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TRUNCATED CONICAL SHELLS AS ABSORBERS OF IMPACT FORCE

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Abstract

In this dissertation, energy absorption capabilities of steel-based truncated conical shells with low base angle and end caps are investigated under axial dynamic loading. The numerical models of absorber were placed between two rigid plates to simulate a crush box around the absorber.

In order to investigate the effect of the design parameters on the energy absorption of the conical shells, three different base conical angle (20°, 25° and 30°), four different impact velocity ($5m/s$, $10m/s$, $20m/s$, $30m/s$), four different absorber thickness ($4mm$, $6mm$, $8mm$, $10mm$) and several impact mass values were analyzed. Numerical analyses were performed by FEM software Abaqus.

The simulation results were compared by means of several performance parameters such as peak reaction force F_p, mean reaction force F_m, absorbed energy E_A specific energy absorption (SEA), crash force efficiency (CFE) and dynamic amplification factor (DAF). In this dissertation, also some guidelines on the design of a truncated conical shell with low base conical angle as an energy absorber are presented.

Keywords

crashworthiness, truncated cone, finite element method, energy absorption

Název Práce

Komolé kuželové skořepiny jako absorbéry rázové síly.

Souhrn

V této dizertační práci jsou zkoumány schopnosti absorpce energie ocelových komolých kuželových skořepin s malým úhlem vzepětí dynamicky zatížených v osovém směru. Numerické modely absorbérů byly umístěny mezi dvě tuhé desky pro simulaci skříně absorbéru.

Za účelem zkoumání vlivu konstrukčních parametrů na absorpci energie kuželových skořepin byly analyzovány tři úhly vzepětí (20°, 25° a 30°), čtyři rychlosti nárazu ($5m/s$, $10m/s$, $20m/s$, $30m/s$), čtyři tloušťky absorbéru ($4mm$, $6mm$, $8mm$, $10mm$) a různé nárazové hmotnosti. Numerické analýzy byly provedeny pomocí MKP programu Abaqus.

Výsledky simulací byly porovnány podle několika parametrů: špičkové reakční síly F_p, střední reakční síly F_m, absorbované energie E_A, specifické absorbované energie (SEA), účinnosti deformační síly (CFE) a dynamického faktoru zesílení (DAF). V této dizertační práci je také uveden návrh konstrukce komolé kuželové skořepiny s malým úhlem vzepětí jako absorbéru.

Klíčová Slova

Metoda konečných prvků, absorpce energie, komolý kužel, odolnost vůči nárazu

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1 Introduction

1.1 Statement of the Research Problem

With the development of the transport technology, there is a substantial increase in number of vehicles and passengers. This increase led to a demand for developing more powerful and faster vehicles. On the other hand, same demand also led to an increase in undesirable situations such as fatal accidents and injuries. The prevention of collisions may not always be possible despite all collision avoidance systems. So it is of utmost importance to control the possible deformation of the vehicle as a result of the collision. Controlling the deformation basically, means to transfer the impact forces to the appropriate sections selected by the designer. The aim here is to ensure that the collision energy is absorbed by the energy absorbers and to minimize or prevent the possible damage to the structural elements of the vehicle. Thus, the undesired damage to the important sections of the vehicle enclosing occupants can be minimized. Picture 1.1 shows various examples of energy absorbers used in different types of vehicles.

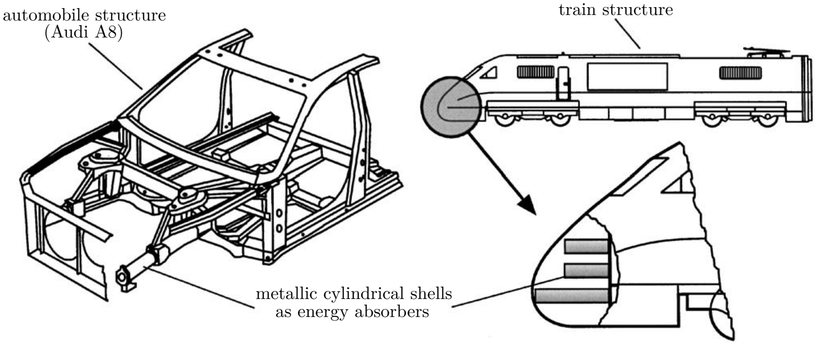


Figure 1.1: Energy absorbers used in various structures. [3]

Another important step of the safety research is to test the developed energy absorbing structure. However, using numerous real vehicles to conduct full-scale crash tests can be quite expensive. A virtual testing method using computer simulations become prominent. The finite element method (FEM) is extensively used in crash simulations. The FEM has the ability to solve complex, highly nonlinear problems in many areas with the development of high-performance computers. Therefore, a number of real vehicle tests that need to be performed can be limited and thereby save costs and time.

1.2 Aim of the Doctoral Dissertation

Current doctoral dissertation study is built upon the current knowledge about the structures used to dissipate impact energy in case of a collision. Current structures being used as impact energy absorbers use mostly the cylindrical tube and rectangular tube geometries more than conical. Thus, most of the studies in the literature are about these type of geometries. On the other hand, there are also too many studies on conically shaped energy absorbers in the literature but most of them have relatively steep conical geometries close to cylindrical tubes.

In this manner, the main aim of this study is to determine the energy absorbing capacity of capped-end truncated cones with relatively low base cone angles and edge ring. Unlike most of the studies, more shallow structures needed to be examined in detail for using as impact energy absorbers. In this manner it is aimed to investigate conical structures with relatively higher thickness over the thin-walled structures encountered commonly in the literature.

1.3 Layout of Thesis

The thesis consists of 7 chapters. A brief description of each chapter is presented below.

Chapter 1: Introduces the background of the idea including the statement of the research problem. Also, introduces the aims of the current study and explanation of the structure of the thesis.

Chapter 2: Involves a detailed information about the crash energy management and energy absorbers. Describes the design requirements and performance parameters which must be considered when designing an energy absorbing structure.

Chapter 3: Includes a summarized literature review about energy absorber structures closely related to the field of this study. Also, a general comparison of the current study with the previous studies in the scopes of the study section takes place.

Chapter 4: Describes the numerical method used in the present study with basic procedures. Numerical difficulties of nonlinearity and time integration methods are presented in detail. Also, includes the terminology of the current FEM software which terms are used in the further chapters of the study.

Chapter 5: Provides a detailed description of numerical simulation techniques performed in this study. This chapter also describes the geometrical parameters, material properties and finite element modeling parameters such as loading conditions, boundary conditions and mesh structure of the numerical models.

Chapter 6: Evaluates a detailed investigation of the results obtained from both quasi-static and dynamic simulations in consideration of different performance parameters such as force-displacement curves, absorbed energy, specific energy absorption, and crash force efficiency. The effects of varying loading conditions and model geometry are investigated and presented. Also some basic comparisons of the simulation results to the current literature for the effect of the variables on the performance parameters are given.

Chapter 7: Presents a summary of major conclusions and contributions to the current study. Also includes some design guidelines and a brief description of the further works planned to improve the results of the present study.

2 Literature Review

2.1 Literature About the Current Problem

Commonly used geometrical shapes of energy absorbers in most studies are cylindrical tube [18, 19], square tube [20, 21] and truncated conical tube [22] also known as a frustum. In the current literature, there are various terms used for identifying the conical structures which are conical shells, cones, conical tube, frustum and frusta. Although most of the studies are focused on cylindrical and rectangular tubes, crashworthiness of conical structures has been studied by many authors.

Langseth and Hopperstad [23], Mamalis et al. [24], Tai et al. [25], Gupta et al. [28] Alghamdi et al. [30], Azimi and Asgari [34] and more authors have investigated various different geometries under axial and oblique loading to obtain the energy absorption characteristics of the structures.

2.2 Scope of the Study

With respect to the aims of the dissertation study as mentioned before, the main scope of the present study is to determine the usability of the conical geometries of low base cone angles as an energy absorbing structure. In this manner, models with various geometric parameters such as the base conical angle and the absorber thickness have been modeled.

A geometry of conical absorbers reversed and connected together was chosen to make the total length of the absorber more adjustable to compare with other absorbers used in the current literature. Based on the aforementioned scope, detailed goals of the study are summarized below.

- To evaluate series of various numerical models for conical structures with different base angle and thickness values in order to simulate the axial impact under various loading velocity and mass values by using the Abaqus/Explicit FEM software.

- To perform analysis on the structures modeled as energy absorbers with variable impact velocities, impact masses and geometrical parameters such as the absorber thickness and base conical angle.
- To process the data from the numerical results with respect to different result parameters to investigate the effectiveness of structures under impact loading to be used as energy absorbers.
- To generate an opinion on the usability of the structure as an energy absorber by taking into consideration of both commonly used structures.

3 Background

3.1 Crash Energy Management

Crashworthiness can be defined as the capability of a vehicle to withstand a crash and protect its passengers from the effects of an accident. Main crashworthiness goals are to absorb the kinetic energy of a collision with an acceptable deceleration pulse and maintain a survival space to protect passengers.Crash Energy Management (CEM) is the sum of the techniques to improve the overall crashworthiness of a vehicle. Possible damages of an accident should be predicted and should be kept under control. With crash energy management systems, damage of a collision is transferred to the parts that designed to absorb the crash energy and protect the main structural elements of the vehicle.

3.2 Energy Absorbers

Energy absorbers absorb energy both in a reversible and irreversible way such as elastic strain energy and plastic deformation energy. Collapsible energy absorbers aim to convert the majority of the kinetic energy of impact into plastic deformation in an irreversible manner.[8]

General Design Requirements

In the design phase of an energy absorber, one must consider the specific requirements of the area that absorber is planned to use. In all cases, the main purpose is to scatter crash energy in a foreordained way. In this manner, some essential requirements are listed and described below.[12]

1. Irreversible Energy Conversion
2. Restricted and Constant Reaction Force
3. Long Stroke
4. Stable and Repeatable Deformation Mode
5. Lightweight and High Specific Energy Absorption
6. Low Cost and Easy Installation

Performance Parameters

Even if the most important parameter of an energy absorber is the amount of dissipated energy, it is not sufficient to estimate the performance of the absorber by considering only the amount of the energy absorbed during the impact. For a reasonable performance estimation, it is needed to define and investigate following parameters:

1. Force-Displacement Curves
2. Energy Absorption
3. Crash Force Efficiency (CFE)
4. Specific Energy Absorption (SEA)
5. Absorbed Energy According to Displacement
6. Stroke Efficiency
7. Dynamic Amplification Factor

4 Numerical Model and Simulations

The numerical models for the simulations were created using the CAE module of the FEM software Abaqus. [36]

4.1 Model Geometry

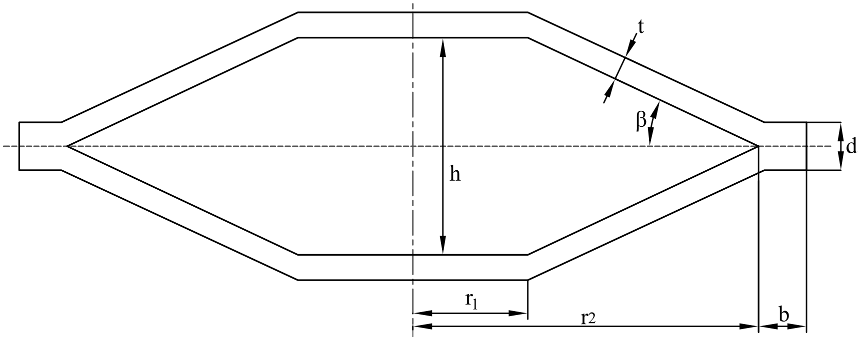


Figure 4.1: Geometry and dimension parameters of the absorber structure.

A basic sketch of the absorber structure is given in Figure 4.1 with dimension parameters. Dimension parameters used to model the structures are, inner diameter r_1, outer diameter r_2, edge ring width b, edge ring height d, thickness t, cone angle β and deformation length h. The edge ring width b is kept constant in all simulations, hence the effect of this parameter on the energy absorbing capability of the structure is not investigated in the current study. Values used for all parameters are given in Table 4.1.

Structures were modeled by creating each plate and the absorber as quarter models of real dimensions of structures. The model assembly includes three equally designed rigid plates and a conical absorber. The conical absorber was positioned between two rigid plates (top and bottom plate) to simulate a crush box and also to control the deformation of the structure. Rigid plates were constrained to the absorber using the constraint definitions explained in further sections.

Table 4.1: Dimension values of the absorber structures.

β [deg]	**h** [mm]	**t** [mm]	**b** [mm]	**d** [mm]	$\mathbf{r_1}$ [mm]	$\mathbf{r_2}$ [mm]
20	72.8	10	20	20	50	150
25	93.3	8		16		
30	115.5	6		12		
		4		8		

The third plate (striker plate) is used to simulate the striking mass crushing to the conical absorber. A gap of $1mm$ between the top plate and the striking plate was modeled to examine the effect of the first contact more conveniently. The general assembly of all parts used in the numerical models are shown in Figure 4.2

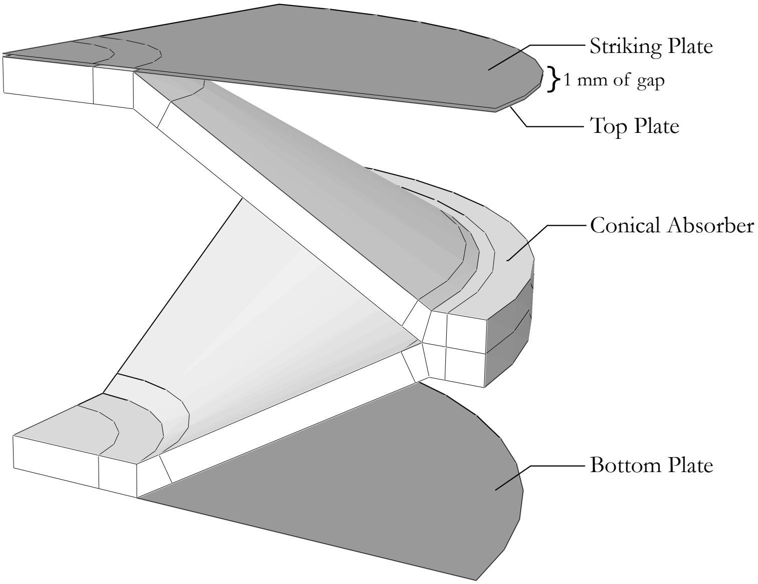


Figure 4.2: Assembly of the absorber and the rigid plates.

4.2 Material Properties

The material used for the simulations were considered to be structural mild steel denominated as S235JR. In numerical analysis, an elastoplastic hardening module was implemented to the material behavior. Mechanical properties of material S235JR are used as; Young's Modulus of $200GPa$, Poisson's Ratio of 0.29 Mass Density of $7980kg/m^3$, Yield Strength of $296.4MPa$ and Ultimate Tensile Strength of $381MPa$.

Material properties are of great importance at crashworthiness and impact studies. The plastic flow of some materials is sensitive to loading speed, which is known as material strain-rate sensitivity, or viscoplasticity. The strain rate sensitivity phenomenon can influence the dynamic response of the energy absorbing structures. Previous studies have indicated that S235 steel displays a significant positive strain rate effect on the yield stress of the material. [44, 45] Verleysen et. al. [44] have investigated the influence of the strain rate on the forming properties of three commercial steel grades including S235JR.

The static tensile test results of the present study and the results from the aforementioned article by Verleysen et. al. [44] are compared and they are found to be essentially identical for the S235JR steel. Due to the technical impossibilities and the lack of equipment for SHTB experiments, the Johnson-Cook model in the study of Verleysen et. al. [44] for S235JR steel with strain rate properties are adapted to the numerical models of the present study. Consequently, the Johnson-Cook plasticity model parameters including strain rate used in this study are given in Table 4.2.

Table 4.2: Johnson-Cook plasticity parameters of S235JR. [44]

A	B	n	C	$\dot{\varepsilon}_0$
280 MPa	667 MPa	0.72	0.071	5.6x10^{-4}

4.3 Loading and Boundary Conditions

In quasi-static numerical simulations, the load is applied very slowly that the deformation of the structure is not affected by the strain rate and inertia forces which are very small and negligible. Loading was applied to the rigid striking plate as a predefined velocity over the longitudinal axis of the model assembly. Quasi-static velocity is selected to be $0.01m/s$.

In dynamic simulations, it is planned to apply the load as kinetic energy. The kinetic energy was generated by defining a velocity and a mass to the striking plate. Used mass quantities are calculated to obtain $100kJ$ of initial kinetic energy for each model. Moreover, mass values of $1000kg$ and $2000kg$ were defined for each impact speed to investigate the effect of the impact mass. Four different impact velocities ($5m/s$, $10m/s$, $20m/s$ and $30m/s$) were selected and simulated for each impact mass, base conical angle and absorber thickness combination.

Interactions between parts were defined using self-contact and surface to surface contact algorithms. Self-contact was used to define self-contact of absorber structure with penalty contact definition with a friction coefficient of 0.3 as tangential contact behavior and hard contact as normal contact behavior. To simulate a crush box, the conical energy absorber was coupled to two rigid plates from the top and bottom surfaces. A kinematic coupling definition was used.

Any movement of the bottom plate was restrained using an encastre boundary condition definition. The top plate and striker plate were allowed for translations on the y-axis direction and any other movement of the plates were restrained. Structures were designed as quarter models to reduce the time cost of the simulations. For this purpose, symmetry boundary conditions were used for both edges of the absorber. X-symmetry definition for the edge on y-z plate and z-symmetry definition for the edge on x-y plate were made.

5 Results and Discussion

5.1 Quasi-Static Response of the Conical Absorber

For the quasi-static loading case, the reference model is chosen with respect to the design parameters and response plots. The thickness (t) and the base cone angle (β) for he reference case are selected to be $10mm$ and 30° respectively. The impact velocity for all quasi-static simulations is selected to be $0.01m/s$ which represents a deformation of $10mm$ per second.

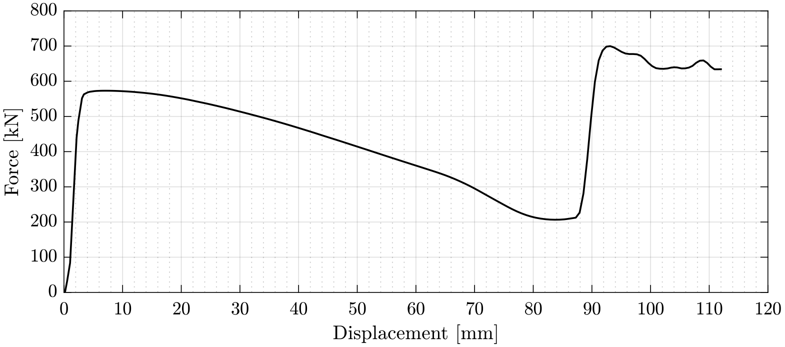


Figure 5.1: Force-Displacement plot of the quasi-static model.

In Figure 5.1, the force-displacement response of the reference case is presented. After $1mm$ of displacement, the first contact between the striking plate and the absorber occurs. A stable deformation of the structure was observed after the first peak load throughout the simulation. At the displacement value of approximately $90mm$, the second contact occurs. Each contact between the surfaces in the model assembly causes a peak load in the reaction force response.

Figure 5.2 shows the absorbed energy and the reaction force response of the quasi-static reference model as a function of displacement. Also the deformed shapes of the model are given in Figure 5.2 for selected points to better understand the behavior of the structure under quasi-static axial loading.

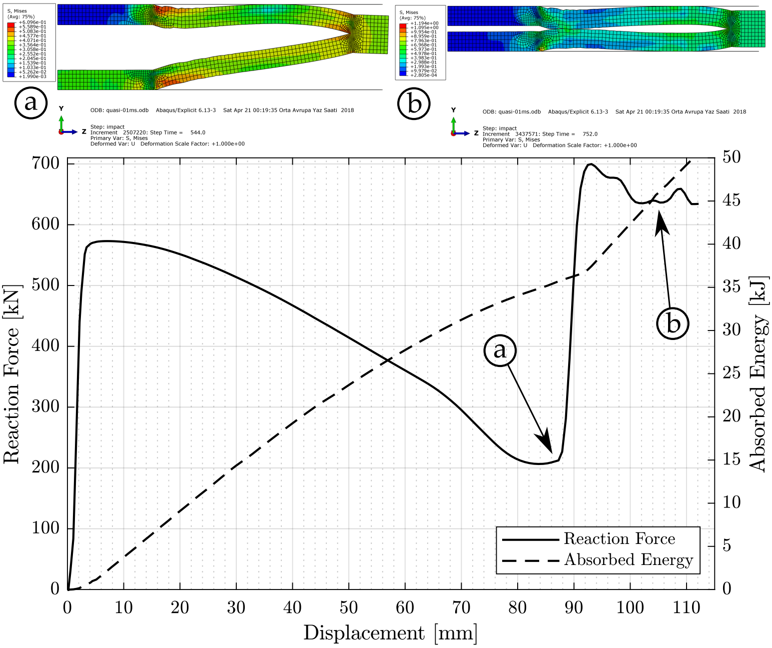


Figure 5.2: Deformation mode for the reference quasi-static case at selected points.

The selected instants for the simulation of the quasi-static reference model are; a) the contact between the conical surface of the absorber and the rigid wall which causes the second peak on the force-displacement response, b) the last contact during the simulation between the conical surface of the absorber and the striking rigid plate. These two instants are selected because at both instants, a sudden change occur on the reaction force response of the structure under quasi-static loading.

5.2 Dynamic Response of the Conical Absorber

The model with a constant impact kinetic energy of 100kJ is chosen for the reference dynamic case with respect to the variations of the design parameters and plots of reaction force and absorbed nergy. The thickness (t) and the base cone angle (β) are chosen as $10mm$ and 30° respectively.

Smoothed force response for the reference case is plotted in Figure 5.3. At 1mm of displacement, the first contact between the striking mass and the absorber structure occurs. As the impact occurs instantaneously, the velocity of the contact surface of the absorber increases immediately. After the first reaction force occurs, the structure exhibits a stable deformation behavior. The reaction force shows a decreasing trend until the next contact between striking plate and the surface of the absorber takes place. This behavior repeats on each contact between surfaces of the absorber and striking plate.

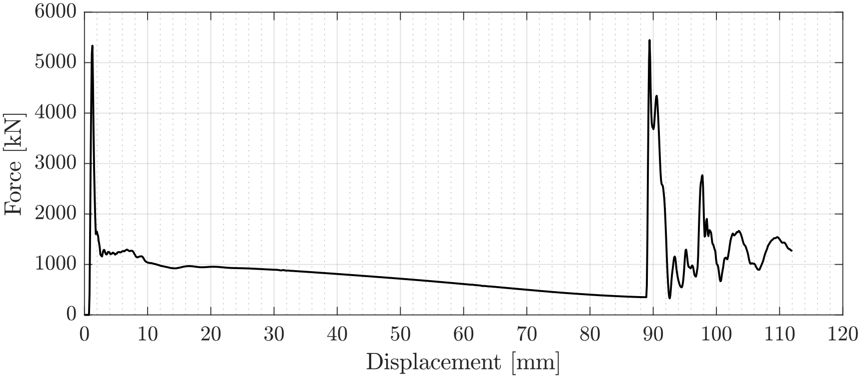


Figure 5.3: Force-Displacement plot of the reference dynamic model.

The dynamic response of the structure by means of the reaction force and the absorbed energy is plotted in Figure 5.4 together. Also pictures of the deformation mode for selected points are shown together to better understand the behavior of the structure.

The selected instants for the reference model are a) the initial contact, and first cone starts bending, b) contact of conical surface to striking plate occurs and second cone starts bending, c) first cone becomes completely flat and contact of the inner surfaces of the cones are achieved.

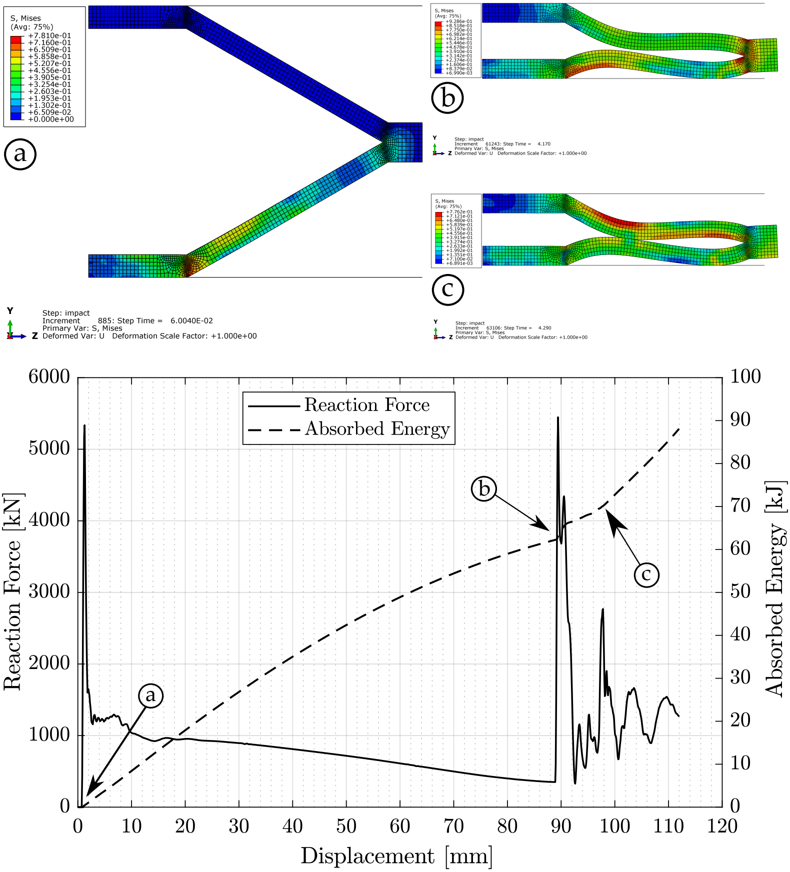


Figure 5.4: Deformation mode for the reference dynamic case at selected points.

5.3 Comparison between Quasi-Static and Dynamic Response

One of the most important performance parameter of an energy absorber is the reaction force. Reaction force response of an energy absorber may change under different conditions such as loading, boundary conditions and material properties. Figure 5.5 shows the comparison of mean dynamic force response of the model with parameters $t = 10mm$ and $\beta = 30°$.

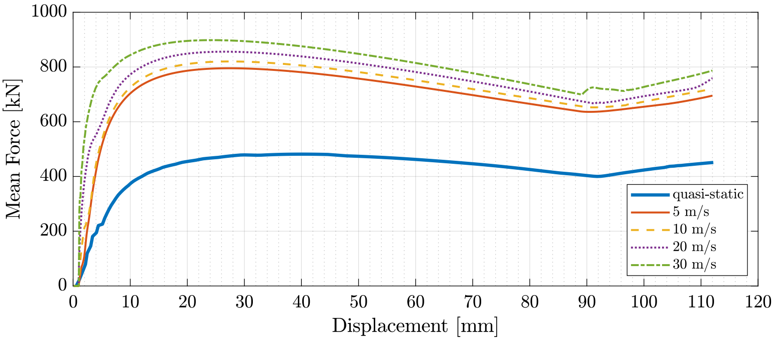


Figure 5.5: Comparison of mean Force-Displacement response of the quasi-static and dynamic models $\beta = 30°$ and $t = 10mm$.

It is observed that there is a significant difference between the quasi-static and dynamic cases in terms of mean reaction force response. This is caused by the strain-rate dependent material model used in this study which changes the structures response under different initial impact velocity conditions.

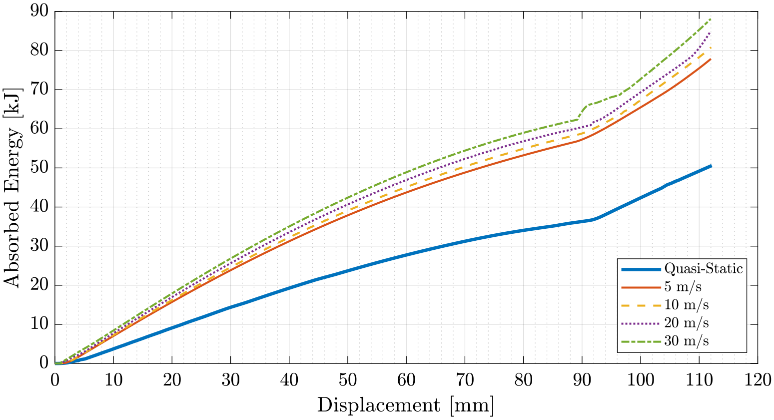


Figure 5.6: Comparison of energy absorption of the model $\beta = 30°$ and $t = 10mm$.

As the energy absorbing capacity of the structures are strictly related to the reaction force response, the absorbed energy curves conform with the force-displacement plots. The absorbed energy response of the numerical model with $\beta = 30°$

and $t = 10mm$ is given in Figure 5.6 as a function of displacement. The energy absorption capacity of the structures increase with increasing impact velocity. For the impact velocity values of $20m/s$ and $30m/s$, both reaction force and the absorbed energy plots have a slightly different behavior.

5.4 Combined Effects on Performance Parameters

In this section, the performance parameters of an energy absorber are investigated individually for all variable parameters. The effect of three different variables (velocity, thickness, base conical angle) are compared for each simulation result output, except for the impact mass variable.

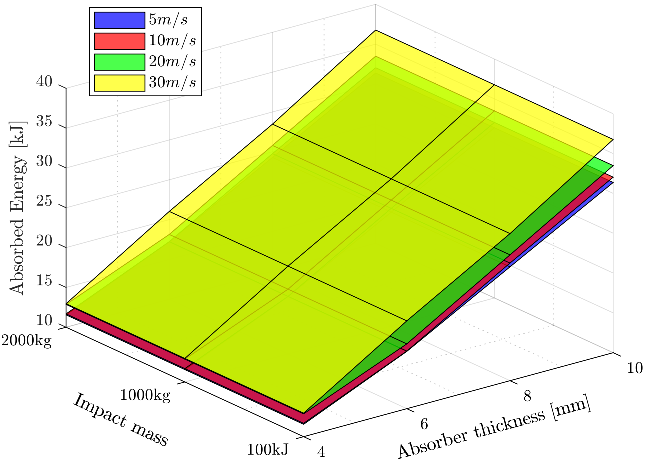


Figure 5.7: Effect of Impact mass, absorber thickness and impact velocity on the amount of absorbed energy.

Figure 5.7 shows the effect of the impact mass, absorber thickness and impact velocity on the absorbed energy. As seen in Figure 5.7, impact mass does not have significant effect on absorbed energy. However, the maximum deformation length is associated with the initial kinetic energy of the system and increases with increasing impact mass. It can be said that the dynamic or non-linear stiffness of the absorber structure is not dependent on the mass of the impactor in the selected mass range. The same result were also observed in the previous studies in the current literature. For this reason, the impact mass parameter is not included to any of the following 3-D plots.

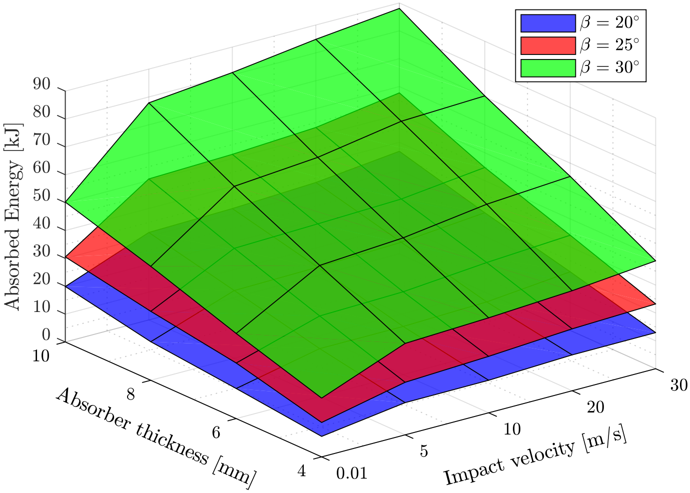


Figure 5.8: Effect of base conical angle, absorber thickness and impact velocity on absorbed energy.

Figure 5.8 shows that the amount of absorbed energy increases in all models as the base cone angle β ,absorber thickness and impact velocity increases. With increasing β angle, structures exhibit more stiff behavior to the axial loading and also gain more deformation length with constant bottom radius and increasing β angle.

This situation allows the structures with higher β angles to dissipate more kinetic energy at the same impact velocity and absorber thickness. Absorbed energy values also increase with the increasing absorber thickness. The impact velocity has also a non-negligible effect on the energy absorption of the structures due to the inertia effects with increasing impact velocity. When compared together, impact velocity has a less significant effect on the energy absorption capacities of structures.

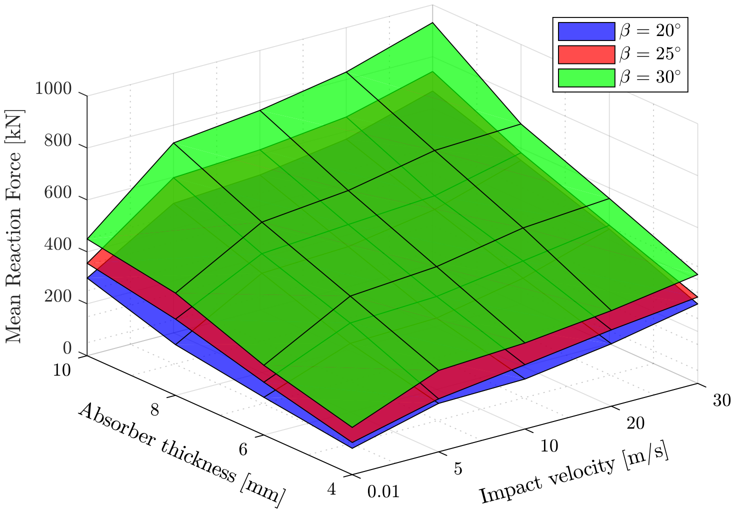


Figure 5.9: Effect of base conical angle, absorber thickness and impact velocity on mean reaction force.

The effect of the impact velocity and the base conical angle on the mean reaction forces are more clearly seen at the higher absorber thickness values. Mean reaction forces have similar behavior with peak reaction forces at different impact velocity, absorber thickness and base conical angle values. The effect of the base conical angle β on the peak reaction forces are more identical at different absorber thicknesses when compared to the mean reaction force. Effects of the variable parameters on mean reaction force values are shown in Figure 5.9.

Crash force efficiency (CFE) values of the structures exhibit a significantly decreasing behavior as the impact velocity increases. The complete dataset of the CFE values are plotted in Figure 5.10. As the peak reaction force response of the structures increase significantly as the impact velocity increses, the CFE values for higher impact velocities are very low when compared to the quasi-static loading case. Also the the conical angle becomes more effective on the CFE values at relatively lower impact velocity values.

It is found that the absorber thickness has a similar effect on both mean and peak reaction force values. Thus, the CFE values does not change significantly within the range of the absorber thickness values of the present study. Overall, the obtained CFE values of the present study are seem to be compatible with the current literature.

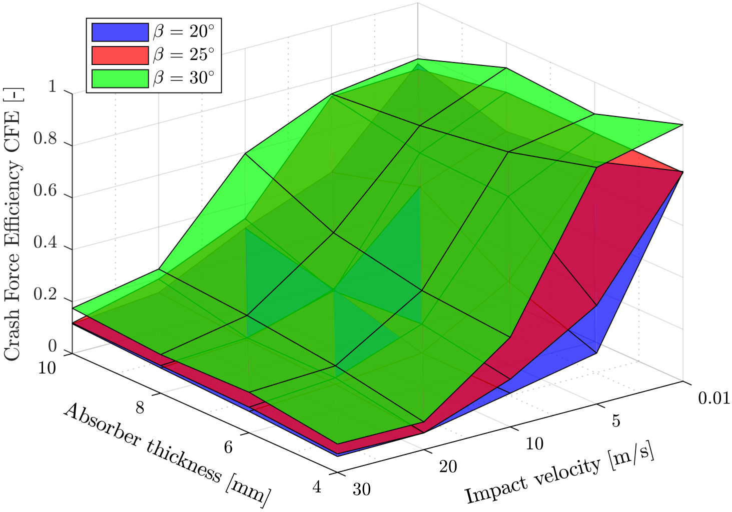


Figure 5.10: Effect of base conical angle, absorber thickness and impact velocity on CFE.

The stroke efficiency is another performance parameter of energy absorbers. It is desired to be as high as possible in order to have a higher maximum deformable length and so the absorbed energy. Calculated values for all models are given in Figure 5.11 by means of base conical angle, impact velocity and the absorber thickness.

Stroke efficiency is directly related to the conical angle β. Besides, the deformation mode has an indirect effect due to the changes in bending shapes of the models. The maximum deformation lengths are seem to be equal for all absorber thickness values due to the selected geometry.

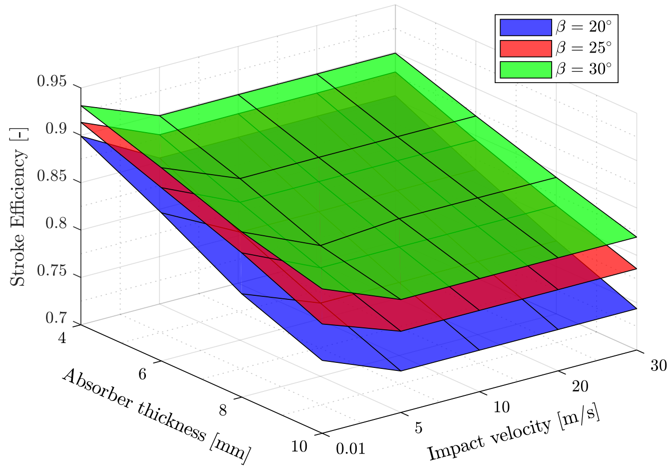


Figure 5.11: Effect of base conical angle, absorber thickness and impact velocity on stroke efficiency.

Under quasi-static loading conditions, stroke efficiency values are obtained to be slightly higher than the dynamic loading case, which is caused by the stable deformation of the structures.

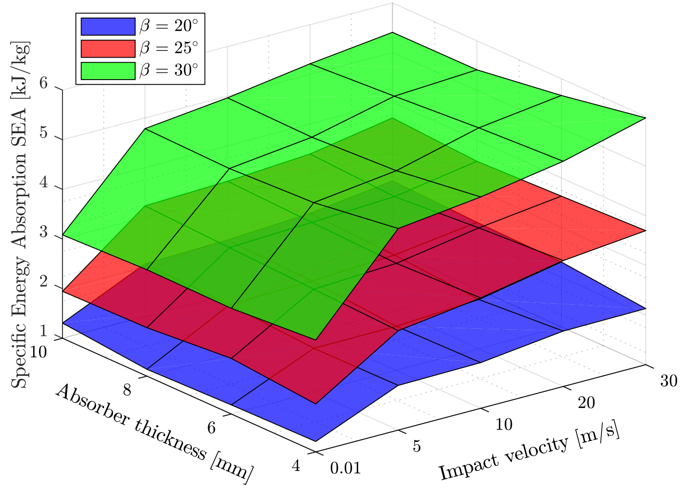


Figure 5.12: Effect of base conical angle, absorber thickness and impact velocity on specific energy absorption SEA.

Specific energy absorption (SEA) values changes significantly under dynamic loading conditions when compared to the quasi-static case. This is caused by the strain-rate dependency of the material model. The SEA have also a slightly increasing behavior for increasing impact velocity under dynamic loading conditions. The SEA is not seem to be significantly affected from the increasing absorber thickness values. This is caused by the increasing effect of the absorber thickness on both the absorbed energy values and the mass of the structure.

On the other hand, the specific energy absorption values are significantly affected from the base conical angle as seen in Figure 5.12. Although the base conical angle increases the mass of the body, the increase in energy absorption capacity is relatively higher.

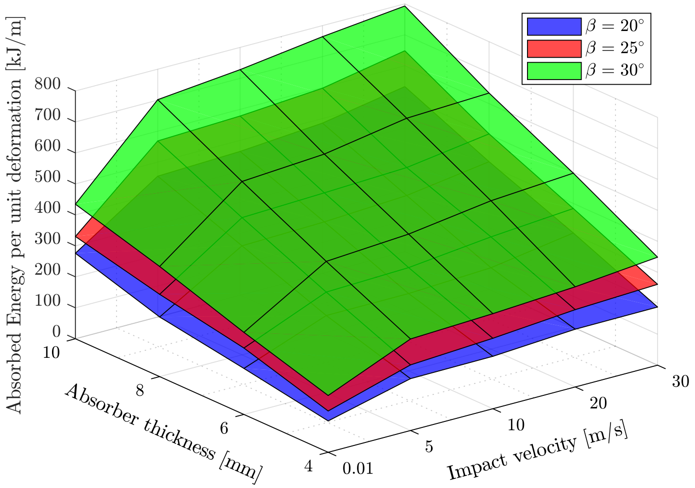
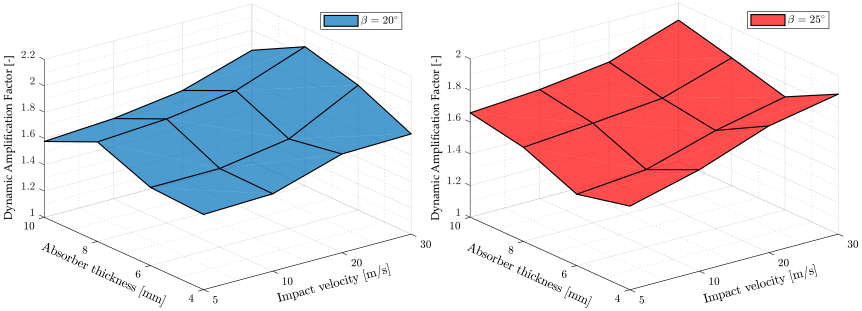


Figure 5.13: Effect of base conical angle, absorber thickness and impact velocity on absorbed energy per unit deformation.

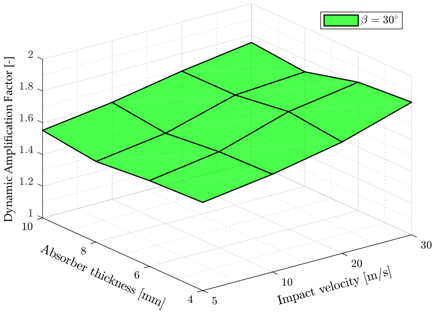
As seen in Figure 5.13, the absorbed energy per unit deformation is affected from both three parameters. The most effective parameter is the absorber thickness because of the increase in the absorbed energy as the thickness increase.

The less effective parameter is the impact velocity because it has the less effect on the energy absorption characteristics at a chosen β angle of structure when compared to others under dynamic loading conditions. The effect of the base conical angle is slightly changed by the absorber thickness and impact velocity values. The comparison surfaces of Figure 5.13 are almost parallel although the conical angle changes the maximum deformable length of the structures significantly.

The dynamic amplification factor (DAF) is another useful parameter for comparing the dynamic effects on the absorbed energy of the structures. The calculated DAF values are plotted in Figure 5.14 for the models of selected parameters.



(a) $\beta = 20°$ **(b)** $\beta = 25°$



(c) $\beta = 30°$

Figure 5.14: Effect of the absorber thickness and the impact velocity on the DAF values.

DAF values slightly increase as the impact velocity increases due to the inertia effects. Also the the conical angle becomes more effective on the DAF values with decreasing absorber thickness. The effect of the absorber thickness on the DAF values are more stable at models with higher base conical angle. Due to the lower angle and thickness, the models are more prone to bending. The geometric stiffness of the models are relatively low and the effect of the inertia forces are observed to be higher.

6 Conclusion

6.1 Summary and Conclusions

A numerical investigation of the conical energy absorbing structure was examined in this study. In the view of obtained information from the current study, some of the significant conclusions and some guidelines on the design of a low base conical angle structure are summarized below.

1. The dynamic force-displacement response of the conical structure is affected by the absorber thickness, base conical angle and the impact velocity. However, it is observed that the impact mass of the striker has no effect on the dynamic force response of the structures. The effect of the angle on the force responses become higher as the thickness increases.

2. The energy absorption response of a low angle conical structure under axial dynamic loading is influenced by the absorber thickness, conical angle and impact velocity. However, the conical angle and the absorber thickness are the most effective on the energy absorption of the selected geometry. In other words, structures with higher thickness and angle absorb more energy within a selected crush distance.

3. The CFE values have a decreasing trend as the impact velocity increases due to the increasing initial peak reaction force. On the other hand, CFE values do not seem to be affected from the absorber thickness. However, base conical angle has an increasing effect on CFE values which is caused by the increasing mean reaction forces due to the bending resistance of the structures with higher β values.

4. The specific energy absorption values are strictly affected from the base conical angle β. Increasing conical angle causes the system to be more resistant to any bending action. However, the absorber thickness does not affect the SEA values significantly.

5. In order to increase the absorbed energy within a given deformation length;

    (a) the conical angle can be increased for the same absorber thickness values and/or impact velocity,
    (b) absorber thickness can be increased for the same base conical angle and/or impact velocity,
    (c) changing the impact mass has no significant effect.
    (d) increasing the initial impact velocity also increase the amount of absorbed energy which is caused by the inertia effects and the strain-rate dependency of the material model. However, the effect of the impact velocity is quite low when compared to the effect of the thickness and the conical angle.

6.2 Contributions of the Thesis

The primary aim of this thesis is to gain a better understanding on the impact and energy absorption behavior of truncated conical structures with relatively higher thickness values and to investigate their application as an energy absorber.

With respect to the objectives outlined in Chapters 1 and 3, this study has investigated the impact response and energy absorption capabilities of truncated shallow cones under axial impact loading. Studies until current stage has provided a good opportunity to investigate and compare dynamic response of truncated cones by means of some important performance parameters.

The energy absorbing capabilities of the current geometry, seems to be promising due to it's relatively high thickness and high energy absorption. However, high thickness leads to a more heavy structure which is not preferable as an energy absorber. Also the conical angle has a great influence on the energy absorbing performance of the structure. Structures with higher angle and lower thickness absorbs slightly more energy than the structures with lower angle and higher thickness. However, current stage of the study is still not sufficient to determine the usability of undertaken geometry as an impact absorber. In consideration of parameters compared above and future work explained below, further studies will be more appropriate to resolve the situation of current geometry to be a possible alternative to the current energy absorber geometry.

6.3 Recommendations for Future Work

In order to obtain sufficient investigation of the geometry undertaken in the current study, amount of the stroke length of an energy absorber is a significant design requirement. It is necessary to have a longer stroke of energy absorbers both to improve the energy dissipation performance of the structure and to gain a comparable length of geometry with the energy absorbers studied in the literature and used in the industry. In this manner, instead of changing the base cone angle of the structure, it should be investigated to use more than one structure coupled together to obtain sufficient deformation stroke.

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