy and heat energy by over-deforming with the effect of the collision force. In this way, the collision force and energy are damped so that the passenger feels the minimum. Academic research has been conducted to increase energy conversion on crash boxes. Academic studies can be divided into three general categories. The design of crash boxes, crash box material improvements and loading conditions are the main focal points of investigation. These three main focal points determine how much of the energy generated during the collision can be absorbed (Abdullah et al., 2020). In past studies, tests have been carried out with different sizes and different materials to improve the performance of crash boxes. The ability to maintain high energy absorption with progressive buckling of the crash box is a critical design goal. In addition, crash boxes have been tried to increase the amount of energy absorbed by creating multicellular structures or applying material reinforcements (Ceyhan & Yıldız, 2023).

The crash performance of thin-walled crash boxes with various cross-sectional geometries has been a subject of curiosity for many engineers. In a study by Nasir Husseyin et al, the energy absorption properties of glass fiber reinforced plastic (GFRP) crash boxes of different geometries were investigated in depth. In his study, it was observed that the absorbed energy ratio of the crash boxes subjected to axial crush loading increased in square, cylindrical, hexagonal, and dodecagonal geometries, respectively. When the maximum reaction force was examined, the maximum reaction force occurred in the dodecagonal structure. The lowest maximum reaction force occurred in the square crash box (Hussain et al., 2017).

Nia and Hamedani investigated the effect of geometric shapes of aluminum crash boxes on crash performance. They examined the crash boxes under quasi-static loads and at the end of their research, they observed that the maximum absorbed energy per unit mass was in crash boxes with a cylindrical cross-sectional shape. In their study, a decrease in energy absorption capacity was observed as the number of sides decreased. It was determined that crash boxes with triangular cross-section have less energy absorption capacity than square or rectangular crash boxes. It was also observed that the gradual increase in cross-sectional area affects the maximum and average force phenomena as well as the energy absorption capacity. It was found that reducing the cross-sectional area significantly reduces the maximum load. Nia and Hamedani made a great contribution to the literature by verifying the analysis results with test results. In the design of crash boxes, the crushing force of the crash box is required to be above a certain value throughout the crush (Nia & Hamedani, 2010). The work done by the crushing force is equal to the crushing force and the length of the crush line. It has been observed in the literature that defects are added to the crash box to make the behavior of the crash box predictable. Ferdynus et al. observed in their study that crush efficiency is significantly improved by adding indentations (Ferdynus et al., 2020). The crush pattern of crash boxes with high width-to-thickness ratio is highly correlated with manufacturing defects. The folding pattern of crash boxes is a function of different parameters such as width-to-thickness ratio, material properties, load and defects. The application of the defect causes faster stress concentration in the defect region and has been observed to prevent the differentiation of the folds in the crash box (Jafarzadeh-Aghdam & Schröder, 2022).

With the increasing speed of vehicles in the automotive industry, studies are continuing to ensure that crash boxes can absorb much more energy in the event of an accident. We can divide the tests performed on new different materials to improve the performance of automotive crash boxes into three main categories. The materials used to produce a crash box can be classified as metal/alloy, composite and composite-metal/alloy.

When aluminum is used in the body structure of a vehicle, weight savings of up to 25% are possible compared to conventional steel structures, which will reduce fuel consumption and therefore carbon dioxide (CO_2) emissions. Furthermore, aluminum has good corrosion resistance and can be made reusable with an energy input equal to 5% of the energy required to produce aluminum (Langseth et al., 1998). When comparing aluminum alloys with commonly used steel grades, aluminum has lower yield and ultimate strength. This means that an aluminum component must be thicker to absorb as much energy as steel. Increased thickness, coupled with the generally lower ductility of aluminum compared to steel, can increase material damage during deformation.

Composite materials are increasingly used in crash boxes where high energy absorption is required. They have been observed to absorb more energy per mass than aluminum steel and its derivatives. Due to the anisotropic nature of composite materials, it is difficult to create and design the correct material model compared to collision boxes made of aluminum and steel derivatives. Composite materials are affected by environmental influences. Since the production of composite materials is much more expensive than aluminum and steel, they are generally preferred in racing cars in the aviation industry than in conventional cars. Hou et al managed to increase the specific energy absorption (SEA) by 16% using carbon fiber reinforced polyamide 6 (PA6/CF) composites (Hou et al., 2023).

Crash boxes are subject to varying loading conditions. The speed and direction of the collision can change in each case. All possible loading conditions must be considered. In the event of a collision, the vehicle may be subjected to many different loads. When designing the vehicle, the design is made depending on the loading conditions in Figure 1. In this way, the possibility of injury in possible accidents is minimized. In this work, the axial load case is examined.

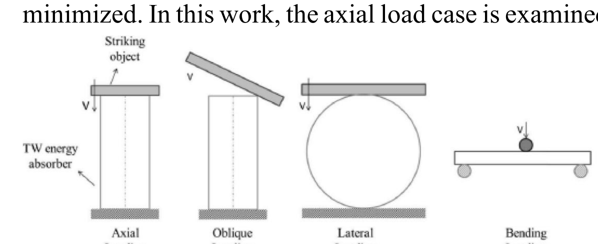

Fig. 1. Loading condition of the crash box (Baroutaji et al., 2017).

The Abaqus program is used for finite element analysis in many fields. For example, Maqableh and Hatamleh analyzed Dental Fiber-Silicone Polymer with the Abaqus program (Maqableh & Hatamleh, 2023). The model they developed is in good agreement with the experimental results in the part before the peak load. Rathnasabapathy et al. created a finite element model of the response of fiber metal laminates to impact under prestress (Rathnasabapathy et al., 2022). With the finite element model they developed, they can also calculate the delamination damage in both metal sheets and composite sheets.

There are also finite element analyses in ABAQUS related to the additive manufacturing process. For example, Polyzos et al. performed delamination analysis of 3D printed composites, while Hachimi et al. performed a finite element analysis of the 3D printing process (Hachimi et al., 2024; Polyzos et al., 2023).

Alidoust et al. developed an analytical model of resistance variation in CNT elastomer nanocomposites (Alidoust et al., 2024). They determined that lower CNT content yielded more significant resistance changes due to fewer percolation pathways. Cui et al. analyzed scraping forces (Cui et al., 2023). In this study, they were based on the orthogonal cutting model. Wu et al. analyzed the cutting process of stone-plastic composite (Wu et al., 2023). The orthogonal cutting model was also used in this study. The ribbon chip deformation process also proved to be the most stable. Jemal et al. performed a finite element analysis of press-brake bending of sheet metal (Jemal et al., 2024). They found that the material thickness affects the amount of springback.

The main objective of the our research is to investigate the exposure of crash boxes of various designs to axial impact loading and to evaluate their energy damping characteristics. This evaluation will be carried out using the finite element method. The crash box should be designed so that it does not exceed a certain area and length depending on the body length and design of the vehicle. In this research, designs of different thicknesses with different cross-sectional designs will be compared with each other. As a result of the literature research, it was observed that by using different designs in crash boxes, the maximum reaction force is not desired to exceed a certain value while absorbing the maximum collision energy that occurs during the accident. For this reason, it has been observed that different designs and different design sizes are tried to obtain a better crash box. In the research process, the length of the crash box is considered constant in order to reduce the number of variables in the crash box. At the end of this study, it aims to contribute to overall vehicle safety by increasing the reliability and effectiveness of crash boxes. It aims to maximize the average energy absorption of crash boxes developed for specific conditions and purposes.

MATERIALS AND METHOD

In this study, the crash box is analyzed in detail in three different cross-sections: circle, square and hexagonal. Here, considering that the crash box should fit in a certain area on the chassis, this area is considered as a constraint. The cross-section diameter was analyzed to vary between 40 mm and 55 mm. Wall thicknesses were assumed to vary between 2.5 mm and 3.5 mm (Figure 2). A comprehensive database of crash speed (FARS) crash parameters shows that at least 90 percent of all frontal crashes occur at speeds up to 56 km/h. Using this information, the crash speed was determined. In case of impact, the impact speed of a 100 kg mass was considered as 60 km/h (Witteman, 1999).

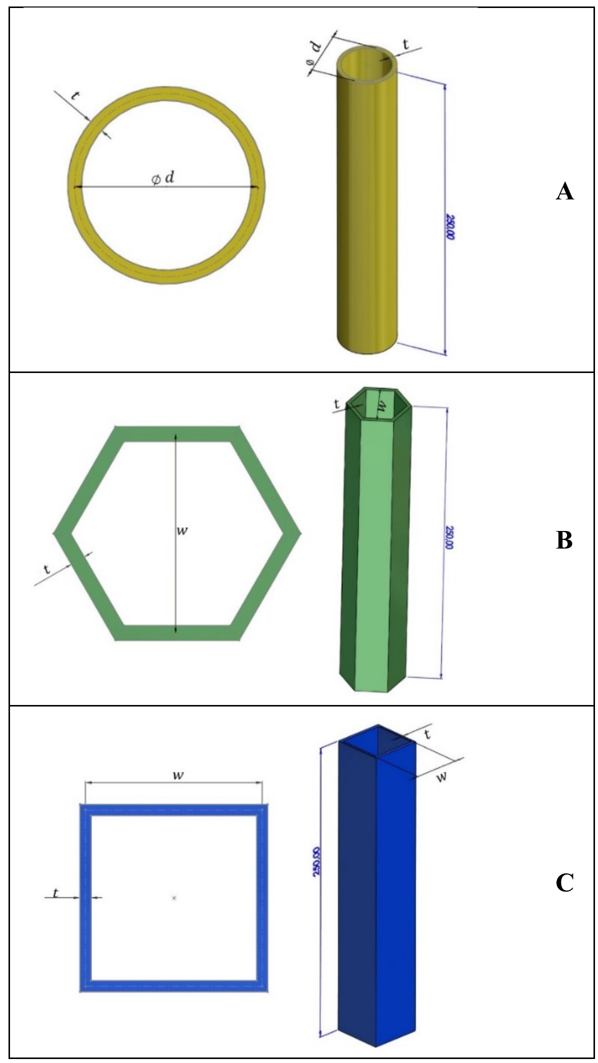

Fig. 2. Diameter of crash boxes

A total of 36 analyses were performed for 3 different geometries. The material of the crash box is AA6063-T6 aluminum alloy. The reason for this is that T6 aluminum alloy has been shown to have a weak sensitivity to strain rate (Dubey et al., 2023). In order to obtain a result very close to the real results, a material with minimum external factor dependence was preferred (Singh et al., 2012). Mechanical properties of aluminum 6063-T6 alloy are given in Figure 3 and chemical properties are given in Table 1.

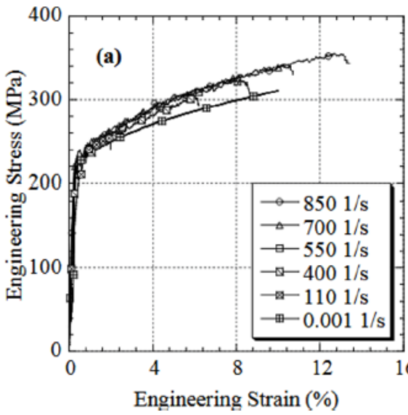

Fig. 3. Mechanical Properties of Aluminium 6063-T6 (Singh et al., 2012)

Table 1. Materials % by weight (*Web Page*, n.d.)

Al	Mg	Mn	Si	Fe	Cu
98.67	0.567	0.022	0.415	0.148	0.055
Ni	Zn	Ti	Cr	Pb	Sn
0.040	0.030	0.003	0.005	0.010	0.025

The above material parameters were used as analysis inputs (Dirschmid et al., 2005). As a result of academic research, it has been observed that BMW has been using ABAQUS software in vehicle design analysis since 1986. Between 2001 and 2003, Dassault Systemes was contracted by BMW and ABAQUS was used in the development of the BMW 5 Series model. ABAQUS was declared to be highly accurate in modelling material behaviour and capturing important physical responses of automotive components and systems. ABAQUS has sufficient crashworthiness capability and has been validated by testing a range of crash loads with real BMW models. ABAQUS is used exclusively for all crashworthiness simulations (Dirschmid et al., 2005; Gülçimen Çakan et al., 2019; Hou et al., 2023). All analysis inputs and work were done with 3DEXPERIENCE structural mechanics engineer role using the abaqus solver.

Mesh size 3 mm was preferred, quad elements were used whenever possible. Element type S4R with indriginated integration point was used as the element. As can be seen in Figure 5 (a), there is no element defect when the mesh quality is examined. When deciding the element size, the analysis was repeated with a smaller element size and the change in the results was examined. It was observed that the change in the results was limited, 3 mm mesh size was preferred to get faster results.

As shown in Figure 4, the pink and blue colored parts are considered rigid. The blue part is defined as having a constant weight of 100 kg and moving downward at an initial velocity of 16.66 m/sec. During the collision, the amount of friction during the crushing of the crash box will also have an effect on the analysis results. Therefore, the coefficient of friction of the dry metal is defined to be 0.2. It is defined how many mm the rigid part in blue is displaced and the reaction forces in the pink colored part should be monitored during the analysis.

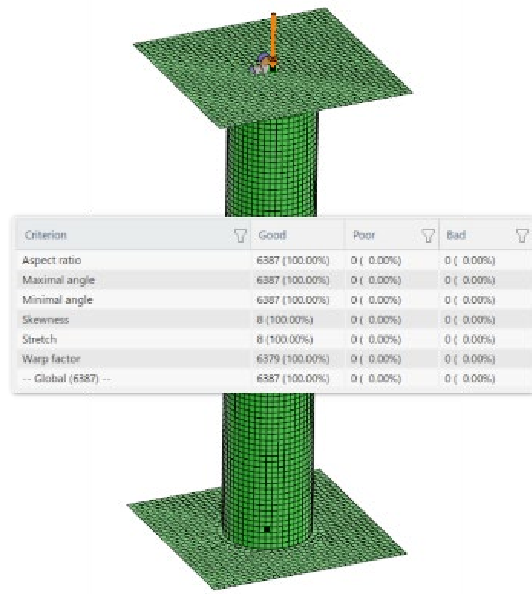

Fig. 4. Mesh quality and boundary conditions.

From past to present, certain indicators have been established in scientific researches in order to correctly analyze and correctly interpret crash boxes (thin-walled structures), which are passive safety elements. It is possible to evaluate the performance of the crash box by looking at the graph shown in the Force - Displacement graph (Figure 5). To interpret the graph below, F_{maks} is the maximum amount of force generated during the collision. $F_{avarege}$ is the average reaction force that occurs as the crash box starts to crush (Rogala et al., 2021).

The area under the Force - Displacement graph shows us the amount of energy absorbed. In other words, the total absorbed energy is defined as the work done by the crushing force (Rogala et al., 2021). Equation 1, F corresponds to the crushing force, while l_0 the length at the start of the collision. $l_0 - l_1$ the amount of crushing that occurs during the collision.

Equation 2 expresses the total amount of energy dissipated by the crash box divided by the amount of crushing that occurred during the collision (Dirgantara et al., 2013).

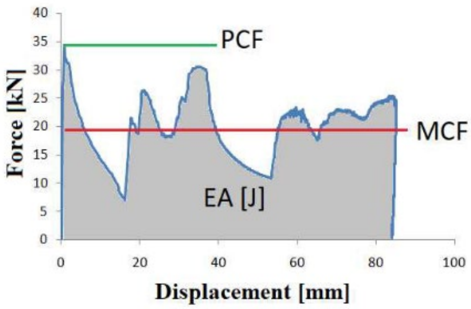

Fig. 5. Example of force-displacement characteristics of an energy absorber (Rogala et al., 2021).

$$\boldsymbol{E_T} = \int_{l_0}^{l_1} F dl \quad (1)$$

$$\boldsymbol{F_{ort}} = \frac{\boldsymbol{E_T}}{\boldsymbol{l_1 - l_0}} \quad (2)$$

The crash box is required to absorb energy during the collision. The peak value of the crash force is the maximum reaction force that occurs during the crash and this value is desired to be as close to the average reaction force as possible. The reason for this is that injuries may occur with the sudden reaction force during the collision, and in order to minimize this possibility, it is necessary to have a controlled maximum crushing force (Dirgantara et al., 2013).

Vehicles are tried to be designed as light as possible, so it is important that the crash boxes are also light. In order to evaluate the crash box design, the amount of energy per unit mass is an important crash box performance measurement criterion. Specific energy absorption is expressed in detail in Equation 3 (Dirgantara et al., 2013).

$$\boldsymbol{E_m} = \frac{E_T}{m} \quad (3)$$

RESULTS AND DISCUSSION

The crash box should absorb as much energy per unit mass as possible. It is one of the most important parameters to be evaluated during design verification. As a result of these definitions, the following analysis results were obtained. Hexagonal design analysis parameters and results are given in Table 2. This table shows the dimensions and thickness of each design. It also shows the maximum peak force and specific energy absorption of each design. When the table is examined, it is seen that the smallest specific energy absorption occurs in the 2nd design (55 mm width, 3.5 mm thickness). The highest specific energy absorption occurred in the 3rd design (40 mm width, 2.5 mm thickness). This is because the part in the 3rd design has the smallest mass. This is because the specific energy absorption is obtained by dividing the energy absorption by the mass (Chen et al., 2021; Özen et al., 2023).

Table 2. Analysis parameters and hexagonal design results

	Case												
Design Parameters		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	Width (mm)	50	55	40	50	55	45	45	55	40	40	50	45
	Thickness (mm)	3	3.5	2.5	2.5	2.5	2.5	3	3	3	3.5	3.5	3.5
Analysis Results	Crash Box Mass (kg)	0.3507	0.4501	0.2338	0.2923	0.3215	0.2631	0.3157	0.3858	0.2806	0.3274	0.4092	0.3683
	Total Amount of Damped Energy (kj)	13.84	14.19	14.74	13.85	13.87	14.07	14.4	13.89	14.14	13.94	14.01	13.81
	Maximum Peak Force (kN)	132.4	171.5	188.5	108.1	118.4	125.1	123.6	143.8	114.5	140.6	159.7	150.7
	Crash Box Compression Amount (mm)	144.4	110	210.9	192.6	191.7	194.4	151.1	138.8	183.4	133.2	112	111
	Specific Energy Absorption (SEA)	39.5	31.5	63.0	47.4	43.1	53.5	45.6	36.0	50.4	42.6	34.2	37.5

Graphs of the design analysis are given below. Figure 6 shows the analysis results for the hexagonal design, Figure 7 shows the analysis results for the square design and Figure 8 shows the analysis results for the circular design. In these analyses, a peak force of 150 kN was considered as the limit value (Hou et al., 2023). The reason for this is that the high reaction force may cause a sudden acceleration of the passenger in the event of a collision. The crush force closer to this limit value is better.

For hexagonal designs, a design with a width of 40 mm and a thickness of 3 mm was chosen as the optimum design (Figure 6). This is because it produces the highest specific energy absorption with a peak force much less than 150kN reaction force. The reason why the reaction force is too high is that the structure is too rigid in designs with low displacement and the structure does not have enough rigidity in designs with high displacement.

The best square crash box design was found to be the design with a width of 40 mm and a thickness of 2.5 mm (Figure 7). The specific energy absorption of the optimum square crash box design was found to be 52.

For the cylindrical crash box, the optimum design is a 40 mm wide by 3 mm thick cylindrical design. This is because it produces the highest specific energy absorption with a peak force much less than the 150kN reaction force. Designs 2, 3, 4, 6 are above this limit. The reason why the maximum peak force is too high in these designs is that the crash box does not have the optimum thickness. Designs numbered 3,4,6 were not rigid enough, so too much deformation occurred and produced high reaction force at the end of deformation. Design number 2 produces high reaction force because it is designed too rigid (Figure 8).

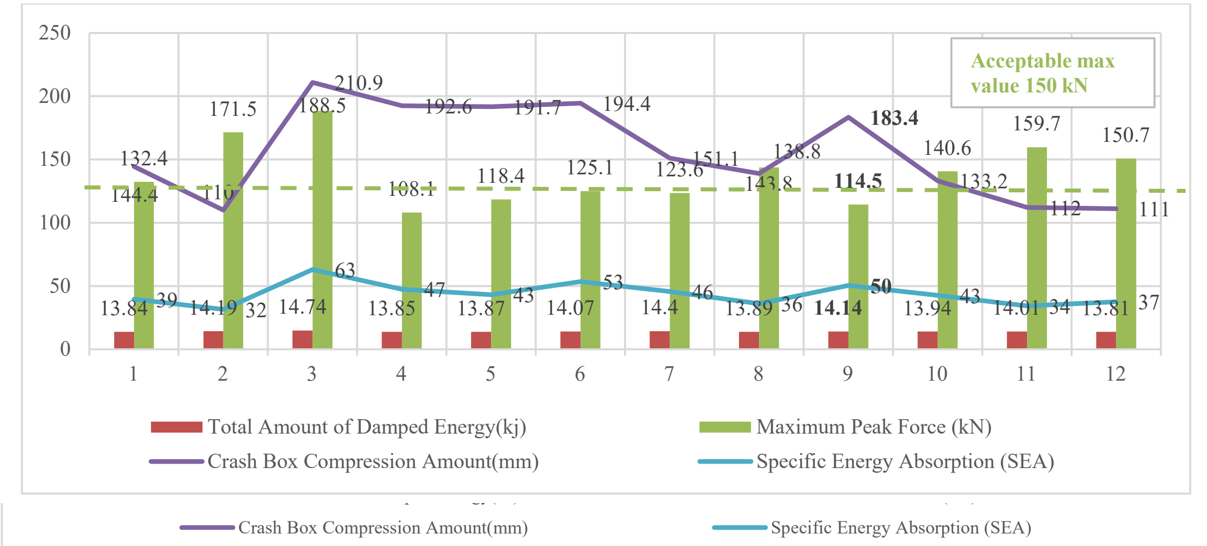

Fig. 7. Square analysis results.

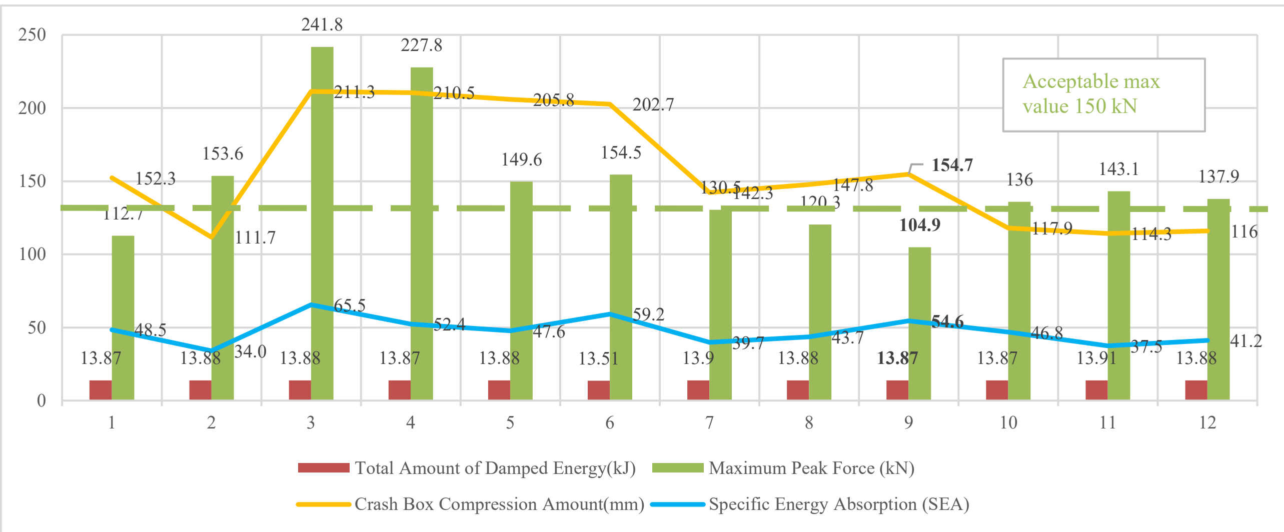

Fig. 8. Circular design analysis results.

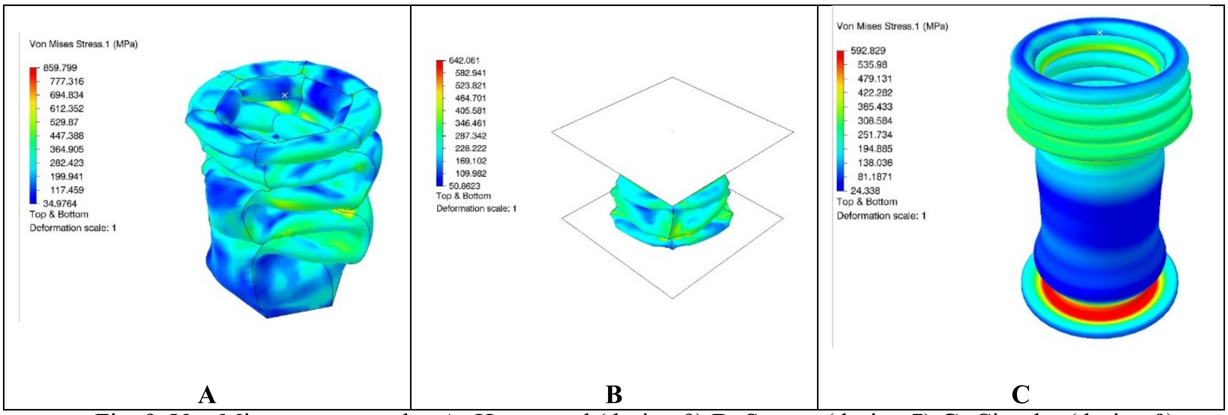

Fig. 9. Von Mises stress graphs. **A:** Hexagonal (design 9) **B:** Square (design 7) **C:** Circular (design 9).

Graphs of Von Mises stress distributions are given in Figure 9. Figure 9.A shows the analysis results for the hexagonal design, Figure 9.B shows the analysis results for the square design and Figure 9.C shows the analysis results for the circular design.

In hexagonal design, the models named as Design 3, Design 4, Design 5, Design 6 were deformed very much. The models named as Design 10, Design 11, Design 12 had very little displacement in case of collision. The fact that the model has very little displacement shows us that the model is too rigid. The models named as Design 3, Design 9, Design 10 do not produce a symmetrical deformation shape under axial load. This result shows us that care should be taken in the designs.

In the stress analysis of the square crash box, the models named as Design 1, Design 3, Design 4, Design 5, Design 6, Design 8 were deformed too much. Too much displacement of the model shows us that the model is not rigid enough.

In the stress analysis of the cylindrical crash box, it is observed that the models named as Design 3, Design 4, Design 5, Design 6 undergo too much deformation. Too much displacement of the model shows us that the model is not rigid enough. When the stress graphs are visually analyzed, it is observed that the models named as Design 2, Design 10, Design 12 undergo very little deformation. The fact that the model has very little displacement shows us that the model is too rigid.

The reaction force-displacement graph of the crash boxes is given in Figure 10. It can be seen that axial crushing occurs in many designs. Figure 10.A shows the analysis results for the hexagonal design, Figure 10.B shows the analysis results for the square design and Figure 10.C shows the analysis results for the circular design.

In the hexagonal design, Design 3 and Design 6, it is observed that the reaction force increases excessively as the displacement increases. Here we can infer that the collision force does not have enough rigidity and is easily crushed. This is undesirable in conventional crash boxes (Reyes et al., 2004). The hexagonal crash box has been analyzed with cross-sections ranging from 40 mm to 55 mm in width and thicknesses ranging from 2.5 mm to 3.5 mm. The cylindrical design with a width of 40 mm and a thickness of 3 mm was selected as the most optimum design. This is because it produces the highest specific energy absorption with a peak force much less than the 150kN reaction force.

In the displacement analysis of the square crash box against the reaction force, axial crushing occurred in many designs. In the graph named as Design 3, Design 4, Design 5, Design 6, it was determined that the compression was too much. From this we can infer that the impact force does not have enough rigidity and is easily crushed.

In the reaction force versus displacement analysis of the cylindrical crash box, it is observed that the reaction force increases excessively as the displacement increases in the graph named as Design 3, Design 4, Design 5, Design 6. The width of the cylindrical crash box varies from 40 mm to 55 mm. The section thickness varies from 2.5mm to 3.5mm. The optimum design was selected as a cylindrical design with a width of 40 mm and a thickness of 3 mm. This is because it produces the highest specific energy absorption with a peak force much less than the 150kN reaction force.

Design and analysis parameters and analysis results for the square crash box are given in Figure 8 and Figure 9. The maximum peak force available for a square crash box in these dimensions is 150 kN. Designs 2, 3, 4, 6, 11 are above this limit. When the designs that meet this condition are analyzed, it is seen that the design named 7 has the highest performance in terms of specific absorption value.

In the Figure 11, collision boxes of different geometries are compared with each other. Each crash box was evaluated on its own. The best design among the hexagonal crash boxes is design 6. The best design among the Square crash boxes is the 7th design. The best design among the cylindrical crash boxes is the 9th design. Figure 11 shows that the cylinder design has the highest specific energy absorption rate. When we look at the energy absorption of the cylinder design, it provides less energy absorption than the square and hexagonal design. It produces much less peak reaction force than the square and hexagonal crash box. The amount of compression is also much less than square and hexagonal.

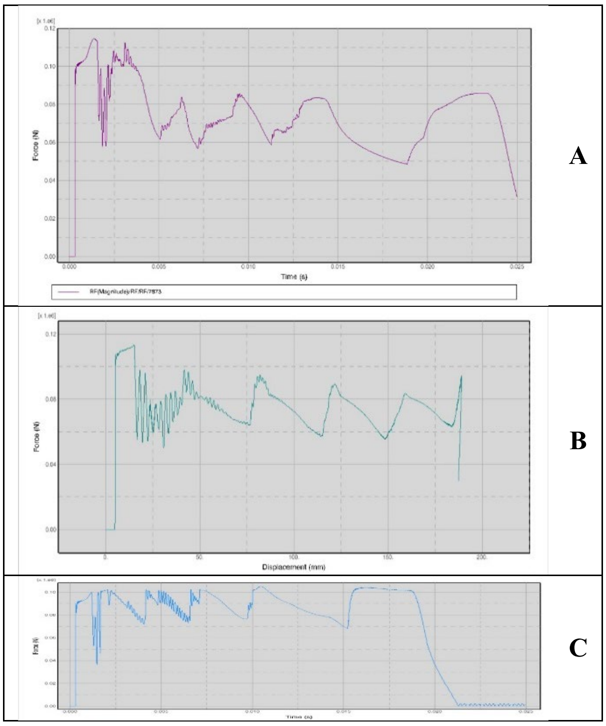

Fig. 10. Relationship between reaction force and crush amount. **A:** Hexagonal **B:** Square **C:** Circular

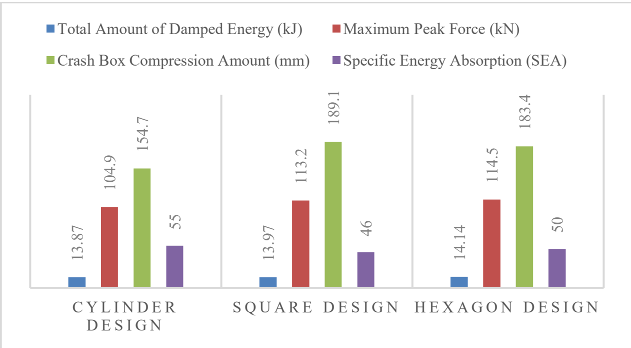

Fig. 11. Comparing of the crash box geometries

Figure 12 shows the cross section of the crash box. When the cross section is examined, it is seen that the crash box is crushed in certain steps under load. This result confirms the force and displacement graph.

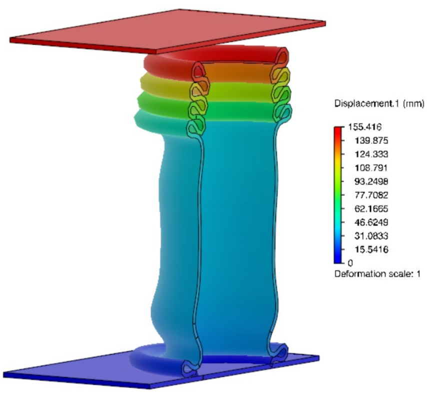

Fig. 12. Cross section of the crash box analysis

CONCLUSIONS

Crash boxes are an effective solution to ensure driver and passenger safety in the automotive industry. In this study, a series of analyses were performed for the optimal design of the crash box. The following conclusions were reached within the scope of the study:

- Cylindrical geometry is the design that performs best within the specified limits.
- The cylindrical crash box provides maximum energy absorption compared to hexagonal crash boxes.
- The specific energy absorption of the cylinder collision box is much better than the others.
- The cylindrical crash box showed much less crushing. This shows that if the crash box is crushed more, the cylindrical crash box will perform better.
- The cylindrical crash box produces the maximum peak reaction force at reasonable values.
- The cylindrical design will cause the crash acceleration to be felt more clearly by the passengers in an accident where it is crushed much more than the 4-name crash box and where the maximum peak force is 2 times that of the other designs. Under these criteria, the best crash box is a cylindrical tube 250 mm long, 40 mm in diameter and 3 mm thick.

Considering the demand for lighter designs today, a cylindrical crash box seems to be more suitable. This optimum design can be used in the automotive industry, especially in passenger vehicles. As a continuation of this study: analyses can be performed for different materials with cylindrical crash box geometry.

REFERENCES

Abdullah, N. A. Z., Sani, M. S. M., Salwani, M. S., & Husain, N. A. (2020). A review on crashworthiness studies of crash box structure. *Thin-Walled Structures*, *153*(July 2019), 106795. https://doi.org/10.1016/j.tws.2020.106795

Alidoust, A., Haghgoo, M., Ansari, R., Kazem Hassanzadeh-Aghdam, M., & Jang, S. H. (2024). A finite element percolation tunneling approach on the electrical properties of carbon nanotube elastomer nanocomposite pressure sensors. *Composites Part A: Applied Science and Manufacturing*, *180*(February), 108111. https://doi.org/10.1016/j.compositesa.2024.108111

Baroutaji, A., Sajjia, M., & Olabi, A. G. (2017). On the crashworthiness performance of thin-walled energy absorbers: Recent advances and future developments. *Thin-Walled Structures*, *118*(November 2016), 137–163. https://doi.org/10.1016/j.tws.2017.05.018

Ceyhan, M., & Yıldız, B. (2023). Investigation of Crash Performance of Multi-Cell Crash-Boxes. *Çukurova Üniversitesi Mühendislik Fakültesi Dergisi*, *38*(3), 613–621.

https://doi.org/10.21605/cukurovaumfd.1377191

Chen, Y., Ye, L., Zhang, Y. X., & Fu, K. (2021). Compression behaviours of 3D-printed CF/PA metamaterials: Experiment and modelling. *International Journal of Mechanical Sciences*, *206*(June), 106634. https://doi.org/10.1016/j.ijmecsci.2021.106634

Cui, Z., Han, L., Dong, G., Gao, Y., & Fan, S. (2023). Modeling and analysis of scraping forces using finite element method. *International Journal of Advanced Manufacturing Technology*, *129*(3–4), 1869–1882. https://doi.org/10.1007/s00170-023-12339-4

Dirgantara, T., Gunawan, L., Putra, I. S., Sitompul, S. A., & Jusuf, A. (2013). Numerical and experimental impact analysis of square crash box structure with holes. In *Applied Mechanics and Materials* (Vol. 393, pp. 447–452). https://doi.org/10.4028/www.scientific.net/AMM.393.447

Dirschmid, F., Hooputra, H., Mader, H. U., & Werner, H. (2005). Migration of Crash Simulation Software at BMW. *ABAQUS Users' Conference*, 1–11.

Dubey, R., Jayaganthan, R., Ruan, D., Gupta, N. K., Jones, N., & Velmurugan, R. (2023). Energy absorption and dynamic behaviour of 6xxx series aluminium alloys: A review. *International Journal of Impact Engineering*, *172*(October 2022), 104397. https://doi.org/10.1016/j.ijimpeng.2022.104397

Ferdynus, M., Rozylo, P., & Rogala, M. (2020). Energy absorption capability of thin-walled prismatic aluminum tubes with spherical indentations. *Materials*, *13*(19), 1–19. https://doi.org/10.3390/ma13194304

Gülçimen Çakan, B., Ensarioğlu, C., & Çakır, M. C. (2019). Comparison of mechanical performances of the crash-boxes filled with various percentages of aluminium foam. *J. BAUN Inst. Sci. Technol.*, *21*(1), 295–305. https://doi.org/10.25092/baunfbed.547179

Hachimi, T., Majid, F., Zekriti, N., Rhanim, R., & Rhanim, H. (2024). Improvement of 3D printing polymer simulations considering converting G-code to Abaqus. *International Journal of Advanced Manufacturing Technology*, 5193–5208. https://doi.org/10.1007/s00170-024-13300-9

Hou, W., He, P., Yang, Y., & Sang, L. (2023). Crashworthiness optimization of crash box with 3D-printed lattice structures. *International Journal of Mechanical Sciences*, *247*(November 2022), 108198. https://doi.org/10.1016/j.ijmecsci.2023.108198

Hussain, N. N., Regalla, S. P., & Rao Yendluri, V. D. (2017). Numerical investigation into the effect of various trigger configurations on crashworthiness of GFRP crash boxes made of different types of cross sections. *International Journal of Crashworthiness*, *22*(5), 565–581. https://doi.org/10.1080/13588265.2017.1286964

Jafarzadeh-Aghdam, N., & Schröder, K. U. (2022). Mechanism of reproducible axial impact of square crash boxes. *Thin-Walled Structures*, *176*(May), 109062. https://doi.org/10.1016/j.tws.2022.109062

Jemal, A., Salau, A. O., & Wondimu, A. (2024). Finite element method–based multi-objective optimization of press-brake bending of sheet metal. *International Journal of Advanced Manufacturing Technology*, *130*(9–10), 4263–4275. https://doi.org/10.1007/s00170-023-12942-5

Langseth, M., Hopperstad, O. S., & Hanssen, A. G. (1998). Crash behaviour of thin-walled aluminium members. *Thin-Walled Structures*, *32*(1–3), 127–150. https://doi.org/10.1016/S0263-8231(98)00030-5

Lee, C. H., Hung, C. H., Lee, P. K., Chiuhuang, C. K., & Chen, F. K. (2022). A Study on Hot Stamping of Tailor Welded Blanks. *Journal of the Chinese Society of Mechanical Engineers*, *43*(5), 431–440.

Maqableh, A. M., & Hatamleh, M. M. (2023). Cohesive Zone Modeling of Pull-Out Test for Dental Fiber–Silicone Polymer. *Polymers*, *15*(18). https://doi.org/10.3390/polym15183668

Nia, A. A., & Hamedani, J. H. (2010). Comparative analysis of energy absorption and deformations of thin walled tubes with various section geometries. *Thin-Walled Structures*, *48*(12), 946–954. https://doi.org/10.1016/j.tws.2010.07.003

Özen, İ., Gedikli, H., & Aslan, M. (2023). Experimental and numerical investigation on energy absorbing characteristics of empty and cellular filled composite crash boxes. *Engineering Structures*, *289*(April). https://doi.org/10.1016/j.engstruct.2023.116315

Polyzos, E., Van Hemelrijck, D., & Pyl, L. (2023). An Open-Source ABAQUS Plug-In for Delamination Analysis of 3D Printed Composites. *Polymers*, *15*(9). https://doi.org/10.3390/polym15092171

Rathnasabapathy, M., Mouritz, A. P., & Orifici, A. C. (2022). Finite element modelling of the impact response of fibre metal laminates under tension preloading. *Composites Part A: Applied Science and Manufacturing*, *157*(January), 106930. https://doi.org/10.1016/j.compositesa.2022.106930

Reyes, A., Hopperstad, O. S., & Langseth, M. (2004). Aluminum foam-filled extrusions Subjected to oblique loading: experimental and numerical study. *International Journal of Solids and Structures*, *41*(5–6), 1645–1675. https://doi.org/10.1016/j.ijsolstr.2003.09.053

Rogala, M., Ferdynus, M., Gawdzińska, K., &

Kochmański, P. (2021). The influence of different length aluminum foam filling on mechanical behavior of a square thin-walled column. *Materials*, *14*(13). https://doi.org/10.3390/ma14133630

Security, D. G. of. (2023). *Traffic Safety in the World*. http://www.trafik.gov.tr/dunyatrafikguv13

Singh, N. K., Singha, M. K., Cadoni, E., & Gupta, N. K. (2012). Strain rate sensitivity of an aluminium alloy under compressive loads. In *Advanced Materials Research* (Vol. 548, pp. 169–173). https://doi.org/10.4028/www.scientific.net/AMR.548.169

web page. (n.d.). Retrieved February 10, 2024, from https://aerospacemetals.com/

Witteman, W. J. (1999). *Improved Vehicle Crashworthiness Design by Control of the Energy Absorption for Different Collision Situations* (pp. 1–191). papers2://publication/uuid/BC6849D6-07FC-4893-BE27-1916CDD992DD

Wu, Z., Buck, D., Zhang, F., Yu, Y., Guo, X., Cao, P., & Zhu, Z. (2023). Finite element method and its application to cutting processes of stone–plastic composite. *International Journal of Advanced Manufacturing Technology*, *129*(9–10), 4491–4508. https://doi.org/10.1007/s00170-023-12601-9