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INFLUENCE OF IMPACT VELOCITY ON ENERGY ABSORPTION PERFORMANCE OF THICK-WALLED TRUNCATED CONICAL SHELLS

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Abstract

The paper deals with the energy absorption capabilities of truncated conical structures with low base angle under quasi-static and dynamic axial loading. The simulation results were compared by means of several performance parameters such as mean crushing force F_m, absorbed energy E_A, specific energy absorption (SEA), crash force efficiency (CFE), dynamic amplification factor (DAF) and absorbed energy per unit deformation. Results are summarized by means of the performance parameters and main conclusions are made.

Keywords

finite element method, energy absorption, truncated cone, crashworthiness

1 INTRODUCTION

With the development of the transport technology, there is a substantial 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 authorities have become aware of this safety situation in transportation and have begun to pay attention to the possible causes of the death and injury incidents. 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.

Commonly used geometrical shapes in most studies are cylindrical tube, square tube and truncated conical tube, also known as a frustum. Although most of the studies are focused on cylindrical and rectangular tubes, crashworthiness of conical structures has been studied by many substantial authors.

Mamalis et al. [1] have investigated the crash behaviour and energy absorbing characteristics of axially loaded steel thin-walled tubes of the octagonal cross-section. A test series of axially compressed octagonal tubes have been carried out under quasi-static loading. Tai et al. [2] have

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analysed the axial compression behaviour and energy absorption of the thin-walled cylinder under impact load. Analysis outcomes showed that the impact kinetic energy is more sensitive to speed than impact mass. Gupta et al. [3] have performed an experimental study on aluminium conical frusta of different semi-apical angles under axial compression. Authors have proposed an analytical model for the prediction of load-deformation and energy-compression curves of the metallic conical frusta. Aljawi and Alghamdi [4] have examined deformation modes of frusta as a collapsible energy absorber. Authors obtained that within the experimental impact speed range of $0-7\ m/s$, the speed of deformation had no effect on the process of inversion and flattening. Eswara and Gupta [5] have examined spherical domes and conical frusta of various sizes. Load-deformation curves and collapse modes of frusta have shown similar behaviour in quasi-static and dynamic tests.

The main scope of the present study is to determine the effect of the impact velocity on the energy absorption of conical geometries of low base cone angle. In this manner, a selected geometry with low base conical angle and relatively higher thickness values is investigated under static and dynamic loading conditions with various impact velocities. All models have been studied numerically with the influence of parameters such as load-deflection curves, crash force efficiency and specific energy absorption values.

2 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 overall performance of a structure. For a reasonable performance estimation, it is needed to define and investigate following parameters:

Mean Crushing Force (F_m) is the average force during the impact. It can be calculated by using force response and total deflection length of the absorber.

$$F_m = \frac{\int_0^{d_{max}} F dx}{d_{max}} \tag{1}$$

where $F\ [kN]$ is the crushing force and $d_{max}[mm]$ is maximum crush distance.

Peak Crushing Force (F_p) is the maximum value of the axial force during crush. Peak force occurs when material yields or buckles. Peak crushing force should be kept relatively low or in other words, it should not be far beyond the mean crushing force.

The total absorbed energy of an energy absorber can be defined as the work done by the crushing force at a deformation distance. By using basic mechanics, absorbed energy is simply the area under the force-displacement curve and can be expressed as;

$$E_A = \int_0^{d_{max}} F dx \tag{2}$$

(1)

where $d_{max}\ [mm]$ is maximum crush distance and $F\ [kN]$ is the crushing force.

Crash force efficiency is described as the ratio of mean crushing force to the peak crushing force during the deformation caused by the impact. It is desired to have CFE close to unity; to approve the system has good crash performance.

$$CFE = \frac{F_m}{F_p} \tag{3}$$

Crash force efficiency can be improved by using trigger mechanisms such or holes to make an imperfection and raise the stress at initial loading to ease buckling and reduce peak force.

Specific Energy Absorption (SEA) is an important parameter for an energy absorber and defined as the ratio of total energy absorbed in the system to the mass of the structure. The higher SEA value refers to a more lightweight absorber, which means more energy can be absorbed with a lighter structure.

$$SEA = \frac{E_A}{m} \tag{4}$$

where E_A $[kJ]$ is total absorbed energy and m $[kg]$ is mass of the absorber.

Dynamic amplification factor is simply defined as the ratio of the energy absorbed under dynamic loading to the energy absorbed under quasi-static loading as given in equation 5.

$$DAF = \frac{E_{dynamic}}{E_{quasi-static}} \tag{5}$$

Despite being an uncommon performance parameter, it is very useful to investigate the dynamic effects such as inertia and strain rate effects. It has been used by several authors for both investigation and estimation of the dynamic effects on the energy absorbers.

3 FINITE ELEMENT MODEL

The numerical models for the simulations were created using the CAE user interface module of the FEM software Abaqus. [6] Depending on the subject of the present study, Abaqus/Explicit solver package have been used to simulate the dynamic loading of the structures. Results obtained from the simulations have been viewed and exported by using the Viewer module of the software.

3.1 Model Geometry

A basic sketch of the absorber structure is given in Figure 1 with dimension parameters. Dimension parameters used to model the structures are, inner radius r_1, outer radius r_2, edge ring width b, edge ring height d, thickness t, cone angle β and deformation length h. Values used for all parameters are given in Table 1.

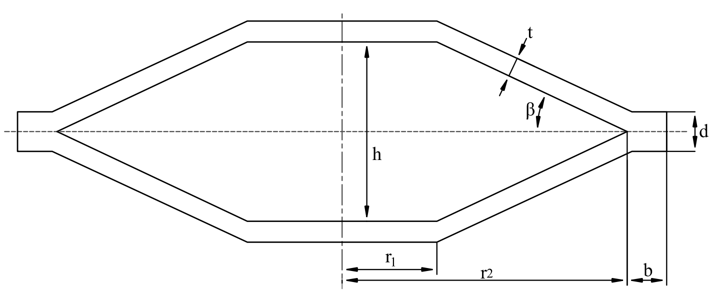
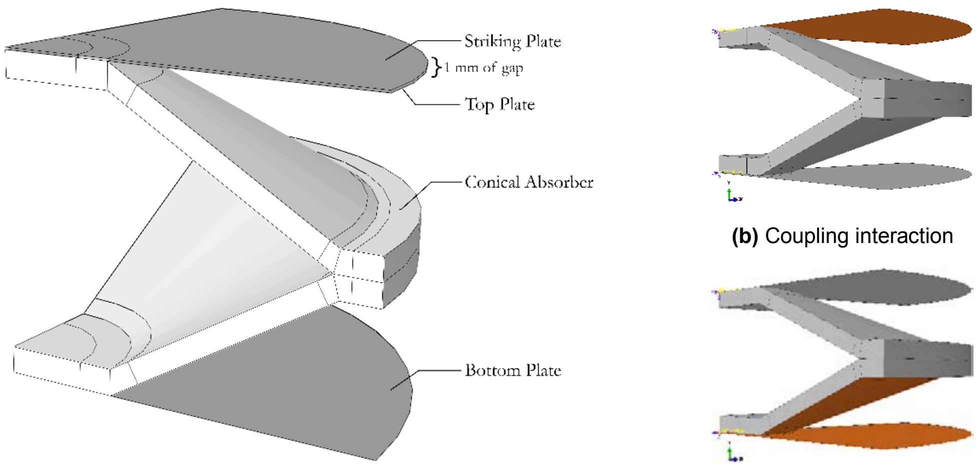


Fig. 1 Geometry and dimension parameters of the absorber structure.

Structures were modelled 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. The third plate (striker plate) is used to simulate the striking mass crushing to the conical absorber. A gap of $1\ mm$ between the striker plate and the top plate of the absorber was modelled to examine the effect of the first contact more conveniently. General assembly of the numerical model is given in Fig. 2 in detail.

Tab. 1 Dimension values of the absorber structures used in simulations.

β	h	t	b	d	r_1	r_2
$[deg]$	$[mm]$	$[mm]$	$[mm]$	$[mm]$	$[mm]$	$[mm]$
30	115.5	10	20	20	50	150



(b) Coupling interaction

(a) Assembly of the absorber and the rigid plates

(c) Pre-defined contact pair

Fig. 2 Model assembly and the interactions between the parts of the model

3.2 Material Model

The material used for the simulations were structural mild steel denominated as $S235JR$. In numerical analysis, an elastoplastic hardening module was implemented to the material behaviour. Mechanical properties of $S235JR$ are used as; Young's modulus of $200\ GPa$, Poisson's ratio of 0.29 mass density of $7980\ kg/m^3$, yield strength of $294.6\ MPa$ and ultimate tensile strength of $381\ MPa$.

The plastic flow of some materials is sensitive to loading speed, which is known as material strain rate sensitivity. The Johnson-Cook plasticity model [7] is a phenomenological model used to describe the plastic and strain-rate dependent hardening of materials. The model introduces three key material responses, which are the strain hardening, strain-rate effects and the thermal softening. These effects are combined in the Johnson-Cook constitutive model in a multiplicative manner.

$$\bar{\sigma} = \left[A + B\varepsilon_{pl}^{n}\right]\left[1 + C\ ln\left(\frac{\dot{\varepsilon}_{pl}}{\dot{\varepsilon}_0}\right)\right]\left(1 - \hat{\theta}^{m}\right) \tag{7}$$

where, $\bar{\sigma}$ is the yield stress at nonzero strain rate [Pa], $\dot{\varepsilon}_{pl}$ is the effective plastic strain, $\dot{\varepsilon}_0$ is the reference strain rate, A is the initial yield stress at $\dot{\varepsilon}_0$ [Pa], B is the strain hardening coefficient [Pa], C is the strain-rate hardening coefficient, n is the strain hardening exponent, m is the temperature exponent and $\hat{\theta}$ is the homologous temperature. In this study, the model is assumed to be simulated in room temperature, thus the effect of temperature on thermal softening of the yield stress is neglected.

Previous studies have indicated that $S235$ steel displays a significant positive strain rate effect on the yield stress of the material. Verleysen et. al. [8] have investigated the influence of the strain rate on the forming properties of three commercial steel grades. The static tensile test results of the present study and the results from the article by Verleysen et. al. [8] are found to be essentially identical for the $S235JR$ steel. Due to the technical impossibilities and the lack of equipment for dynamic tensile testing, the Johnson-Cook model of the $S235JR$ steel with strain rate properties are adapted to the numerical models of the present study. Consequently, the Johnson-Cook plasticity model parameters used in this study are given in Table 2.

Tab. 2 Johnson-Cook plasticity parameters of $S235JR$. [8]

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

3.3 Loading and Boundary Conditions

In quasi-static numerical simulations, the load is applied to the rigid striking plate as a predefined velocity along the longitudinal axis. Quasi-static velocity is selected to be $0.01\ m/s$. In dynamic simulations, the load is applied as kinetic energy. The kinetic energy is generated by defining a velocity and a mass to the striking plate. Used mass quantities are calculated to obtain $100\ kJ$ of initial kinetic energy for each model.

Interactions between parts were defined using self-contact and surface to surface contact algorithms. To simulate a crush box, the conical energy absorber was coupled to two rigid plates from the top and bottom surfaces using a kinematic coupling definition. 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 movements were restrained. Structures were designed as quarter models to reduce the time cost of the simulations.

4 RESULTS AND DISCUSSION

One of the most important performance parameter is the crushing force during the deformation of the absorber, which may change under different conditions. In this case, the effect of loading on the energy absorbing performance of the conical structure is investigated. The force-displacement responses are plotted in Figure 3.

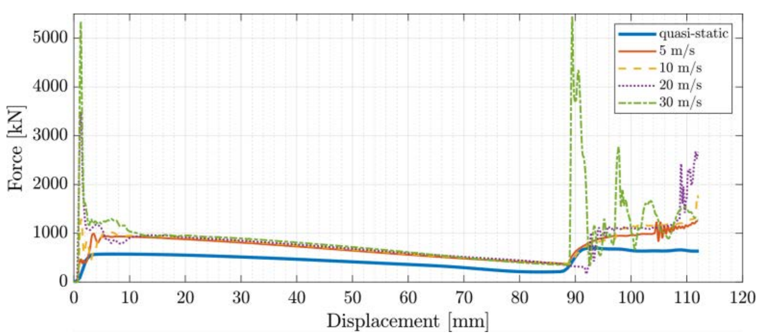


Fig. 3 Comparison of quasi-static and dynamic Force-Displacement response of the model.

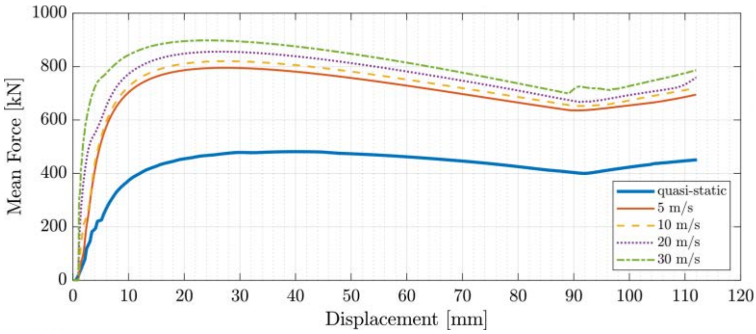


Fig. 4 Comparison of mean Force-Displacement response of the quasi-static and dynamic models.

It is observed that there is a significant difference between the quasi-static and dynamic cases in terms of mean crushing force response. This is caused by the strain-rate dependent material model, which changes the structures response under different initial impact velocity conditions. The force-displacement responses indicate that up to a certain value of impact velocity, the response of the structure has a similar behaviour with the quasi-static case. In other words, the inertia effects on the impact response of the structure become apparent for the velocity values more than $10\ m/s$.

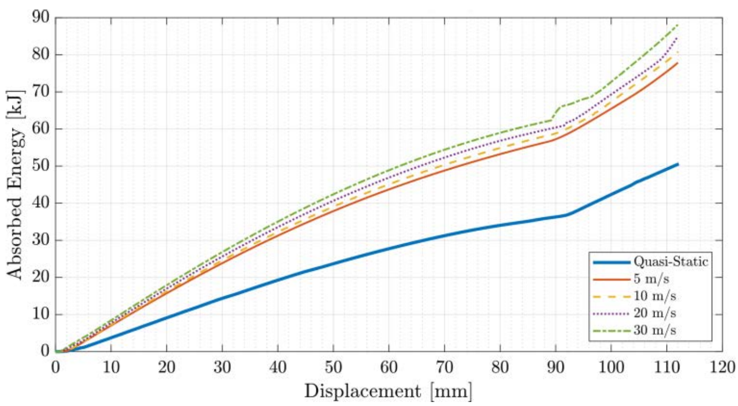
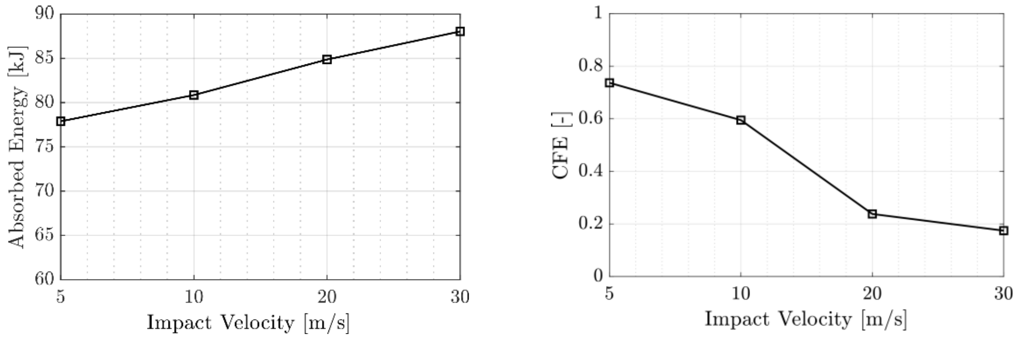


Fig. 5 Comparison of energy absorption for quasi-static and dynamic models.

As the energy absorbing capacity of the structures are strictly related to the crushing force response, the absorbed energy curves conform with the force-displacement curves. Absorbed energy response of the models are given in Figure 5 as a function of displacement. The energy absorption capacity of the structures increases with increasing impact velocity. For the impact velocity values of $20\ m/s$ and $30\ m/s$, both crushing force and the absorbed energy plots have a slightly different behaviour.

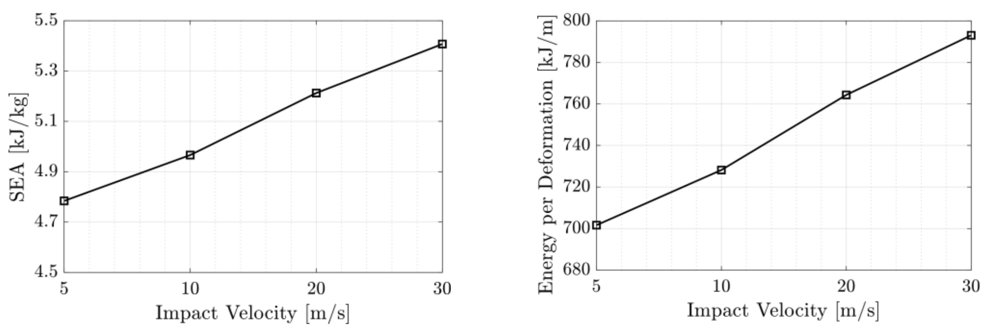


(a) Absorbed energy **(b)** Crash force efficiency

Fig. 6 Effect of the impact velocity on the absorbed energy and the CFE values of dynamic simulations.

The increase of the first peak crushing force also significantly change the crash force efficiency values of the structures. CFE values are plotted in Figure 6b as a function of impact velocity for models with different absorber thickness and base conical angle. The CFE values significantly decrease as the impact velocity increases.

The change of the SEA values are shown in Figure 7a as a function of impact velocity. SEA values also increase as the impact velocity increases. This is an expected behaviour because this parameter is directly related to the mass of the structures and the absorbed energy values.



(a) Specific energy absorption **(b)** Absorbed energy per unit deformation

Fig. 7 Effect of the impact velocity on the SEA and the absorbed energy per unit deformation values.

The models with same conical angles have the same constant maximum deformation lengths due to the geometry and all models are completely deformed. Therefore, the absorbed energy values per unit deformation have an increasing behaviour as the absorbed energy values increase with increasing impact velocity as seen in Figure 7b.

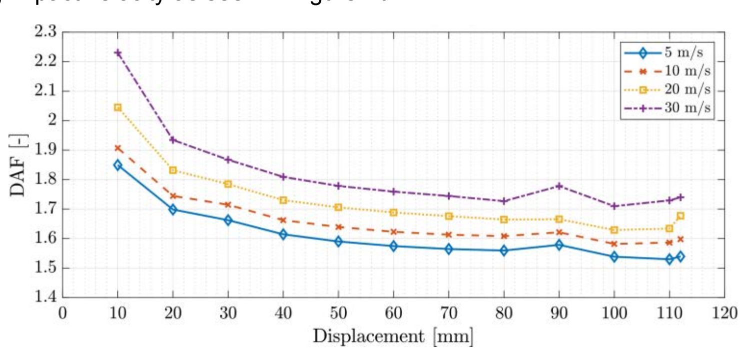


Fig. 8 Comparison of dynamic amplification factor of the dynamic models.

The same situation can also be observed in the dynamic amplification factor values. As seen in the Figure 8, DAF values have decreasing trend with increasing deformation which may be caused by the decremental effect of strain-rate and inertia effects as the crushing of the absorber continues. However, DAF values have a notable difference as the impact velocity increases. DAF values at the displacement values of $10mm$ and $90mm$, at which contact between surfaces occur, are of great importance. It is seen that the increase on the DAF values of the models with impact velocities of $20\ m/s$ and $30\ m/s$ are greater than the models with lower initial velocity. This situation indicates that some inertia effects may be present at the impact velocity values higher than $10\ m/s$.

4.1 Presence of the Inertia Effects

In structural dynamic problems, dynamic loading is modelled using the initial kinetic energy of the system. The increased kinetic energy by changing the impact mass has no influence on the crushing force and absorbed energy values of the models. [9] However, the increase in the impact velocity affects the general response of the structure even if the kinetic energy is kept constant. The increase of the absorbed energy with increasing impact velocity may be associated with the inertia effects including plastic stress wave propagation and nonlinear response. A similar effect has been observed for axial impact loading of square tubes with a strain rate insensitive material model. [10]

In the present study, the strain-rate dependency of the used material is taken into consideration. Thus, the increase of the absorbed energy with increasing impact velocity may be associated with the velocity sensitive material model. For this reason, the strain-rate sensitivity properties of the current material model are removed, and the simulations were repeated.

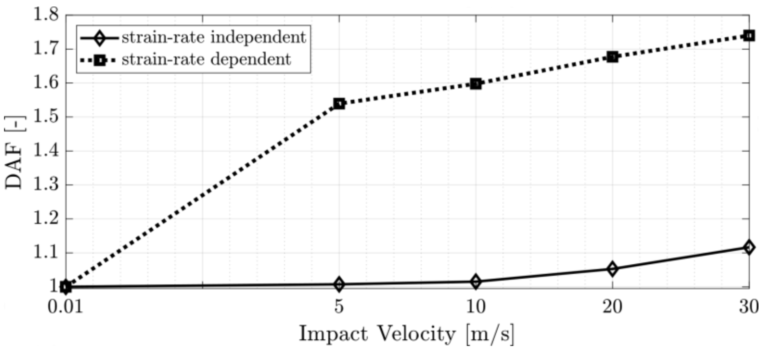
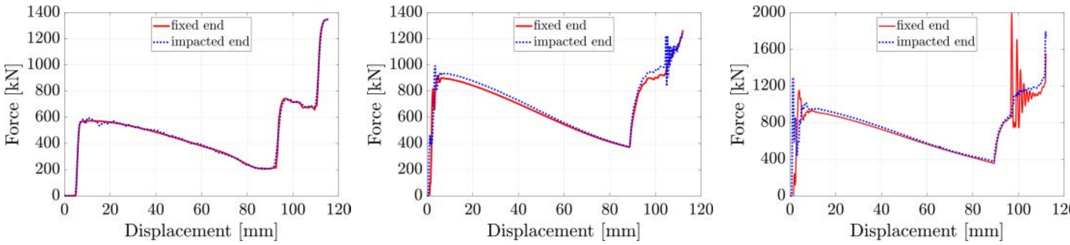
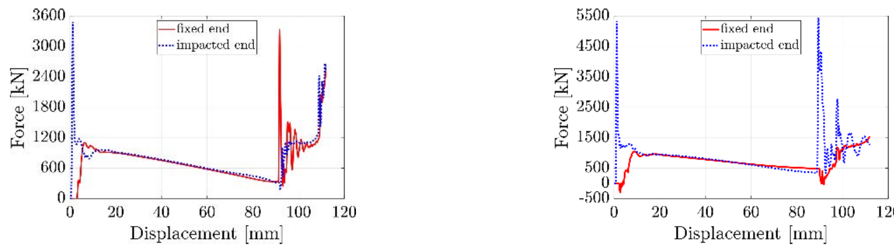


Fig. 9 Effect of strain rate dependency of the material on the dynamic amplification factor of the models.

Figure 9 shows the dynamic amplification factor values of the models with and without strain-rate properties. It is clearly seen that the dynamic absorbed energy values increase with increasing velocity even if the strain-rate dependency of the material is neglected. Thus, the increase may also be associated with the inertia effects including plastic stress wave propagation and nonlinear response. The presence of the axial inertia effects can be identified by comparing the force response of at the impacted end and the fixed end of the structure. This approach has been used by several authors to investigate the inertia effects on various structures. [11]



(a) $quasi-static$ (b) $V = 5\ m/s$ (c) $V = 10\ m/s$



(d) $V = 20\ m/s$ (e) $V = 30\ m/s$

Fig. 10 Force-displacement response of the models for different impact velocities.

As seen in Figure 10, the load response, at both ends of the structures have similar values for the models with impact velocity values up to $10\ m/s$. For the models with higher impact velocity, the force-displacement responses significantly change. Moreover, the initial peak load seems to be much higher at the impacted end of the structures. Also at higher initial velocity values, negative forces were observed during first impact due to the oscillations of the top surface of the absorber.

As a result, the dynamic response of the conical structure under axial loading is affected by the impact velocity at relatively higher velocities $(\geq 10m/s)$. Thus, the effect of the inertia forces emerge with increasing velocity, even if the strain-rate dependency of the material is neglected.

5 CONCLUSION

A numerical investigation of the conical energy absorbing structure was examined in this study. To investigate the presence of the inertia effects during loading, both strain-rate dependent and independent material models were implemented into the simulations and compared. In the view of obtained information from the current study, some of the significant conclusions on the design of a low base conical angle structure are summarized below.

According to the results of this study, it can be said that increasing the impact velocity of the loading increases the absorbed energy. As the absorbed energy increases, the crush force also increases. The crash force efficiency values have a decreasing trend as the impact velocity increases due to the increasing initial peak crushing force response of the structures. The presence of the axial inertia effects was identified by comparing the force response of at the impacted end and the fixed end of the structure. The initial peak load seems to be much higher at the impacted end of the structures. The dynamic response of the conical structure under axial loading is affected by the impact velocity at relatively higher velocities $(\geq 10m/s)$. Thus, the effect of the inertia forces emerge with increasing velocity, even if the strain-rate dependency of the material is neglected.

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