



# Effect of Section Geometry and Material Type on Energy Absorption Capabilities of Crash Boxes

*Kesit Geometrisinin ve Malzeme Tipinin Çarpışma Kutularının Enerji Emme Yeteneklerine Etkisi*

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## Abstract

In this study, the energy absorption capabilities of crash boxes, which provide energy absorption during an accident in the automotive transportation sector, were investigated. For this purpose, crash boxes in two materials and four geometries, Al6063 and A36 steel, were designed. The effects of triangle, square, circular, and hexagon cross-section geometries and material type on energy absorption were investigated using the finite element method, provided that the cross-sectional areas remained the same. In order to minimize the effect of mesh size on the analysis results made with the finite element method, a mesh free preliminary study was performed. Then crash boxes made of all geometric sections and materials were subjected to crash tests under the same boundary conditions. As a result of the analysis, damage patterns, force-time curves, and energies absorbed by crash boxes were obtained. According to these results, the order from the most energy absorbing to the least energy absorbing geometry is hexagon, circle, square, and, triangle. The same results were obtained for both material types. Steel material showed about ten times more reaction force than aluminum material.

**Keywords:** Crash box, Crashworthiness, Finite element method, Geometric section.

## Öz

Bu çalışmada, otomotiv sektöründe kullanılan ve meydana gelen bir kaza sırasında enerji absorpsiyonunu sağlayan çarpışma kutularının enerji absorpsiyon yetenekleri araştırılmıştır. Bu amaçla Al6063 ve A36 çelik olmak üzere iki farklı malzeme ve dört farklı geometride çarpışma kutuları tasarlanmıştır. Üçgen, kare, dairesel ve altıgen kesit geometrilerinin ve malzeme tipinin enerji absorpsiyonuna etkileri, kesit alanları aynı kalmak şartıyla sonlu elemanlar yöntemi kullanılarak incelenmiştir. Sonlu elemanlar yöntemi ile yapılan analiz sonuçlarında mesh boyutunun etkisini en aza indirmek için meshten bağımsızlaştırma ön çalışması yapılmıştır. Daha sonra farklı geometrik kesitlerden ve farklı malzemelerden oluşan çarpışma kutuları aynı sınır şartlarında çarpışma testlerine tabi tutulmuştur. Analizler sonucunda, çarpışma kutuları tarafından emilen enerji miktarları, hasar modelleri, kuvvet-zaman eğrileri elde edilmiştir. Bu sonuçlara göre en çok enerji yutan geometriden en az enerji yutan geometriye doğru sıralama altıgen, daire, kare ve üçgen şeklindedir. Her iki malzeme türü için de benzer sonuçlar elde edilmiştir. Çelik malzemenin, alüminyum malzemedeki yaklaşık on kat daha fazla reaksiyon kuvveti gösterdiği tespit edilmiştir.

**Anahtar Kelimeler:** Çarpışma kutusu, Çarpışmaya dayanıklılık, Geometrik kesit, Sonlu elemanlar metodu

## 1. Introduction

Crash boxes are passive safety systems such as seat belts and airbags. While the seat belt restricts the forward movement of the passengers in the event of an accident, the airbags reduce the possibility of death and injury by absorbing the

severity of the blows that the passengers may receive in the event of a possible collision. Crash boxes, on the other hand, absorb the impacts that may occur in the event of a possible collision and ensure that the passengers are affected by these impacts at the minimum level. Crash boxes are located at the front and rear of the vehicles and provide safety in both front and rear collisions (Kılıç 2018). Crash boxes, which are used in automobiles and located on the front bumper, are fasteners that can absorb the kinetic energy that occurs in frontal collision accidents by deforming them. In the event of an accident, if the impact forces that the crash boxes are exposed to cannot sufficiently absorb, it causes these forces

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to be transferred directly to the passenger compartment in the vehicle. This situation will both cause fatal injuries to the passengers in the vehicle and cause a high amount of material damage to the vehicle.

An ideal crash box, energy absorption and crush force efficiency values are expected to be high. In other words, while the crash box is expected to absorb high energy, it is also desired that the forces generated in the collision zone are close to each other. The fact that the forces generated in the collision zone are close to each other means that the passengers in the vehicle are minimally affected by the impacts that occur during the collision. Therefore, it is desired that the difference between the maximum force and the average force in the collision zone should be small. Although these two conditions are important, they increase their importance in other cases day by day. For example, vehicles are required to be light in order to reduce both fuel consumption and carbon emissions. Therefore, it is important that crash boxes are also light. For this reason, specific energy absorption, which is another concept, is expected to be high. Although energy absorption is tried to be increased in the studies for the development of crash boxes, it is also necessary to lighten the crash boxes.

Energy dissipation characteristics vary depending on the microstructure of the materials, the geometric forms of the fabricated structures and the application conditions of the impact force. For this reason, the suitability of the designed structures for the purpose, their mechanical behavior when exposed to impact loads and the types of damage should be determined during the design process (Marzbanrad et al. 2009). While examining the structures of crash boxes, the issues that are generally discussed are; energy absorption, maximum crush force, average crush force, total displacement, specific energy absorption and, crush force efficiency (Cerit 2011). Impact absorbing materials used in vehicles absorb the vehicle's kinetic energy to a certain extent by undergoing plastic deformation.

The energy absorption capacities of the crash boxes differ according to the designs made. Although crash boxes have variable geometries, they can generally be classified as tubular energy absorbers, conical energy absorbers, polygonal columns, sandwich plates, honeycomb structures and other forms (Alghamdi 2001). In most of the studies, crash boxes generally have a flat structure (Cerit 2011). Crash boxes used in vehicles are available in empty and full profiles. Empty profiles have different energy absorption abilities according to the properties of the materials they are made

of. At the same time, it is possible to increase the energy dissipation capacity of hollow profiles as a result of various secondary processes. In order to increase the damped energy capacity, the cross-sectional geometries of the materials used as shock absorbers were changed and they were filled with high-strength materials. Some studies in this field in the literature are summarized below.

Langseth et al. (1996) experimentally investigated the behavior of a square section crash box with aluminum alloy 6061 material under axial loads. According to the tests, they state that the energy absorbed with deformation and the permanent displacement occurring axially are in a parallel relationship, and the deformation that occurs symmetrically in the profiles varies according to the profile wall thickness and the hardness degree of the material used. In addition, they stated that symmetrical or asymmetrical folding due to crushing in the face of static and dynamic loads affects the damped energy, and more energy is absorbed when it is symmetrical. Hou et al. (2007) made optimizations on the maximum deformation force and specific energy absorption of single and multi-cell crash boxes. Analysis of the crash boxes was done using the finite element method. The square cross-section crash boxes used in the study were designed as single-cell, double-cell, three-cell and, four-cell. The design variables were determined as different base widths and wall thicknesses. As a result, they determined that the specific energy dissipation capacity increased with increasing the number of cells in the sections. In addition, they stated that increasing the number of cells causes an increase in the maximum deformation force required for the crash boxes to initiate the first deformation. Demirci et al. (2014) performed finite element analysis in order to determine the energy absorption capacities of crash boxes with different geometries in frontal crash situations. They experimented by changing the wall thickness and geometry of the profiles. The material of the crash boxes was determined as steel and finite element analysis was carried out by axially striking a rigid wall with a mass of 80 kg at a speed of 15.6 m/s with LS-DYNA software. According to the results, it has been determined that the wall thickness has a great effect on the absorbed energy. In a study on conical and thin-walled crash boxes by Nagel et al. (2004). They investigated the changes in energy absorption capacity of crash boxes under axial impact loads using the finite element method. In the study, they determined the wall thickness of the profiles, the semi-conicity angles and the number of inclined surfaces as variable parameters, and investigated the effects of these variables

on the energy absorption capacities of the crash boxes by performing dynamic loading at 10 m/s, 15 m/s and 20 m/s speeds. As a result, they stated that reducing the lengths and increasing the width of the profiles would increase the energy absorption capacity per unit mass. They also stated that inclining the surfaces also reduces the crushing forces, and increasing the load angle reduces the energy capacity of the damped under slow compression loads. Aktay et al. (2011) applied compression tests to aluminum profiles filled with honeycomb structure under axial loads and investigated the energy absorption capacities of these profiles. The authors applied compression tests to the profiles in such a way that they deform 50% to 80% of their height. As a result of the study, it was stated that when the cell diameter of the honeycomb structure placed inside the crash box is 3.2 mm, the specific energy absorption capacity is 9.68 kJ/kg. When the cell diameter is increased to 4.8 mm, the specific energy absorption capacity is 9.14 kJ/kg and when it is increased to 6.4 mm, it is determined as 8.11 kJ/kg. With the increase in cell diameter, the specific energy absorption capacity began to decrease. Energy dissipation studies are being tested on materials with various shapes. It has been shown in the studies that the energy dissipation ratios change with the change of the profiles. A study proving this was done by Elgalai et al. (2004) in experiments, they tested two types of crash boxes, consisting of glass fiber and carbon fiber. The angle of the corner groove bends of the tested crash boxes was adjusted to be between 10 and 40 degrees. With the tests performed, it was determined that the energy absorbing ability, specific energy absorption and crushing force increased with the increasing number of grooves in the crash boxes. They also determined that the crash boxes produced with carbon fiber material with an angle of 40 degrees have the highest energy absorption capacity. Peroni et al. (2009) stated that crash box is a deformable device, which is able to dissipate kinetic energy. The efficiency of devices depends on the thin wall prismatic column, geometry of device at front rail, material thickness, dimensions of the cross section, structural material used in fabrication as well as the application of joining system used. The research concluded that high capacity of energy absorption could be obtained using adhesive bonding and continuous welding in structures subjected to crash (Yusof et al. 2017). From the above review of the literature, it is concluded that crash box must have the ability to absorb energy during collision. The crash box must undergo plastic deformation prior to other parts to minimize the vehicle damage. Researchers had come up with new design to improve the energy absorption

capability. The parameters often determined to improve crash box performance included thickness, cross section dimensions, types of material and the ditches on the crash box, called crash bead (Kosedag and Ekici 2022, Kosedag et al. 2022).

Samer et al. (2013) examined the effect of the geometry of the crash boxes they created from aluminum alloy under static loading. According to the results, it was revealed that the increase in the cross-sectional area leads to an increase in the absorbed energy. According to the data obtained as a result of axial loading on crash boxes made of composite material, an increase was observed in peak force as the number of edges increased (Hussain et al. 2017).

Researchers and manufacturers spend a significant amount of time and money on product development. Since it is costly to evaluate the performances of the designed product, SEM etc. methods are important for saving both time and money. When FEM is modeled according to reality, it gives results very close to reality. This has been proven by many studies in the literature (Kösedağ and Ekici 2021, 2019, Şen et al. 2018, Ekici and Kosedag 2017).

In this study, crash boxes with the same cross-sectional area and height were designed in four geometries (circular, triangle, square, hexon). Crash boxes were modeled using two structural materials (structural steel and aluminum alloy) and crash tests were analyzed using the finite element method. With the analysis, the energy absorption capabilities of the crash boxes with the same weight and different geometry were determined, and the time-dependent changes of the forces transferred on the crash boxes were transferred to the graphics and presented.

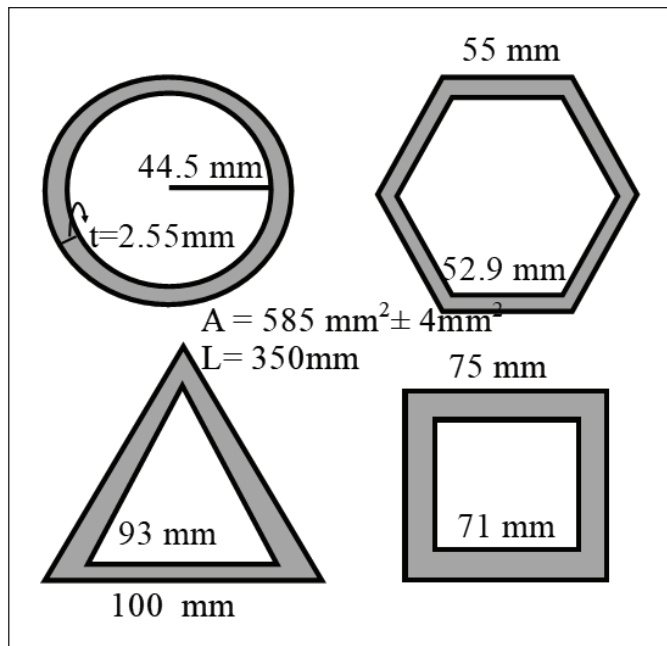
## 2. Finite Element Analysis

Crash box analysis designed in four different sections was performed. Crash box geometries are triangular, square, hexagonal, and circular. As can be seen in Figure 1, the cross-sectional areas of all geometries are approximately equal. Besides, they are equal in length and therefore all crash boxes made of the same material have equal weight. The cross-sectional areas of the crash boxes are approximately 585 mm<sup>2</sup> ( $\pm 4$  mm<sup>2</sup>) and their length is 350 mm. other geometric variables are presented in Figure 1. Triangular and hexagonal geometries are equilateral.

Analyzes were carried out using the finite element method and firstly, mesh decoupling was performed so that the results were not affected by mesh sizes. For this, analyzes

**Table 1.** Mechanical properties (Al6063) and Johnson-Cook (A36) parameters and of the materials used (Tarlochan et al. 2013, Dirgantara et al. 2018).

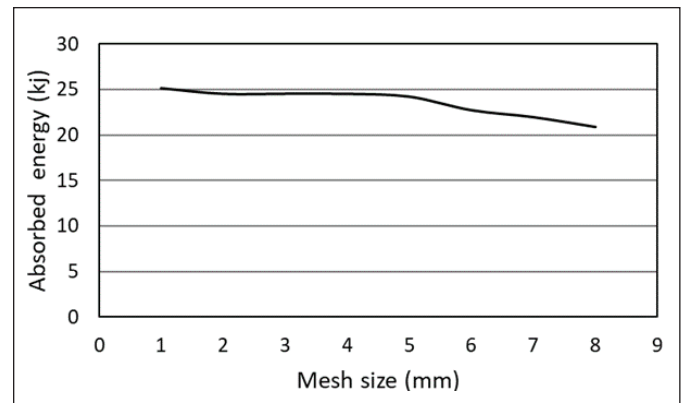
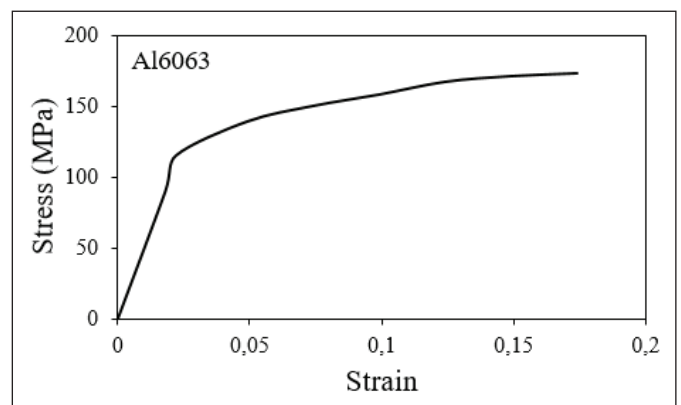
	E (MPa)	Poisson's ratio of	Density (tonne/mm <sup>3</sup> )	A	B	n	m
A36 Steel	200000	0.26	7.85E-9	146.7	896.9	0.320	0.323
Al 6063	68210	0.3	2.7E-9	-	-	-	-

**Figure 1.** The designed geometric sections and dimensions.

were carried out under the same conditions by meshing in different sizes, and the mesh size was decided from the dimensions where the result did not change anymore. The result of the work done for this is given in Figure 2.

As can be seen in Figure 2, starting from 8 mm mesh size, the meshes are reduced at equal intervals up to 1 mm and the energy absorbed by the crash box is obtained. When the results were evaluated, it was seen that the result did not change under 5 mm mesh size, and therefore, it was decided that the mesh size should be 5 mm in the future analyzes.

Using aluminum and structural steel materials, a total of 8 types of crush analyzes were carried out in two different materials and four different geometries. The 8 types of analysis statements originate from 2 types of materials and 4 types of geometry. Aluminum 6063 and A-36 steel used to define the material properties, for aluminum, the elasto-plastic properties that can be seen in the Figure 3. In addition, Johnson-Cook parameters of A-36 steel are also defined. All these values are shown in Table 1.

**Figure 2.** The amount of energy absorbed versus the mesh size made for mesh free operation.**Figure 3.** Stress strain curve for Al 6063 (Dirgantara et al. 2018).

Finite element analysis was performed using the ABAQUS trial version package program. The modeling process was done with 4 node shell continuum (S4R) shell elements. The impact velocity and the weight of the impactor were determined as 15 m/s and 270 kg, respectively, taking into account the literature (Tarlochan et al. 2013). As the boundary conditions (Figure 4), the crash box was designed with tangant properties with a friction coefficient of 0.2 between the walls. Besides, movement of the impact wall only in the direction of the axis of the crash box was allowed.



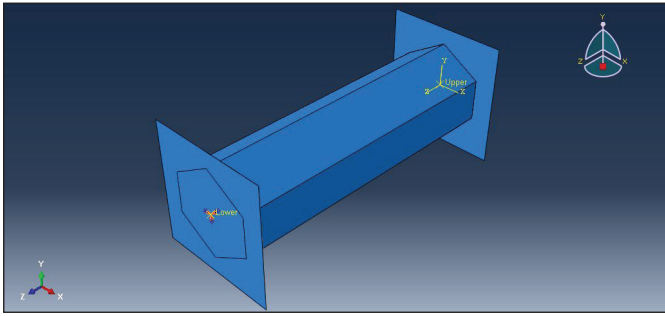


Figure 4. Boundary conditions of the design.

### 3. Result and Discussion

Al6063 and A-36 steel materials were defined, crash boxes in four different geometries were designed, and a 270 kg obstacle was hit with a speed of 15 m/s with finite element analysis. As explained in the second section (Finite Element Analysis), mesh free operations were carried out so that the analyzes were not affected by the mesh size. Figure 5 shows the gradual collision images of materials in triangular (A), square (B), hexagonal (C), circle (D) sections with aluminum 6063 material defined. The cross-sectional areas of the materials are kept approximately equal and their lengths are equal. So their volumes and hence their weights are equal. Each image shows the damage in the first 8 steps. When the figures are examined, it is seen that the geometry in the triangular section has a more intense regional stress load (red color) than the other geometries. For this reason, the more intensely loaded regions in the triangular section were deformed faster. In addition, it is observed that as the number of edges increases, the edges provide resistance and distribute the stress more uniformly. Besides, since there is no edge in the circular section, it has been observed that the folding numbers are more resistant than the others due to the fact that they are more early and more numerous. It can be seen that the folded regions in the upper part of the circular region provide support for the lower parts.

Finally, it is observed that the folding in the triangular section becomes more and more irregular starting from the middle of the impact process. It is the crash box with the most uniform folding circular cross-section. However, folding occurs earlier in the circular section than in the hexagonal section and more folding occurred.

In Figure 6, how the forces acting on the Al6063 crash boxes change over time is plotted. Each force peak seen in the graphs gives us the forces at which folding takes place. Accordingly, the multiplicity of the number of folds in the circular section can also be seen in the peak excess in Figure

6. In addition, the reaction force for the circular section decreased sharply immediately after the folding took place, and the force increased immediately after the next folding. In the hexagon structure, the folding peaks are less and the force resistance shown after folding is higher than the other geometric sections. According to Figure 6 graphics, the weakest geometry in terms of force resistance is seen as a triangular section.

Sequential macro images of crash boxes made of steel in triangular (A), square (B), hexagonal (C), circle (D) sections during the collision are presented in Figure 7. It is also possible to see results similar to aluminum results here. However, when the stresses on the images (red color) are taken into account, it can be seen that less stress occurs compared to the aluminum material. According to Al6063, the folding irregularity in the triangular section has increased, and the folding irregularity in the square section has become evident. Similarly, it was determined that the hexagon and circular sections exhibited more uniform behavior and the circular section crash box showed more folding behavior. In addition, due to the higher strength of steel material than aluminum, steel crash boxes exhibited a more resistant behavior and it was determined that the amount of crushed parts was less than aluminum. However, it should not be forgotten that the weight of the steel (7.8 g/cm<sup>3</sup>) material is approximately 3 times more than aluminum (2.7 g/cm<sup>3</sup>).

In Figure 8, the time variation of the reaction forces of steel crash boxes in circular, hexagon, square, triangle sections during the collision is given. The abundance of force peaks, which proves the excess of the folding numbers in the circular section, can be seen here as well. Similarly, it can be seen that the triangular form shows lower force resistance than the other forms, and the hexagon is more resistant when the average force is taken into account.

While the initial reaction force of crash boxes during the collision is around 250 kN in steel boxes, the initial reaction force in aluminum is in the range of 50-60 kN. steel crash boxes exhibited an average of 5 times higher reaction force.

As it is known, the areas under the force deformation curves give the energies absorbed by the crash boxes. One of the results obtained from the analyzes is the amount of energy absorbed by the crash boxes. The variation of absorbed energy amounts according to geometry and material type is presented in Figure 9. According to these results, ranking from the highest energy absorbing box to the lowest for both material types; hexagon, circular, square, and triangle. These results agree with the results of macro pictures and force-time

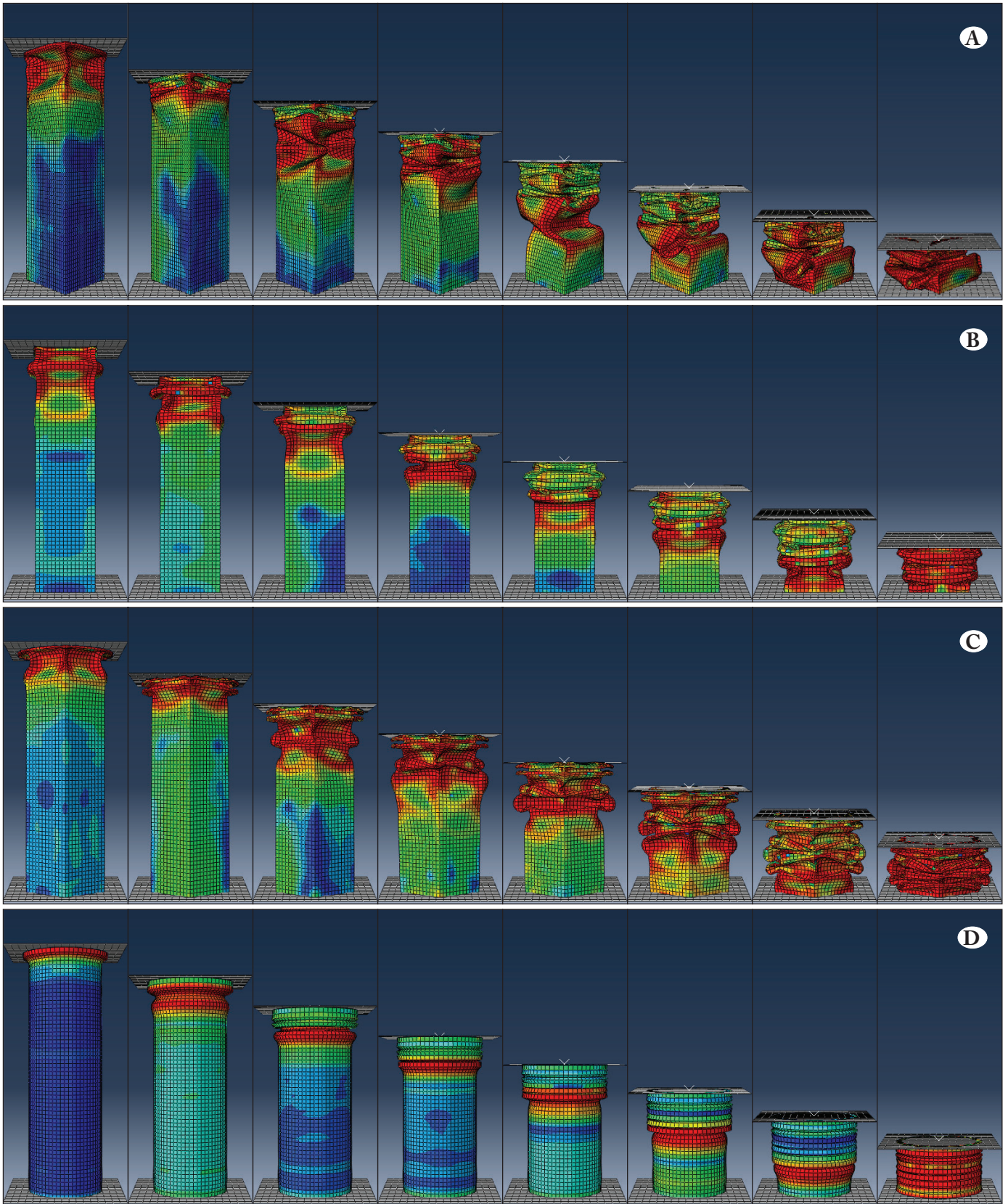
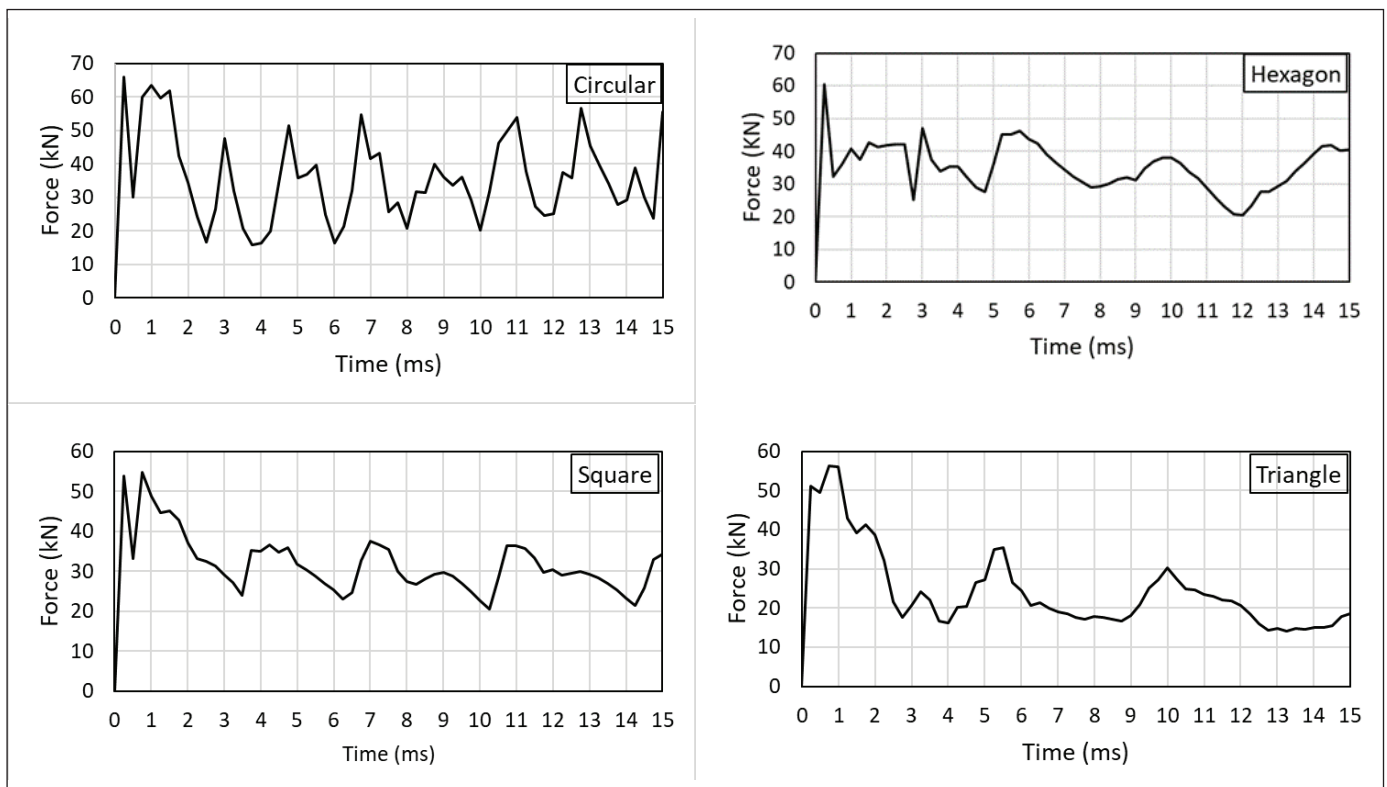


Figure 5. Progressive crushing of triangular (A), square (B), hexagonal (C), circle (D) form made of Al6063 material.



**Figure 6.** Force variation over time on crash boxes of different geometric cross-sections made of Al6063.

curves. The absorbed energies in the steel material model are 3.11, 3.35, 3.42, and 3.48 kJ for materials in hexagon, circular, square, and triangle sections, respectively. In the same order, the amount of energy absorbed by aluminum crash boxes is 0.230, 0.285, 0.324, and 0.353 kJ. Compared to aluminum, it has been determined that steel crash boxes absorb 13.5 times more energy in triangular section, 11.75 times more in square section, 10.55 times more in circular section, and finally 9.85 times more energy in hexagon sectioned material. It is seen that the difference between steel and aluminum decreases from the crash box geometry that absorbs the most energy to the one that absorbs the least energy. According to the geometry of crash boxes made of steel material, the amount of energy absorption changes less than aluminum. For example, aluminum hexagon absorbs 53% more energy than aluminum triangle, while this is only 11.9% in steel material.

#### 4. Conclusion

In this study, the effect of cross-section geometry and material on the energy absorption of crash boxes was investigated. For this purpose, crash analysis was performed using the finite elements method using 4 different geometries and two different materials. The materials used

are Al6063 and A36 steel. Crash boxes in hexagon, triangle, square, circular geometry were modeled, provided that their cross-sectional areas were approximately equal. In order for the results of the study to be minimally affected by the mesh size, analyzes were performed after the mesh free study. All crash boxes were analyzed under the same boundary conditions and loading conditions. A wall weighing 270 kg crashed into the crash boxes at a speed of 15 m/s. As a result of the analysis, deformation analysis was performed on macro images. How the forces on the crash boxes changed over time were plotted and finally the amount of absorbed energy was calculated. According to the results obtained, crash boxes made of steel absorb more energy than those made of aluminum. It was determined that the cross-section geometry had a significant effect on energy absorption. Accordingly, the order from the most absorbing to the least is as follows; hexagon, circle, square, and triangle. According to this result, it was concluded that the energy absorption ability of the material increased with the increase in the number of corners. In addition, it was expected that the absence of corners in the circular crash box would have a negative effect, but this did not happen. However, the fact that it is easy to fold in the form of a circle and the number of folds is high, provided resistance to the material



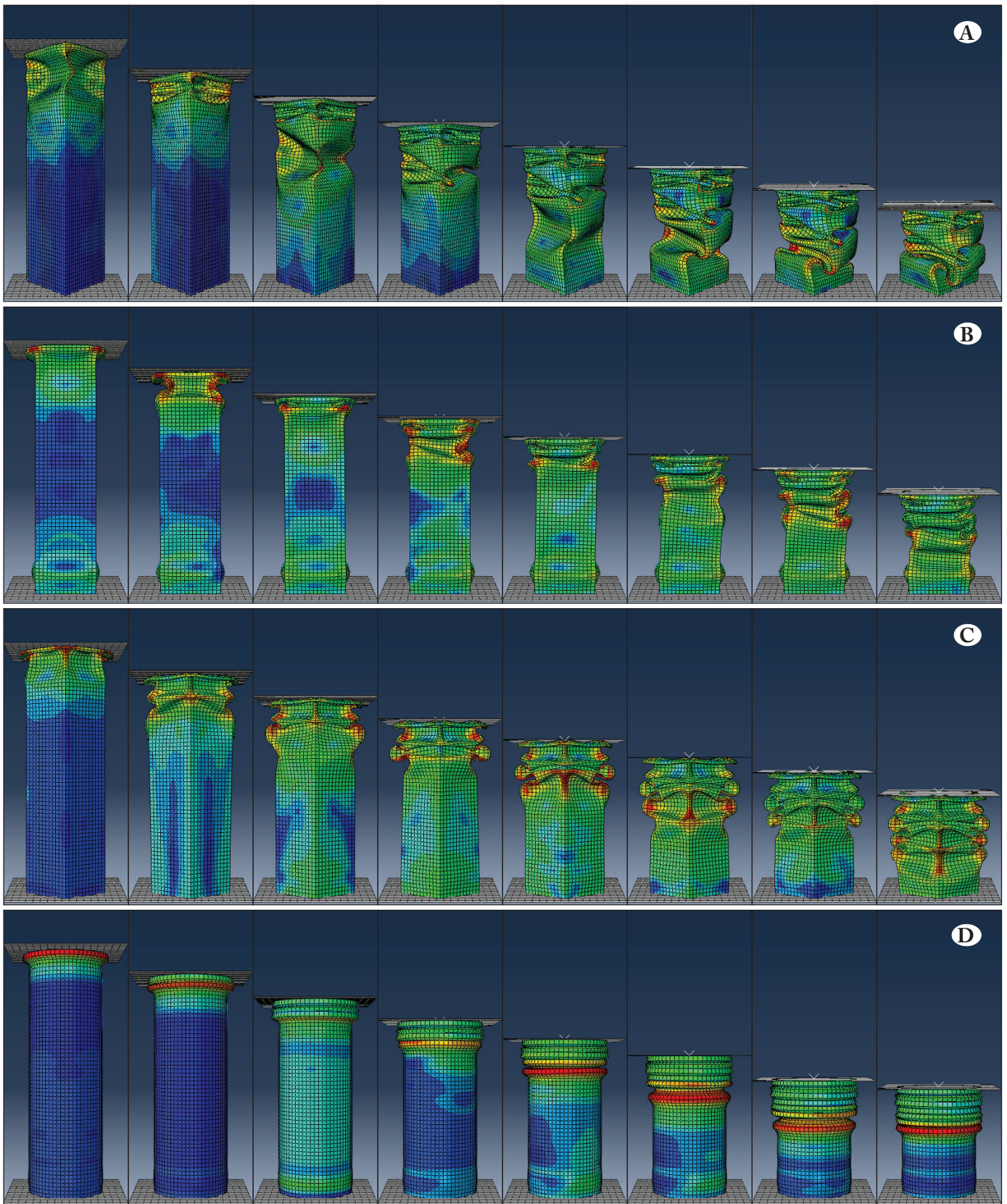


Figure 7. Progressive crushing of triangular (A), square (B), hexagonal (C), circle (D) form made of A-36 material.



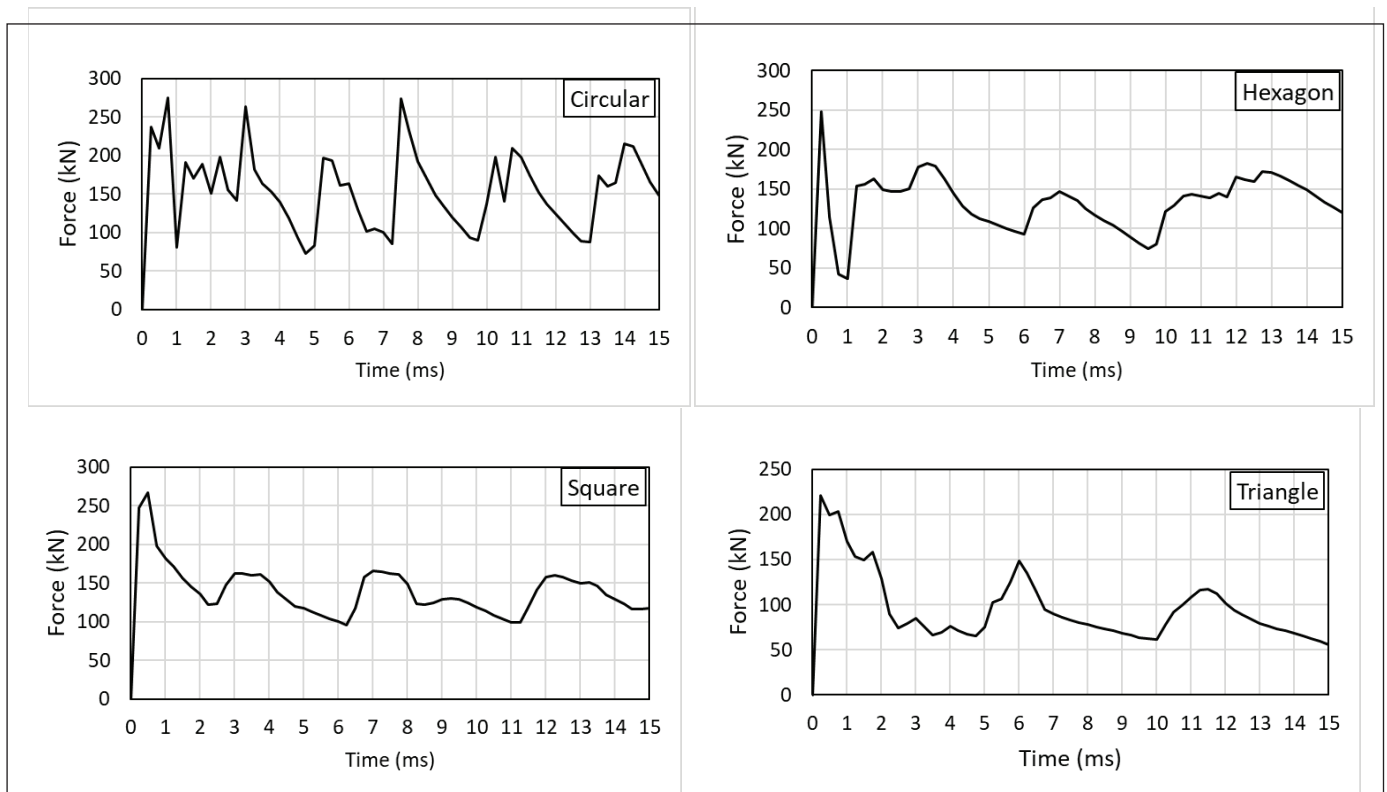


Figure 8. Force variation over time on crash boxes of different geometric cross-sections made of A-36.

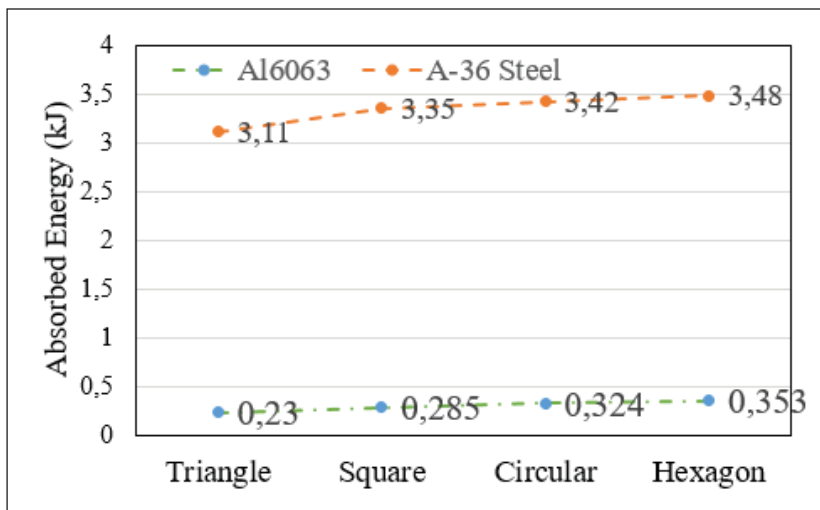


Figure 9. The energies absorbed by crash boxes according to material and geometry.

and exhibited the most durable performance after hexagon geometry. It has been determined that the results of both materials modeled from both aluminum and steel materials are in harmony with each other.

#### Conflict of Interest

All authors declare that they have no known competing financial interests or personal relationships that could appear to have influenced the work reported in this paper.

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