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Design and Analysis of Impact Attenuator for Formula Student Car

Yahya Mohseni[1]

Hossein Geramizadeh[2]

Sattar Jedari Salami[3]

In this article, the axial crushing behavior of energy absorbers is analyzed to mitigate collision damages in the military, transportation, and other industries. Thin-walled structures are preferred for energy absorbers due to their lightweight, simple geometry, ease of construction, and efficient collapse mechanism. Numerical analysis compares absorbers with various cross-sections such as circular, square, hexagonal, conical, and square frustum under impact loading, using ABAQUS Workbench finite element software. The effect of velocity on proportions such as the type of deformation during impact, energy absorption density, and maximum collision strength values have been investigated. This study identifies and interprets the variations and parameters affecting the adsorbent efficiency. Additionally, the initial peak force of the conical section was significantly reduced, achieving 21% higher specific energy absorption compared to other designs. This study also focuses on dynamic energy absorbers for Formula Student competitions, aiming to improve their efficiency. The addition of grooves and holes increased the efficiency of the crushing force (η) by 38% and significantly enhanced the energy absorption per unit mass known as specific energy absorption (SEA) is also presented, which is an innovation not previously explored. By reducing the initial maximum force, increasing the crushing length, and incorporating symmetric folding, a new model was developed, enhancing both energy absorption capacity and overall efficiency.

Keywords: energy absorbers, force-displacement diagram, Abaqus software, impact loading, energy absorption capacity

[1]Department of Mechanical Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran
[2]Department of mechanical engineering, Central Tehran branch, Tehran, Iran.
[3]Department of Mechanical Engineering, Central Tehran branch, Islamic Azad University, Tehran, Iran

1. Introduction

The use of energy absorbers to strengthen dangerous devices and equipment is of particular importance. Collision of objects with each other creates sudden shocks, which if not restrained, will result in financial damages. Energy absorbers are used to reduce the stopping acceleration of moving equipment, and they reduce the velocity and absorb collision energy with their deformation and axial collapse. The higher the energy absorption capacity of these structures, the more effective and efficient they will be. In many engineering systems, especially in mobile devices such as military equipment and public transportation systems, various energy absorption systems are used to prevent or reduce damage. Energy-absorbing devices or shock absorbers use various mechanisms such as wear, cutting, bending, compression twisting, stretching, periodic plastic deformation, fracture, metal cutting, extrusion, etc. Collision Energy is used to overcome friction. Plastic deformation or breaking in parts in the impact is a type of dynamic loading, which is also called shock, sudden, or impulsive loading. Car bumpers or car wheels going into bumps are examples of shock loading.

Shock absorbers or energy absorbers are among the components that are used in some systems to absorb kinetic energy and convert it into other forms of energy. Mechanical shock absorbers absorb impact energy in various modes, such as crumpling or by collapsing in their geometry and physics against the axial load, by converting kinetic energy into plastic work, these shock absorbers irreversible include tubes or cylindrical shells, sandwich panels (plates), hexagonal, frusta (circular cone) and other structures used elsewhere. Among all the different mechanisms, the axial collapse mechanism that leads to the creation of folds along the absorbers is of particular importance in terms of energy absorption. Factors affecting the type of collapse of energy absorbers, including tube geometry (inner or outer diameter, length, thickness, or the ratio between them), properties of absorbent materials (including elasticity and plasticity behavior of the material), initial conditions and boundary conditions applied to the absorber (which it includes the physics used in the problem, including the initial defect in the geometry of the structure, the amount of mass and velocity of the impactor, applied loading and whether the end of the absorber is closed or free) and the type of axial load applied to the absorber (quasi-static or dynamic). Improving energy absorption capacity, high strength to increase safety, and reducing weight and cost of construction are the goals that engineers and scientists are looking for when designing energy absorbers. The energy absorption efficiency depends on many factors, including the properties of the materials used, the configuration of the cross-section, the wall thickness, and the boundary conditions and loading of the structure. Therefore, lightness, high-energy absorption capacity, small space, high crushing length, better stability during crushing, high ratio of energy absorption to weight, availability, and economic efficiency are the advantages that make thin wall structures one of the best absorption systems. Impact and the research for the use of these energy absorption systems as well as the optimization of these systems is a new scientific topic in the topics of impact mechanics. In recent years, the behavior of thin wall structures under axial load that have efficient energy absorption has been studied stably. A comprehensive review of this issue can be seen in the theoretical, experimental, and numerical studies conducted on the collapse of these structures under axial load, their initial maximum force, average axial force, and energy absorption characteristics. The demand for increased safety, especially in saving the weight of vehicle structures, has led to the promotion of the use of high-strength steels, aluminum alloys, etc. Although the use of aluminum alloys is common in the construction of airplanes and helicopters, recent studies have delved deeper into optimizing the energy absorption behavior of thin-walled structures. For example, Shariati et al. performed experimental and numerical analyses to examine how different geometries of stainless steel shells influence on energy absorption under quasi-static axial loading, helping to refine energy absorption models for practical applications in engineering [1]. Additionally, Zhang et al. conducted research on optimizing the crushing performance of thin-walled tubes with various cross-sectional shapes, demonstrating that geometric configuration plays a crucial role in enhancing energy absorption efficiency under axial impacts [2]. Moreover, Lee et al. examined how the dynamic loading of thin-walled columns with square and circular sections

influences their energy absorption capacity, offering insights into the effect of material selection and geometry on impact resistance [3]. These contributions underscore the evolving nature of energy absorption studies, especially in the context of improving safety and performance in engineering systems.

The research conducted in the field of impact energy absorption shows that the way of crushing due to impact and the amount of energy absorbed in different sections of thin wall profiles (pipe, square, etc.) can be controlled by creating different patterns on them and increase the efficiency of this type of adsorbent. There are important indicators of energy absorbers, the most important of which are energy absorption, maximum crushing force, and crushing force efficiency. The maximum crushing force plays a role in the formation of the first crease, and also the maximum force in thin wall absorbers is related to the change of elastic shape which decreases rapidly after the beginning of plastic deformation. Most energy absorbers are disposable. Once they change the shape of the plastic, they are thrown away, therefore, the design requirement for such a device is usually to achieve high energy absorption with less mass and rely on high specific energy absorption. Thin-walled structures are widely used as structures for high-volume energy absorption in the automotive, train, and shipbuilding industries. These structures have high-energy absorption; they are relatively cheap and light in weight. Energy absorbers are designed to absorb energy and repel impact force in a controlled manner. As a result, an energy absorber must be able to absorb the kinetic energy caused by the impact force and disperse it in the form of other forces. This idea is irreversible [4].

Among the different designs of absorbers, the process of axial crushing usually includes the following three stages: First, the crushing force reaches an initial maximum to overcome the initial resistance of the tube. Second, the force decreases and fluctuates, because fragmentation progresses. Third, the force increases rapidly and increases the crushed parts until the end of crushing [5].

Energy can be absorbed by changing the shape of structures such as tubes, columns, honeycomb structures, or other types of structures under different loads. The ability to absorb energy is very important in many structures such as cars where collisions occur. Energy is wasted by various failure mechanisms including plastic deformation and fracture. During the last two decades, many experimental and numerical works have been done to investigate the mechanisms of "plastic deformation". These studies are important for a better understanding of energy absorption to reduce collision damage [6].

Any comparison of energy absorption for various materials is difficult because there are different factors like deformation. Some are symmetrical and asymmetrical, and there are furthermore factors like the effects of inertia and the sensitivity of material strain rate and its failure. For example, high-strength materials are better at static loading compared to mild steel. However, in dynamic loading, the strain rate of high-strength materials is lower than that of mild steels, and its fracture resistance is lower than usual. Also, some of the advantages observed in static loading are lost in dynamic loading [7].

The ability of soft and malleable metals to absorb a large amount of energy during plastic strain makes these materials inherently suitable for use in vehicles, machines, structures used in various industries, and in general, subject structures to collisions. [8, 9]. The demand for increased safety, especially in relation to saving the weight of structures, has led to the promotion of the use of soft steel, aluminum alloy, etc. From this point of view, the material selected for the desired structure in this project is a sample of mild steel.

The theory of the dynamic behavior of structures, made of ideally rigid or perfectly plastic flexible materials, has been developed to a great extent, and very good approximations have been found to answer these problems. According to the obtained results, it promises that solid-plastic theories will expand in the coming years. The effects of inertia and strain rate sensitivity of materials, the effects of transverse shear force, and several failure criteria have been discussed. These analytical methods

are supported by various tests that are very useful in the design of structures, and the lack of information about the dynamic behavior of materials during impact loading causes problems. The rigid plastic theory is very useful for choosing a range of experimental values used for critical situations. The presented methods are used to improve the protection of structural systems and evaluate the capabilities of the structure under dynamic and impact loads. Also, good physical insight has been obtained from the dynamic plastic responses of useful structures in expanding the design of structures under shock loads [10].

The process of plastic deformation in an energy absorber depends on the magnitude and type of loading, loading rate, deformation pattern, material properties, and many other parameters such as support conditions. For an irreversible energy absorber that is subjected to various loadings such as axial, transverse, and oblique loading, several plastic deformation mechanisms have been presented to estimate the amount of absorbed energy, and the most common of these mechanisms can be axial sprain, inversion, lateral expansion, and axial tear are mentioned. For example, Shariati et al. [11] performed experimental and numerical analyses on the control of energy absorption by stainless steel shells with different geometries under quasi-static axial loading. Today, thin-walled structures with different geometries are widely used as kinetic energy absorbers [12]. Regardless of the efficiency of an energy absorber, there are many types of irreversible energy absorbers in terms of geometry, the most important of which are tubes [13], frosts, thin-walled multi-ear cans, honeycombs [14], sandwich plates, and pointed cubic cells [15]. This research is dedicated to the investigation of dynamic energy absorbers in student formula competitions. Student Formula competitions are one of the most attractive and important mechanical engineering and automotive events in the world. In these competitions, students face different challenges by designing and building their team's driving cars in competition with other teams. One of the important aspects in designing the cars of these competitions is increasing safety and improving the performance of energy absorbers. Energy absorbers cause absorption and loss of energy when the car collides with various obstacles or very important surfaces. The main goal of this research is to improve the efficiency and effectiveness of dynamic energy absorbers in racing cars. To improve the performance of energy absorbers in student formula competitions, this research deals with the implementation of numerical simulation of axial shock loading on absorbers with different sections in Abaqus finite element software. Dynamic simulation of shock loading by sharing accurate information and results with racing teams can help racing students use more optimal energy absorbers in their cars and improve the performance and safety of their cars. In this research, after carrying out numerical simulations of impact loading on energy absorbers with different sections, the contour, numerical, and graphical results of the analyses are examined more carefully. These results show the forces, locations, velocities, and energy absorbed in the system of absorbers over time. In this study, the temporal changes in response behavior and deformation of absorbers under different shocks are carefully observed. By examining the graphs of force location, velocity-time, and absorbed energy, During the impact period, more detailed changes in the response and performance of the absorbers can be seen. This information helps us to compare the performance of different absorbers and identify the best cross-sections and measurements to improve the shock absorption performance of the absorbers. By analyzing and reviewing the results, the best solutions for optimizing and designing energy absorbers with different sections for different needs and applications can be found. These things allow us to use the results of this research in a comprehensive and practical way in industry and technology and facilitate the improvement of the level of science and technology in this field [16].

Assuring the safety and integrity of structures under impact conditions is a pressing concern in a number of engineering fields, including the military, transport, and automotive. The axial crushing behavior of energy absorbers, in particular thin-walled structures, is thus analyzed due to their inherent advantages of being lightweight, having simple geometries, ease of construction, and efficient collapse mechanisms. This paper presents a detailed analysis of how different geometrical configurations of energy absorbers can significantly enhance performance in mitigating collision

damages. Advanced numerical analysis using the ABAQUS Workbench finite element software has been used to compare systematically the impact performance of absorbers with different cross-sections such as circular, square, hexagonal, conical, and square frustum. Critical parameters including deformation types, velocity over time, energy absorption capability, and force-displacement characteristics were extensively analyzed. It has been shown that some geometric shapes can enhance the energy absorption capability and efficiency of absorbers greatly. The work is practically applicable in the context of student formula competitions, where enhancing the efficiency of dynamic energy absorbers in racing cars is prime. Based on the developed analysis, a new model was made, which optimized energy absorption by developing symmetric folding and reducing initial peak forces. This model not only makes a contribution towards the performance of racing cars but also satisfies the acute safety and performance criteria required in such competitive environments. Implications of the research extend beyond student competitions. The paper provides insights into the design and optimization of high-efficiency energy absorbers, hence providing contributions toward larger efforts for enhancing safety in the automobile industry and associated sectors. Such design of absorbers that can, with minimal compromise to their structural integrity, very effectively attenuate impact forces can result in safer vehicles and structures that are capable of actually saving lives and property. This research underscores the critical role that innovation in engineering plays in advancing safety and performance in high-impact scenarios.

2. Definitions, principles, and theoretical foundations

The initial maximum force (P_{peak}), average force (P_m), energy absorption capacity (E_a), shape coefficient (η), and energy absorbed per unit weight (SEA $a=E_a/W_m$) are the parameters used to analyze the absorber. These parameters are so significant in the design system and weight is a limiting factor. The amount of absorbed energy is calculated based on the area under the force-displacement curve. Also, the shape coefficient or the effect of the breaking force is obtained from the ratio of the average force to the initial maximum force. This coefficient is a good idea for the structure to check better energy absorption and prevent maximum force transfers to car occupants. One of the most important parameters in the design of shock absorbers, which is to check the efficiency of energy absorbers, is the behavioral information that can be extracted from the force diagram in terms of displacement [17]. This behavioral information provides great help in the design and selection of collapse absorbers. This information can be divided into several important parts, which are:

a) Maximum force (P_{peak}):

The maximum force in the force-displacement diagram of bumpers corresponds to the elastic deformation of the absorber due to axial impact. Once the plastic deformation begins, this maximum force decreases rapidly. [18].

b) Average force: (P_m)

In collapsing impactors, the average force should remain constant and not fluctuate. After an initial drop from the maximum force, the force-displacement relationship should stabilize around this average value. Relevant parameters are given by the following equations:

$$P_m = \frac{E_a}{x_2 - x_1} \tag{1}$$

c) Shape coefficient (η)

The shape coefficient, derived from the ratio of the average force to the initial maximum force, indicates the efficiency of energy absorption. A shape factor closer to 1 is more effective in absorbing

energy and preventing maximum force transmission to vehicle occupants compared to a shape factor closer to 0. [19].

$$\eta = \frac{P_m}{P_{peak}} \tag{2}$$

d) Absorbed energy and impact energy:

The area under the force-displacement diagram represents the amount of energy absorbed. Practically, this energy absorption is calculated by integrating the force-displacement curve.

$$E_a = \int_{x_1}^{x_2} F(x)dx \tag{3}$$

The kinetic energy generated by the impact is given by the following equation [18].

$$E_{ie} = \frac{1}{2}mV^2 \tag{4}$$

e) Weak form of the governing equations:

To better describe the theoretical background, the weak form of the governing equations must be considered. The principle of virtual work states that the internal virtual work should be equal to the external virtual work. This can be expressed as follows:

$$\int_V \sigma \cdot \delta\varepsilon dV = \int_V f \cdot \delta u dV + \int_\Gamma \rho\ddot{u} \cdot \delta\ddot{u} d\Gamma \tag{5}$$

where σ, $\delta\varepsilon$, f, T, δu and $\delta\ddot{u}$ is the stress tensor, virtual strain tensor, body force, traction on the boundary Γ, virtual displacement and velocity fields, respectively. This weak form is fundamental in finite element formulations and helps in discretizing the problem.

3. Finite Element modeling

In this study, to achieve more accurate and realistic results, the absorber sections were first loaded under an initial buckling analysis with the aim of creating an initial defect in the structure. With this action, in fact, the absorber cross-sections are practically out of the ideal state without defects and become like the real cross-section model. It should be noted that this action is necessary and the basis of work to reach the values of the main parameters, especially the maximum force. In continuation, the crumple and impact analysis is performed as a post-buckling analysis. In fact, a two-stage analysis will be conducted.

The simulation of the problem mirrors the impact of a moving object against a rigid obstacle. Here, our aim is to evaluate the effectiveness and deformation characteristics of the absorber utilized within the moving object. Consequently, the analysis pertains to low-velocity impact scenarios, wherein the absorber functions to absorb energy through deformation, such as crumpling or crushing. To achieve a more realistic depiction of the absorber's behavior, the momentary and frame-by-frame axial collapse is dynamically modeled. Drawing from referenced studies, the absorber's physics is represented using thin-walled shell sections, while the barrier or wall against which the object impacts is treated as a completely rigid plate without deformation. To commence our analysis, rigid plates are assembled in alignment with the absorber and the combined system's behavior upon impact against the rigid barrier is subsequently evaluated. Key parameters governing the dynamic behavior

of the impact are identified and subjected to analysis. The geometry of the problem is first defined using Abaqus software modules to observe the absorber's deformation in three dimensions. Subsequently, properties and cross-sections are assigned to the absorber and assembly components, with the definition of impact loading being implemented through nonlinear dynamic analysis with contact conditions between all surfaces. This approach enables us to simulate the interaction of absorbent layers and the subsequent deformation. By applying support and movement constraints, including axial constraints and the problem's initial velocity, a comprehensive representation of the scenario is ensured. Finally, the convergence study with respect to the absorber's dynamic behavior is verified by specifying mesh size and element types. [20].

In modeling and designing dynamic absorbers, the regulations and specifications outlined in the student formula are considered. These regulations encompass criteria and predefined values utilized in student formula competitions. By aligning with these regulations, the designed energy absorbers are finely tuned to the competitive environment, ensuring optimal performance under competition conditions. In this study, the sizes, shapes, and characteristics of the energy absorbers are meticulously designed and simulated to meet the requirements of student formula competitions and effectively mitigate axial impact loading while absorbing and dissipating impact energy. By adapting the simulation models to the characteristic laws of student formula, the results of this research will be reliable and practical and can help to develop and improve the performance of racing cars and the performance of energy absorbers in student formula competitions. This compliance with the characteristic rules of competition increases the importance of this research and its application in the automotive industry and related fields.

3-1. Modeling in the Part module:

In this work, a three-dimensional model for the absorber was adopted based on references and the intended crumpling behavior. The absorber was represented as a deformable shell, specifically a Shell Deformable - Extrusion model. Similarly, the mobile and wall components were modeled as Shell Rigid - Planar plates. Leveraging the theoretical capabilities of the Abaqus software, which allows for closed geometric models and meshing possibilities, these plates were treated as discrete rigid objects (Discrete Rigid) in the modeling approach for different sections of the absorber and the rigid plate in the Abaqus software, as illustrated in Figure 1. Additionally, the geometry of the sections was defined with a length of 200 mm (D), a diameter (or side) of 200 mm (H), and a thickness of 100 mm (d), with a minimum thickness of 2 mm (T), as depicted in Figure 2.

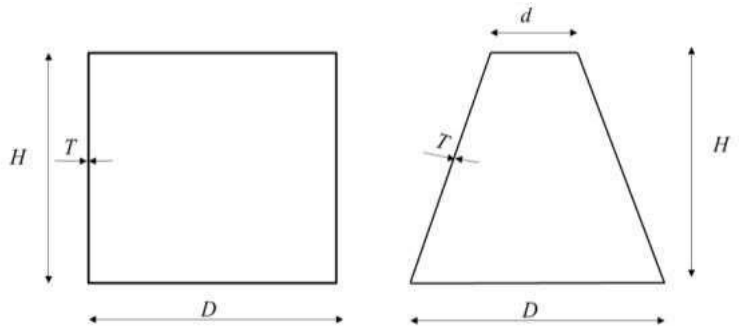


Figure 1. a. Model of circular and square conical sections b. Model of square and cylindrical sections

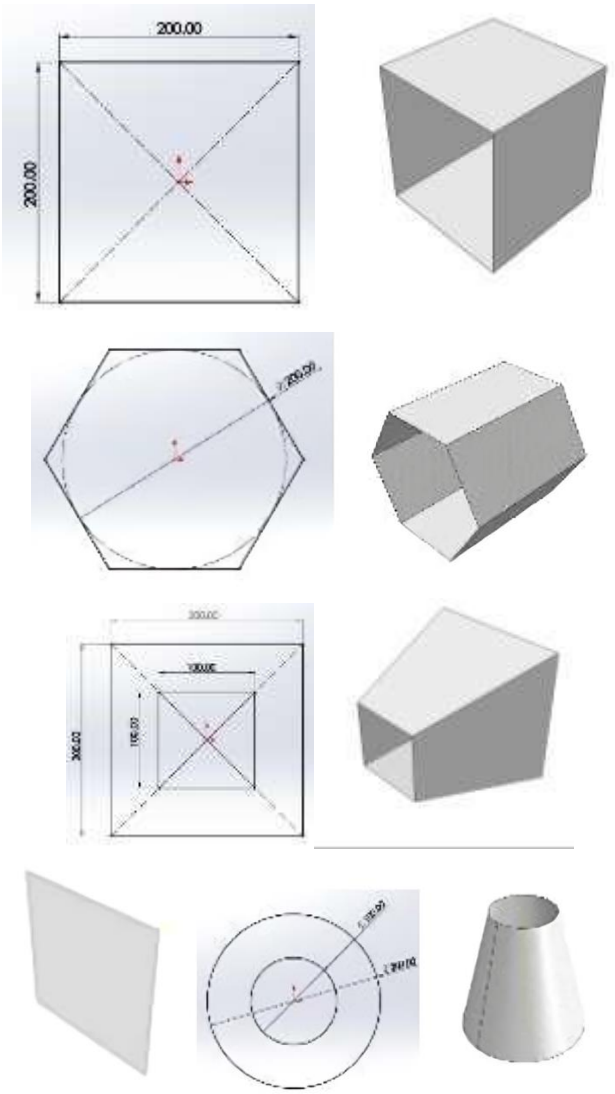


Figure 2. Model of different sections and different pages

4. Definition of material properties and cross-section in the Property module

In this study, the rigid plates do not require the definition of mechanical properties as they undergo no deformation, and stress calculations are not applicable to them. Essentially, these rigid plates serve as energy absorbers with predefined characteristics, obviating the need to specify mechanical properties for modeling and analysis purposes. Furthermore, the cross-sectional properties of the absorbers under investigation have been determined based on reference sources and their respective specifications. These properties encompass density, Young's modulus, Poisson's ratio, yield stress, and yield strain. For the analysis, aluminum alloy (Al 6063 T6), with specified characteristics outlined in Table, has been utilized. Moreover, the definition of the absorbers' cross-section and its assignment to homogeneous shell absorbers, with a thickness of 2.025 mm, has been carried out as part of the modeling process.

Table 1. Mechanical properties of absorber sections

ρ [kg/m³]	E [Gpa]	υ	σ_y [MPa]
2700	68.9	0.33	225

4-1. Assembling parts in the Assembly module:

In the assembly module, the physical representation of the problem is constructed by assembling rigid plates on both sides of the absorber sections. It is important to highlight that to establish contact and boundary conditions between these components, they are bound together in subsequent modules of the software, and the various sections of the absorber in the assembled state are illustrated in Figure 3.

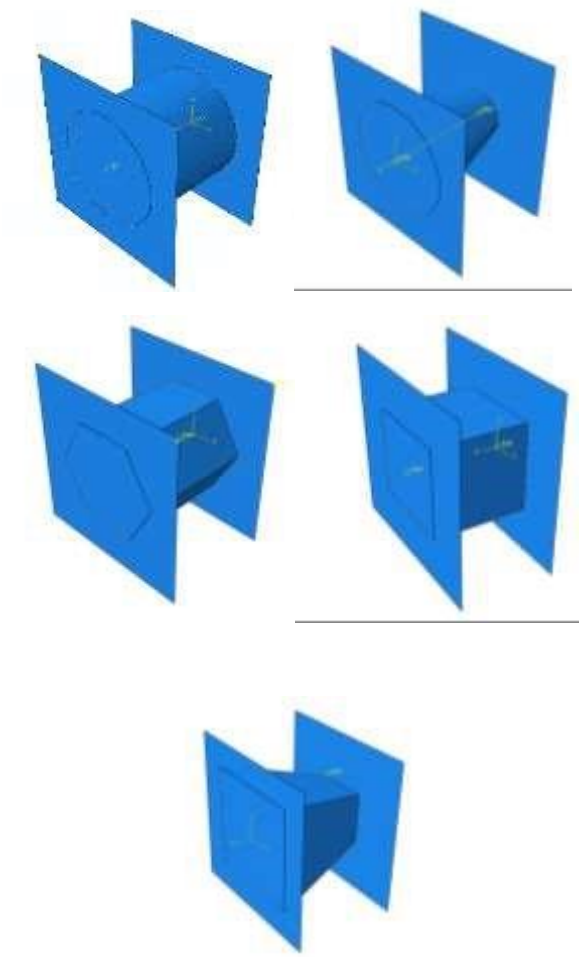


Figure 3. Assembly models simulated in Abaqus

5. Defining the type of analysis in the Step module

In the Step module, The Dynamic Explicit solver was employed, known for its robustness in handling impact scenarios and its capability to capture instantaneous results and temporal changes in the absorber's behavior. A time increment of 0.05 seconds was chosen to ensure adequate resolution

of the dynamic behavior over time. This dynamic solver enables us to observe the momentary collapse of the absorber at various time intervals. To enhance the realism and accuracy of the analysis, the analysis was conducted in nonlinear mode, with all possible solutions and parameters being considered. Nonlinear effects (Nlgeom) were specifically accounted for to investigate the absorber's nonlinear response to shock loading, accounting for its varying properties. Throughout the analysis, the explicit dynamic solver type was defined and field output parameters were specified, including stress, strain, force, displacement, velocity, and other relevant parameters. These measurements enable us to derive precise and reliable insights into the behavior of energy absorbers under impact conditions, facilitating a comprehensive understanding of the absorber's response over time.

6. Defining contact properties of parts in the Interaction module

In this study, upon entering the "Interaction" module of the software, the contact rules and relationships between the absorber parts and the moving object were defined. The selection of the "General Contact" type is considered pivotal in establishing suitable conditions for impact simulations due to the numerous contact surfaces involved and their complexity. Additionally, specifying tangential properties and setting a friction coefficient of 0.01 for the contacts enable accurate and realistic modeling of contact forces in the analyses. To account for inertia effects, a moving object with a concentrated mass of 300 kg was introduced, ensuring comprehensive consideration of dynamic effects and yielding more optimal and realistic results regarding absorber and object behavior upon impact.

Furthermore, to create an integrated and coordinated system comprising the moving body and the absorber, where they collide with a rigid wall together, the "Tie" type of contact, also known as "glued" or "welded," was utilized. This type of contact facilitates the interaction between two parts, allowing for the exploration of force transfer and collision effects. By implementing these settings and incorporating more accurate and realistic physics into the software, the simulation results become more valuable, enhancing the analytical capabilities and predictive capacity regarding the behavior of absorbers and objects during collision.

7. Defining the initial and boundary conditions and loading in the Load module

In the "Load" module, careful consideration was given to the importance of loading steps and boundary conditions in the impact analysis of energy absorbers. Applying a very small load for the buckling of the absorber sections demonstrates the precision and sensitivity of the calculation model, thereby enhancing the quality and accuracy of the results in simulating absorber behavior. In the impact analysis, fully restrained boundary conditions and limited degrees of freedom are employed to more realistically and accurately simulate the behavior of the absorber and the moving object upon collision with the obstacle. These constraints play a crucial role in determining the absorber's response characteristics to impact and accurately portraying the transfer of forces and collision effects. Moreover, it is essential to consider the absorbing and moving velocities as a combined system at the moment of collision for correct and precise modeling of the objects' behavior toward each other. This information enables a more accurate depiction of the collision reality, resulting in reliable and trustworthy outcomes. By integrating these aspects into the analytical stages, this research contributes to a deeper understanding of energy absorber behavior in impact scenarios, with significant implications for military, industrial, and automotive applications. The square section is illustrated in Figure 4.

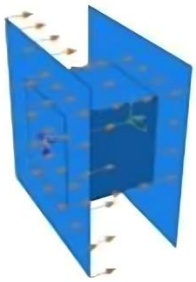


Figure 4. The square cross-section model in the Load module of the software

8. Defining the meshing of parts in the Mesh module

In the "Mesh" module, precise meshing of parts was conducted in accordance with relevant principles and techniques. Factors such as element shape, meshing technique, algorithm, element size, family, and other meshing details were carefully considered, given the analysis's nonlinear nature and the importance of solution accuracy. For instance, absorbent sections were meshed with 3 mm elements, while rigid plates were meshed with 0.01 m elements. Figure 5 displays meshing for absorber sections with circular and square cross-sections, along with rigid plates. Linear 3D homogeneous shell elements with a reduced integration method (S4R) were employed for absorber sections, while 3D elements (4-sided - 4-nodal) of rigid plates (R3D4) were utilized. Given the dynamic nature of the analysis, the explicit library of the software was used for a more precise solution. Following meshing, analysis is performed in the "Job" module, and results are visualized in the software's "Visualization" environment.

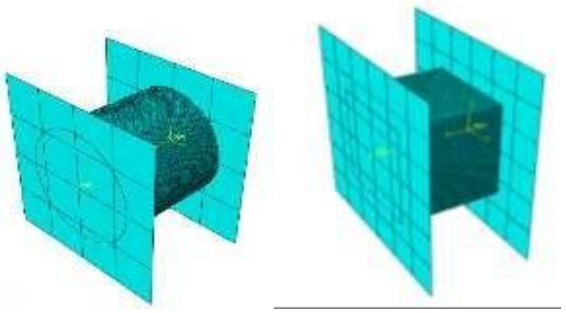


Figure 5. The meshing of the absorber model with circular and square cross-sections along with rigid plates in Abaqus

9. Results of contour changes

In this phase of the research, contour and shape alterations of various absorber sections are scrutinized at two critical time points: the midpoint and the end of the analysis. Figures 6 to 10 depict changes in absorber shape and size at different points and times, alongside von Mises stress values indicating areas of highest stress in elements and nodes. The results illustrated in Figures 6 to 10 reveal a symmetric collapse of the absorber, demonstrating uniform deformation and stress distribution across the absorber at both the midpoint and end of the analysis. These results highlight the good strength of the absorber to resist and dissipate impact energy and point out their structure and mechanical appropriateness. It is also noted that the cross-sectional geometry has a significant effect on the collapse characteristics of the absorbers, and cylindrical and conical sections exhibit symmetric buckling. From the contour points, it can be indicated that the maximum stress is developed at the impact interface with the fixed wall or the surface, and the rest of the absorber resists. As there are a

number of surfaces on a hexagonal cross-section, it develops a compressive stress on the complete shell and thus the arrangement is symmetric. However, this property is a drawback for this device, as it loses the resistance and thus the absorber reaches the maximum force at the earliest and is unable to withstand the force in the shortest period. In the case of the square cross-section absorber and the square Frustum absorber, both have four surfaces, but there is a difference in their behavior. The presence of the angles is quite supportive for the device and thus there is a more uniform collapse than that of the square absorber. The two absorbers exhibit a symmetrical stress distribution, but the presence of the angles gives more uniform and regular collapse than the square absorber. It can also be noted that the highest stress reaches in the initial section of the absorber. From the figures, it should be noted that the maximum von Mises stress in the absorber is developed and is 2.25e+8.

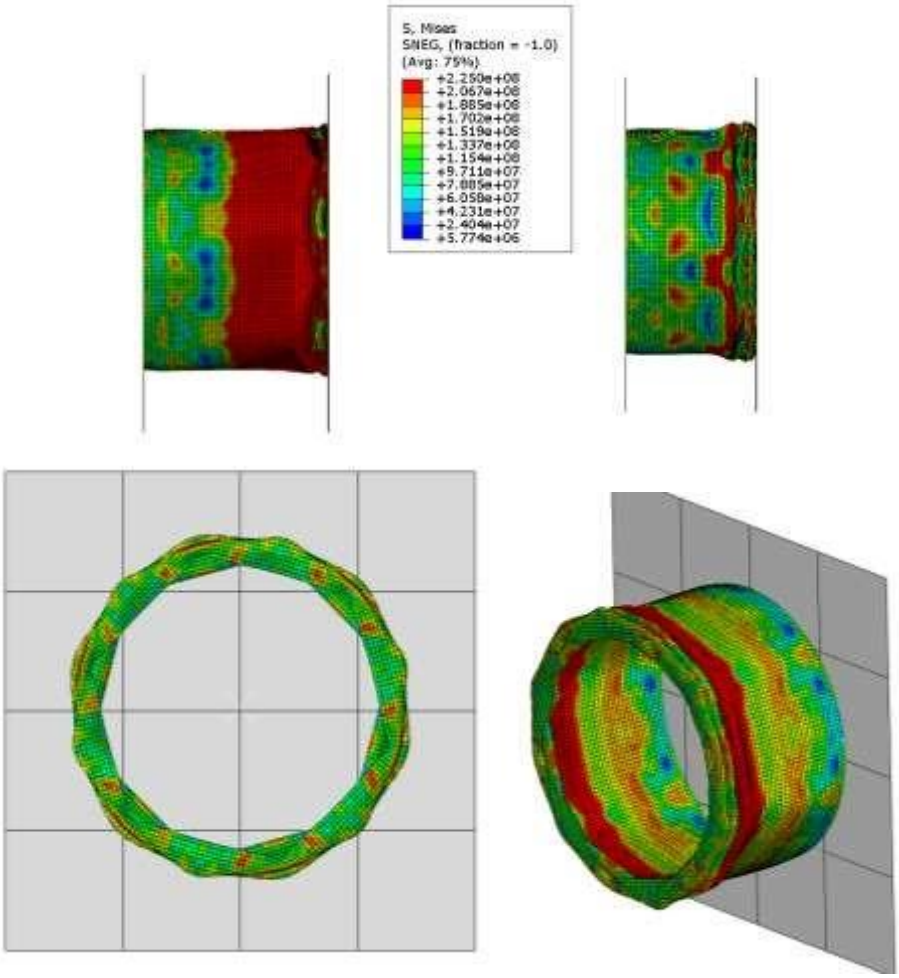


Figure 6. The contour results of circular section shape change in Abaqus software

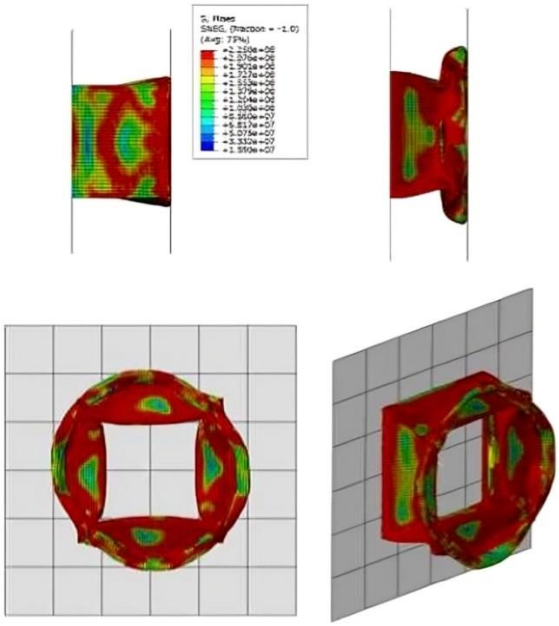


Figure 7. The contour results of square section shape change in Abaqus software

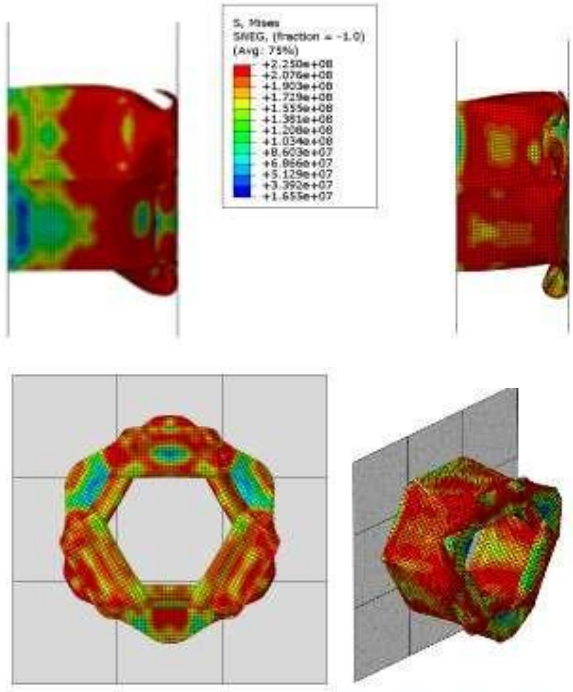


Figure 8. The contour results of changing the shape of the hexagonal section in Abaqus software

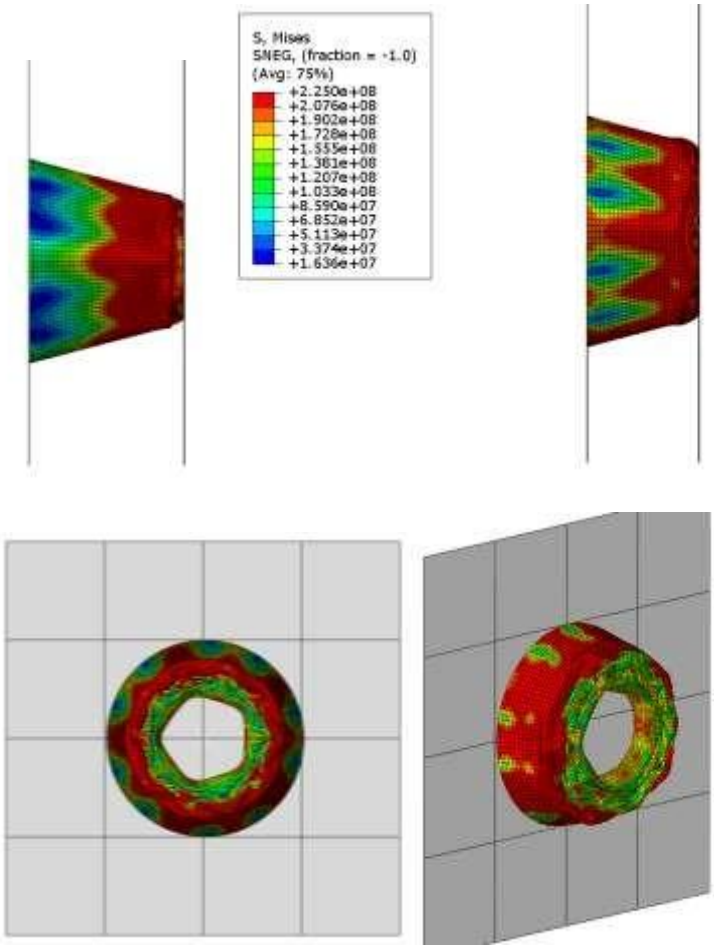
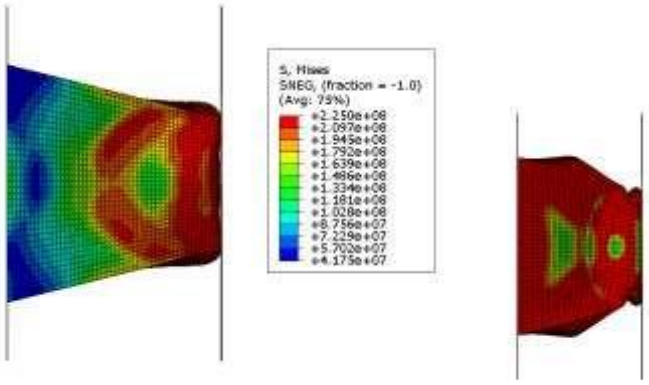


Figure 9. Contour results of changing the shape of conical sections in Abaqus software



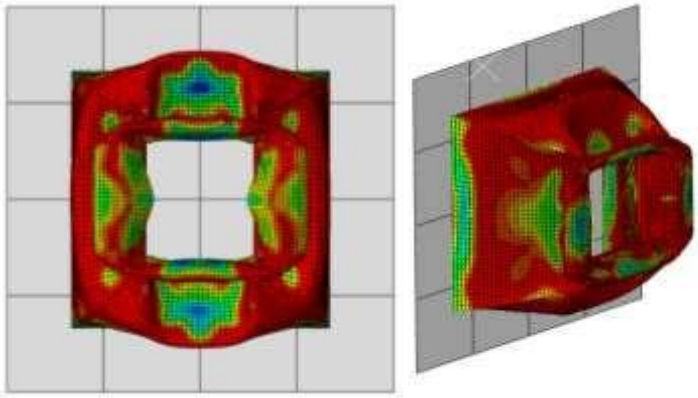


Figure 10. The contour results of changing the shape of the square frustum section in Abaqus software

10. Mesh sensitivity

In this section, a mesh sensitivity analysis was performed by varying the initial mesh dimensions and running the Abaqus program separately. For the circular cross-section, the force-displacement diagrams and the numerical values of the maximum force and energy absorption capacity were examined. To identify the appropriate mesh within the specified convergence criteria, the mesh size was incrementally increased from 2 mm to 3 mm, 4 mm, and 5 mm per element. The effect of these variations on the relevant parameters was analyzed. The initial peak values of the force were increased proportionally with the mesh size up to a certain point. However, when a 1 mm mesh was used, the non-linearity of the analysis and the substantial increase in program execution time led to illogical data and divergent analysis results.

A convergence study was performed to determine the optimum mesh size for the proposed impact attenuators. Similar to the study conducted on thin-walled tubes, the variation of section force with mesh size was examined, with the conical frustum design selected for these investigations [21, 22]. Tests were conducted with different mesh dimensions of 2, 3, 4, and 5 mm. It was observed that a mesh size of 3 mm × 3 mm provided better convergence and a lower error percentage (1.1%) compared to the reference mesh from the study (see Table 2 and Figure 11 [23]). These results indicate that the numerical values and the shape of the graph are more consistent with the real values, and the maximum force is significantly close to the expected value, achieving an acceptable percentage of error. Figure 11 demonstrates the convergence of the initial peak force in relation to mesh size, confirming that the 3 mm mesh size is sufficiently accurate, a finding supported by numerous researchers in crash analysis literature [22, 23].

Table 2. Comparison results

	maximum force F(KN)	Average force (KN)	The length of the squeeze δ(m)	Absorbing energy E(J)	Shape factor (η)	SEA kJ/kg
Ahmed Oshinibosi [23]	141720	70860	1.01	7200.61	0.5	10604.73
Circle Tube	140329	75300.6	0.1	7306.03	0.5	10742.58

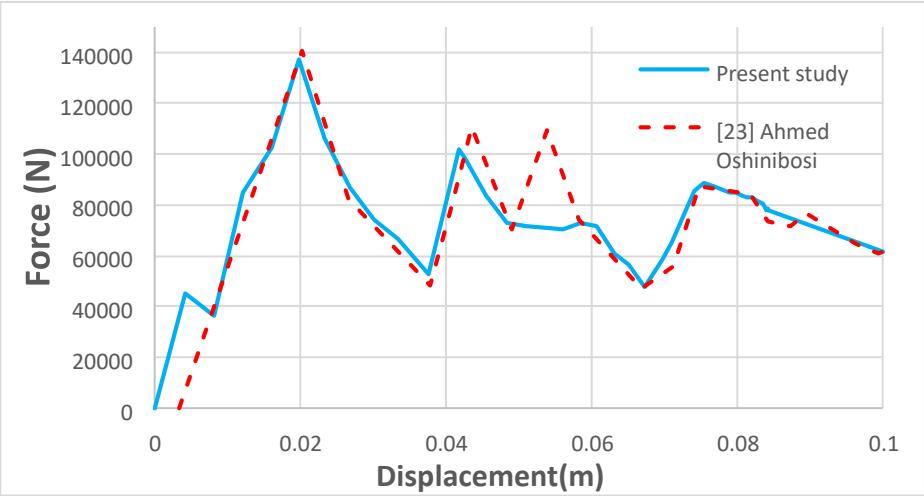


Figure 11. The force-displacement diagram of the reference and the performed test

11. Effects of impact velocity and contact time

In this study, it was observed that absorbers with a hexagonal cross-section profile, due to their special structure, stop the moving velocity faster and reduce it to zero. It provides important results about the changes in velocity and stopping of mobiles when they collide with energy absorbers and can be useful in better design of energy absorbers for different applications.

Table 3. Time table of moving stops by energy absorbers

Sections	Circle	Square	Hexagonal	Conical	Square frustum
Time to stop	0.0246	0.0396	0.018	0.034	0.044

According to Figure 12, testing various impact absorbers demonstrated that the time required for them to come to a complete stop varied significantly based on their geometric shapes. Specifically, the square frustum shape exhibited the longest resistance time before reaching zero velocity. In contrast, the hexagon cross-section had the shortest stopping time due to its geometrical properties. The hexagon's multiple surfaces and symmetrical shape facilitated a more efficient and rapid folding pattern, causing it to stop quicker than the other shapes tested. Cylindrical and conical shapes fell in the middle, exhibiting average stopping times that were neither the shortest nor the longest. The comparative analysis indicated that the angularity of the geometric shapes plays a crucial role in energy absorption and stopping times. For instance, the conical and square frustum shapes, with their distinct angular features, tended to increase the resistance time compared to the more straightforward cylindrical and square shapes. This suggests that the angularity and surface characteristics of an absorber significantly influence its ability to dissipate energy and bring the moving object to a stop efficiently.

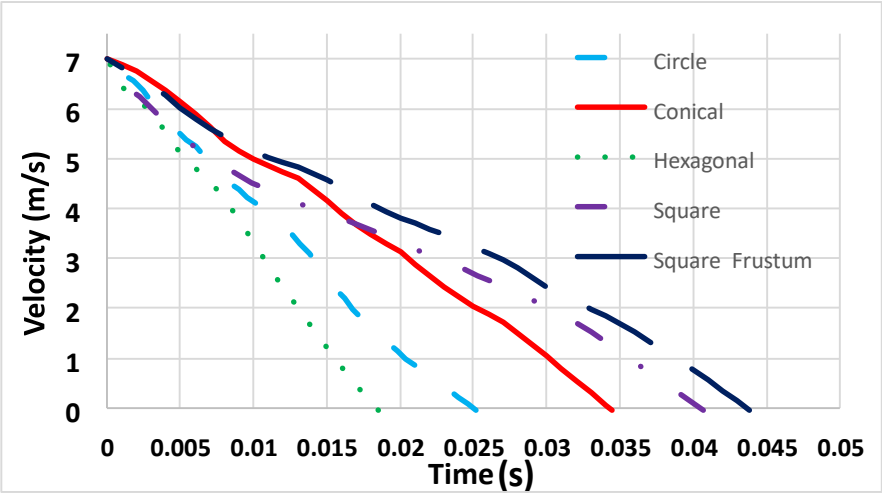


Figure12. Numerical results of changes in the velocity-time diagram of the absorber

12. Analysis of initial design concepts

In the design of energy absorbers, it is always tried to reduce the maximum force and to increase the energy absorption capacity of the area under the force-displacement diagram. According to Figure 13, it can be concluded that the circular section (blue curve) has the highest maximum force and the lowest amount of crushing is related to the hexagonal section (green dashed line curve) and the angular square section (dark blue curve) has the lowest maximum force, and they have the highest amount of crushing. Also, according to this figure, the force-displacement diagram of the conical section (red curve) is more symmetrical and uniform than all other sections, and as can be seen, the values of maximum force and average force are closer to each other in this section, which causes an increase the capacity and efficiency of energy absorption will be.

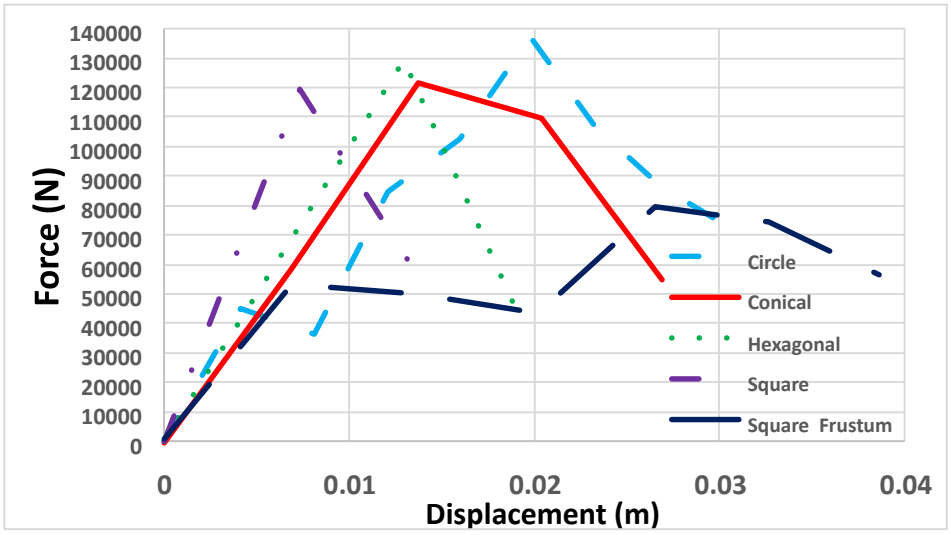


Figure 13. Variations of contact force-displacement diagrams for various absorber sections

13. Time history of absorbed energy

As mentioned earlier, the area under the force-displacement diagram gives us the amount of energy absorbed. By integrating, the amount of energy absorption was obtained, and these results are given below. According to Figure 14, it can be seen that the changes in energy absorption values for all absorbers are almost close to each other. As a result, the absorbed energy per unit weight of these absorbers will be a decisive parameter in measuring their efficiency. Figure 15 shows the bar graph related to the maximum absorbed energy in all absorbers.

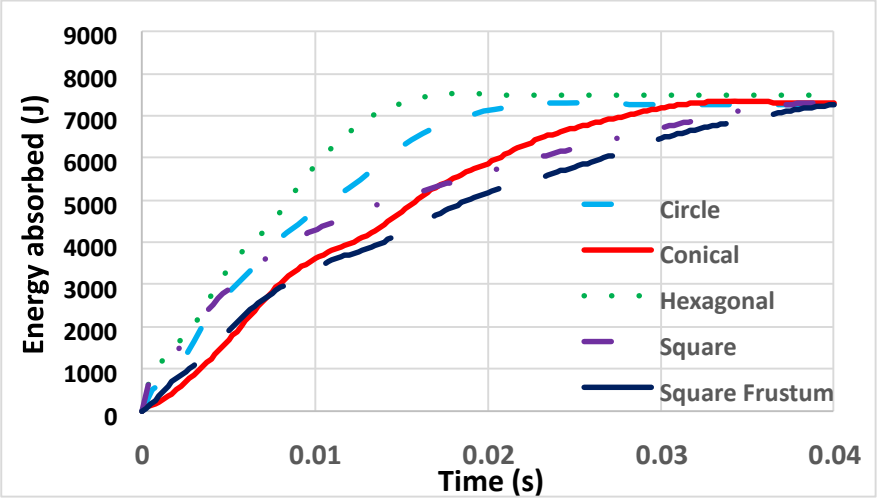


Figure 14. Numerical results of changes in the absorbed energy diagram related to absorber sections

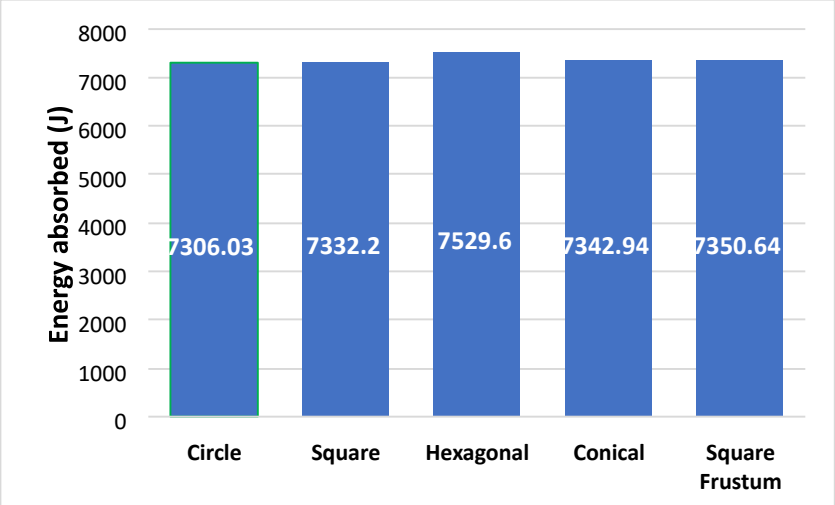


Figure 15. The maximum values of the absorbed energy corresponding to the absorber sections

14. Effects of parameters in the characterization of the absorber behavior

One of the other important parameters in energy absorbers is the shape factor or crushing force efficiency. The closer this coefficient is to one, it indicates the closeness of the values of the average force and the initial maximum force and also indicates the efficiency of the absorber, stable collapse, and better energy absorption capacity. The shape factor is calculated for all the samples in Table 4. As stated, the determining parameter of SEA, which is the specific energy (energy per unit weight) will be equal to the ratio of absorbed energy divided by the weight of the absorber, its values are

listed for each section in Table 4. In this table, the maximum force is related to the initial peak of the force-displacement diagram, which is related to the elastic deformation of the material. According to the results, the energy absorption capacity (SEA) of the conical cross-section is about 21% higher than the square frustum cross-section (in the second order).

Table 4. The effective parameters in defining the deformation behavior of absorbents

Sample section	absorbent weight (kg)		maximum section force (KN)		Average force (KN)	The length of the squeeze δ(m)	absorbing energy E(J)		Shape factor(η)	SEA (KJ/kg)	
	Ref	Present study	Ref	Present study			Ref	Present study		Ref	Present study
circular	679	680.1	14172	140329	75300.6	0.1	7200.61	7306.03	0.5	10604.73	10742.58
square	524	865.94	11989	119532	46071.7	0.13	7370.27	7332.2	0.38	8378.79	8467.33
square frustum	668	666.88	8113	79574.8	43321	0.15	7366.04	7350.64	0.54	10667.84	11022.43
conical	524	523.62	11233	121731	59791.3	0.12	7362.58	7342.94	0.56	13665.15	14023.41
hexagon	749.92		132494		91661	0.06	7529.6		0.69	10040.53	

One of the important goals of energy absorbers is to reduce the initial maximum force. In order to reduce the initial maximum force, different methods are used and designed, such as grooves layered on top of each other, inspired by the palm tree geometry of the absorber body. Therefore, with the aim of reducing the initial maximum (peak) force and also increasing the parameter that determines the specific absorption energy (by reducing the weight of the profile), a new model with grooves and holes and layering on the optimal model of the conical section in the form of figures 16 and 17 is considered. It should be noted that the dimensions of the absorber model include the diameter, the length of the fixed conical cross-section, the groove and the hole, and the layers installed on the model according to Figure 16.



Figure 16. A new mixed model with groove and hole modeled in Abaqus software

According to the observations from Table 5, the efficiency and energy absorption capacity (Specific Energy Absorption, SEA) of the primary absorber design increased by 30% compared to the simple conical section. The secondary design showed a further 0.2% increase in efficiency and SEA over the primary design, totaling increases of 30% and 0.2%, respectively. Additionally, the

shape factor improved by approximately 38% for the first design and 15% for the second design compared to the first design. These results indicate that incorporating grooves, holes, and plates into the conical section model enhances and optimizes the energy absorber design, boosting its efficiency and capacity. The improvement in SEA and shape factor reflects a higher amount of absorbed energy and better efficiency of the absorber across various energy applications. Consequently, the cone model with grooves and holes, and the palm-shaped geometry model with holes, are recommended as robust options for use as energy absorbers in diverse industries and applications.

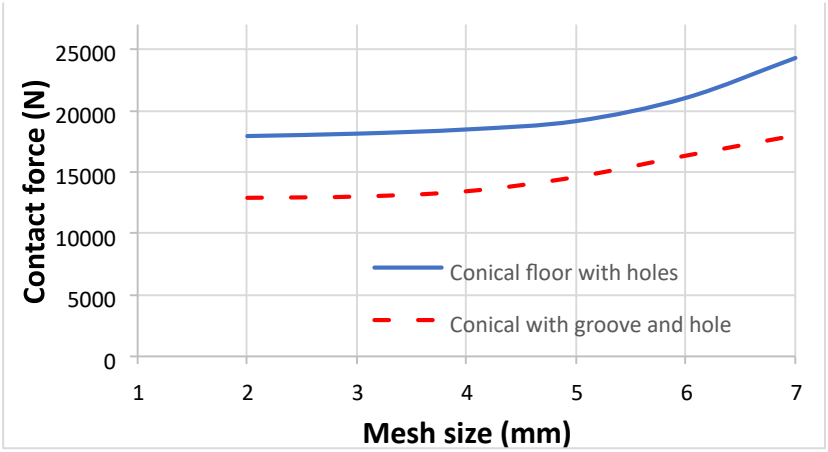


Figure 17. Convergence of initial peak force vs. Mesh size conical sections with groove and holes

The solutions obtained from solving problems with the finite element method are dependent on the size of the mesh and the elements used. By increasing the density of the mesh (decreasing the size of the elements and thus increasing the number of elements), the results converge quickly. However, a finer mesh increases the computational cost. Due to the dependency of finite element solution results on the mesh size used, the convergence of the mesh should always be checked in areas of the model where the values of stress, strain, contact pressure, or any other parameter must be accurately calculated. The improvement of the mesh size should be done intelligently to avoid a drastic increase in the computational time. In this study, mesh convergence was investigated for two conical energy absorbers using different mesh dimensions (2, 3, 4, 5, 6, and 7 mm) as seen in Figure 17. Due to hardware limitations and the high numerical analysis time in Abaqus software, it was not possible to use a 1 mm mesh. The purpose of this analysis was to find the appropriate mesh size to achieve convergence and accuracy in the results. The obtained results show proper convergence for both absorbers with 3 and 4 mm mesh sizes. In other words, the force resulting from these mesh dimensions tends to be a constant number, with fewer changes and higher accuracy. For example, for the first absorber, the resulting force from the 3 mm and 4 mm meshes indicates good convergence at these mesh dimensions. Mesh convergence analysis showed that for conical energy absorbers, mesh dimensions of 3 and 4 mm provide the most optimal convergence and accuracy. These mesh dimensions make the resulting forces tend to a constant number, and more accurate results are obtained. These findings can help engineers to design energy absorbers more efficiently and effectively. According to the findings of this study, using a mesh with dimensions of 3 and 4 mm is suggested as the appropriate size for the numerical analysis of conical energy absorbers.

Table 5. Effective parameters in characterization the behavior of the deformation of the conical and conical models with holes and holes

	Sample section	absorbent weight (kg)	maximum force F(KN)	Average force (KN)	The length of the squeeze δ(m)	absorbing energy E(j)	Shape Factor (η)	SEA kJ/kg
	**Conical**	523.62	121731	59791.3	0.12	7342.94	0.56	14023.41
	**Conical with groove and hole**	357.97	13452.5	12281.14	0.19	7257.01	0.91	20272.67
	**Conical floor with holes**	358.19	18487	17171.86	0.19	7278.07	1.07	20319.02

15. Conclusion

In designing energy absorbers in order to improve their performance and efficiency, the main goal is to reduce the initial maximum force and increase the crushing length. This action leads to an increase in the energy absorption capacity (SEA) and a decrease in the average force compared to the initial maximum force. Therefore, the main parameters such as specific energy (SEA) and shape factor (η) are of great importance. By applying grooves and holes on the conical model, two key parameters, namely the specific energy and the shape factor, are improved dramatically. The results show that this optimized absorber model offers better usability as an energy absorber. These additives increase the crush and decrease the initial peak force, and as a result, the energy absorption capacity and efficiency of the adsorbent are improved.

In response to the optimization of energy absorber configurations, the configurations considered in this investigation were selected based on prior research and practical constraints. The main goal was to examine the deformation mechanisms and energy absorption characteristics under dynamic loading. Although the study does not include a formal optimization framework, such as topology optimization, we acknowledge that such approaches could significantly enhance the absorber's performance by identifying optimal parameters. The application of topology optimization is, therefore, a promising direction for future work.

In summary, the cone model with grooves and holes is introduced as an effective option in the design of energy absorbers. This improved model with high efficiency and more energy absorption capacity is a suitable choice for various applications of industries and technologies. From the analysis of specific energy and shape factors for different sections of absorbers, it is concluded that the conical absorber has the highest energy absorption capacity and efficiency among the circular, square, hexagonal, and conical sections. This means that the conical cross-section has about 21% of the highest energy absorption capacity (SEA) compared to the hexagonal cross-section (in the second order). These criteria show that the conical absorber with grooves and holes has better efficiency and performance in absorbing energy and is suggested as a superior choice for various applications in industries and technologies.

According to the studies and graphs of absorbed energy for different sections of absorbers, it can be seen that in thin-walled absorbers where the final velocity has reached zero and almost all the impact energy has been absorbed, the energy absorption values do not differ much, and the determining parameter in the efficiency and selection of absorbers is always the specific energy (SEA). As a result, the mass of adsorbents and finally the sum of adsorbents and mobiles will be an effective factor in their efficiency. This result shows that to improve the efficiency of energy absorbers, trying to reduce their mass and weight is considered an effective solution.

As a result of examining the changes in the geometry of the optimal model of the conical section and the effect of creating grooves and holes in the absorber model, due to the reduction of the initial maximum force and the increase in the length of crushing and symmetric folding in this case, a new model was presented that improved the energy absorption capacity and the amount absorbed efficiency. By creating grooves and holes in the model, the shape coefficient or crushing force efficiency (η) has increased up to 38%. These results show that the use of new models by creating grooves and holes can significantly improve the performance of energy absorbers and increase their efficiency.

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