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Hexagonal Hollow Tube Based Energy Absorbing Crash Buffers for Roadside Fixed Objects

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Abstract. The purpose of this study was to investigate the deformation of the energy absorbing hexagonal hollow tubes in a lateral compression. The aim is to design cost effective and high energy-absorbing buffer systems, which are capable of controlling out-of-control vehicles in high-speed zones. A nonlinear quasi-static finite element analysis was applied to determine the deformation and energy absorption capacity. The main parameters in the design were diameter and wall thickness of the tubes. Experimental test simulating the lateral compressive loading on a single tube was performed. Results show that as the diameter and the thickness increase, the deformation strength increases. Hexagonal tube with diameter of 219 mm and thickness of 4 mm is shown to have the highest energy absorption capability. Compared to existing cylindrical and octagonal shapes, the hexagonal tubes show the highest energy absorption capacity. Hexagonal tubes therefore can be regarded as a potential candidate for buffer designs in high speed zones. In addition, they would be compact, cost effective and facilitate ease of installation.
Keywords: Hexagonal hollow tubes, energy absorbing buffer, finite element simulation, deformation strength.

1. Introduction

Enormous amount of people around the world are involved in road accidents every year. One of the unforgiving types of crashes is vehicle's impacts with roadside fixed objects, e.g. utility poles or trees. More importantly, such collisions result in fatal injuries to occupants, in addition to the cost of repairing damaged objects or structures involved [1]. For instance, between 2000 and 2011 alone in South Australia, 36% of fatal road crashes are the result of vehicle's impact with fixed objects [2]. While improved vehicle, road design and safety have decreased the fatality rate to some extent, such events have still been remained as a serious concern across the world.

In order to minimize the risk of collisions with fixed objects, passive safety measures such as roadside barriers are employed. Commercial buffers, often known as 'impact attenuators' such as QuadGuard [3] and Absorb360 [4] are used as the breakaway barriers and they are often found to be large in size and highly expensive. Cylindrical hollow tube based metallic energy absorbing buffers are recently applied for roadside fixed objects [5]. They seem to have been quite successful; however, they suffer from issues such as assembly of tubes in buffers is not strong, causing tubes dislodged under the high impact collisions. The tube's energy absorption capacity is even low due to its geometric shape and hence they may not suitable to be employed in high speed roadways. In other words, the tube/s or buffers will be deformed or broken too quickly, leaving the vehicles/occupants to be impacted seriously, instead of taking the impacts up by buffers, during collisions. Larger tubes may be considered to solve the issue. However, they incur further cost and large space for installation. Thus, a new design of energy absorbing buffer is sought, which will have high energy absorption capability, be compact and cost effective. The current paper aims to investigate the deformation and energy absorption ability of a new hollow hexagonal tube based crash buffers for roadside fixed objects. Using FE simulation and experiment, a parametric study is performed to evaluate the effect of tube's geometric parameters, e.g. diameter and thickness, on the deformation. The benefit of hexagonal tube over existing tubes (e.g. cylindrical and octagonal) and its potential use for buffer designs are discussed and addressed.

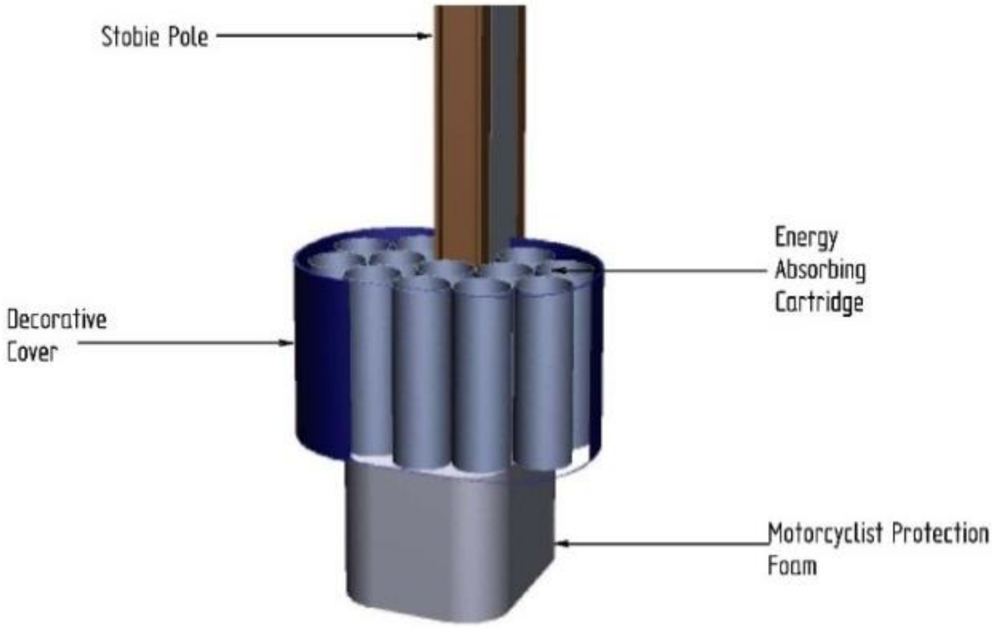

Figure 1. Existing energy absorbing buffer system

2. Issues with current buffer designs

Hollow tube based impact attenuators are widely used to prevent damages and injuries in many applications such as automotive, rail. The kinetic energy of the out-of-control vehicles are absorbed through the progressive deformation of the tubes, hence minimizing impacts on vehicles and occupants. Such deformable bodies are generally installed within the vehicle structure, which often don't consider impacts with roadside fixed objects. Automotive Safety Engineering (ASE) Pty Ltd first introduced cylindrical hollow tube based crash buffers which are used around the fixed objects such as Stobie poles to protect the pole and more importantly, vehicle occupants in the event of impacts with fixed objects. Such design and technology have been tested successfully and preliminary well received by the state governments for its use in roadways [6].

Figure 1 shows an example of cylindrical tube based crash buffer installed around the pole. As can been seen in figure 1, due to their nearly round shape, the buffers can take impacts at both frontal and sideways. The problem with the current cylindrical tube design is however that it is quite difficult to assemble tubes together due to its round faces. Under the impact, the tubes are often displaced and/or dislodged from the original locations, and hence, the buffer loses its deformation or energy absorption capacity. Because of its geometry, the deformation rate of the cylindrical tube is relatively high, making it too soft and flexible. As a result, the tubes cannot withstand large impact, i.e. it deforms and fails too quickly at even a small impact force. To tackle this, often large diameter and thick tubes are needed to be used, causing an increase of cost and installation space. In place of cylindrical geometry, octagonal shaped tubes are another option often considered as an energy absorbing structure [7]. It has flat faces which can be used to assemble with nearby tubes to form a crash buffer. Recent analysis showed that they may not be a complete solution as they either behave like a cylindrical tube or often pose fabrication complexity because of their inherent structure with having more geometric transitions. Therefore, it is important to seek for a new geometric shape which can be strong, flexible/deformable, cost effective and capable of absorbing large impact energy.

3. Materials and method

3.1. Proposed hexagonal tube.

This study proposes a hollow hexagonal tube as energy absorbing structure. The new shape is a modification of octagonal tube previously designed and studied by the same authors. The new hexagonal shape has six flat faces for easy and secured assembly of tubes together. Because it has a more rigid structure the deformation and energy absorbing capacity would be expected to be large, as opposed to cylindrical and octagonal tubes. It is a simple shape and requires less processing steps, thus reducing associated costs. Figure 2 shows an example of proposed hexagonal tube and its geometry (outer diameter = 195 mm and wall thickness = 1.5 mm). The tubes possess vertical and horizontal slots to increase the flexibility to deform. Horizontal slots also allow fastening tubes together by bolt-nut fasteners. In order to find an optimum geometry which will offer the best deformation ability, we have done a parametric study of the proposed shape by varying its outer diameter (of 165, 195 and 219 mm) and wall thickness (of 1.5, 2, 2.5, 3 and 4 mm) while the length or height (of 510 mm) is kept constant. Geometry of tubes are grouped by '*Tube A'* (diameter = 165 mm), '*Tube B*' (diameter = 195 mm) and '*Tube C*' (diameter = 219 mm) according to the size order. The values are chosen based on their availability at the local suppliers.

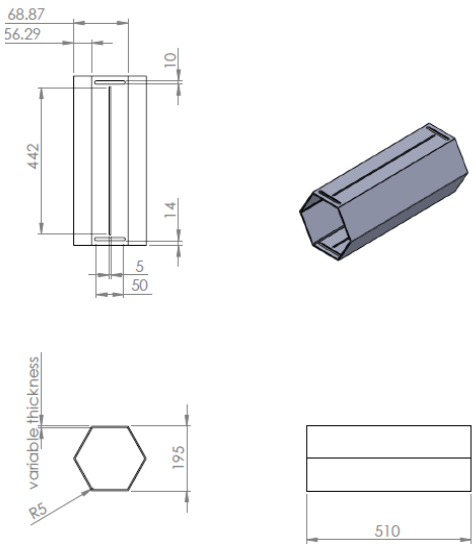

Figure 2. Definition of hexagonal tube

3.2. Simulation.

A nonlinear quasi-static simulation using finite element (FE) method was conducted in order to gain a greater understanding of how the individual tubes. We performed FE analysis on single tubes with geometric parameters mentioned in the previous section. The simulation setup was designed in such a way that it could be replicated by a real experiment for the purpose of comparison. As can be seen in Fig. 3, the FE model consists of a tube placed between a top and a bottom plate, where, the bottom plate was fixed while the top plate was allowed to move only in the vertical direction. The top plate was assigned a vertical displacement that would force the tube to be compressed laterally. A reaction force probe was applied to the bottom surface of the top plate to estimate the force against the displacement.

Finite element code built in Solidworks software tool was applied to solve the contact problem. 8-node solid elements were used in the FE model. The material of the tubes was mild steel. The multi-linear isotropic hardening stress-strain data of the material was obtained from experimental study [8]. Frictional contact between the tube and the plates was studied and showed a negligible effect. Hence, the contact was assigned as frictionless throughout FE study. This was found to reduce computational effort in simulation.

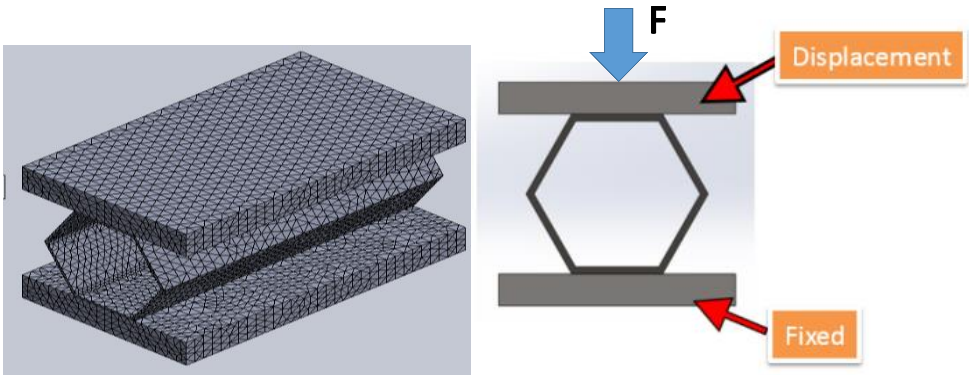

Figure 3. FE model of hexagonal tube

3.3. Experiment.

Experiments involving lateral compression were conducted in order to investigate the deformation of the individual tubes. The aim was to validate the quasi-static FE simulation. The tests involved the deformation of a tube located between two plates at top and bottom. The bottom plate was fixed and the top plate (push plate) was attached to a 20-tone hydraulic cylinder so that the tube was deformed in a controlled way that would enable the reaction force acting on the top plate to be recorded. Figure 4 shows the experimental setup. At a certain rate of push plate movement, reaction load and displacement were measured by a hydraulic pressure gauge and a linear encoder, respectively. In order to verify the efficacy of FE modelling, as a representative, *Tube C* (d_o = 219 mm) with t = 2mm was used as the specimen. The tube was deformed up to 213 mm until it becomes approximately flattened (75% of its total deformation).

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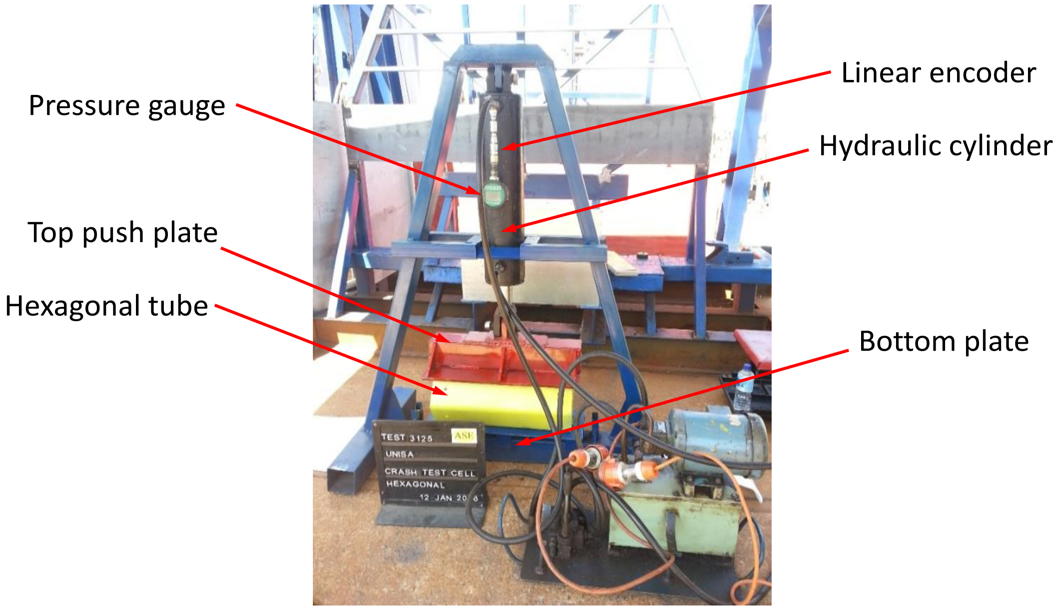

Figure 4. Experiment setup

4. Results and discussion

4.1. Comparison between simulation and experiment.

Figure 5 shows a comparison of tube deformation pattern of *Tube C* obtained from experiment and simulation. Both experiment and simulation display almost the same trend of the deformation until the tube reaches its maximum deformation level. The tube undergoes both elastic and plastic deformations. Figure 6 illustrates a comparison of load-displacement data obtained from experiment and simulation for *Tube C*. Results show that both simulation and experimental plots follow approximately the same trend of deformation as the loading increases. At displacement up to about 45 mm, the tube undergoes elastic deformation till the yield state and at this zone, simulation result matches with experiment. After that, the plastic deformation is more dominant till 200 mm. Experiment shows about 20% lower strength in the plastic zone than simulation. This would be due to the slight difference in material properties used in simulation and experiments. It is to be noted that mild steel tube specimen used in experiments might have pores, cracks and internal stress concentration, thus lowering the strength of the material. Overall, the results for a single tube justify the accuracy of the current FE model, thus indicating that the model would be able to reasonably estimate the accurate deformation of other tubes and potential buffer system consisting of a series of individual tubes.

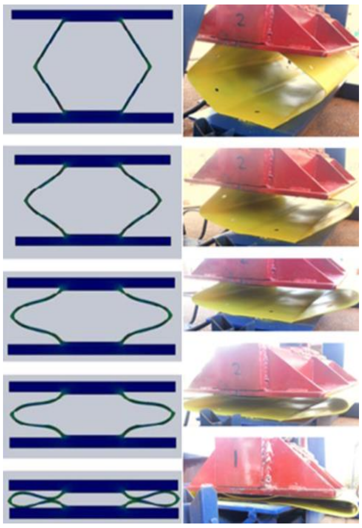

Figure 5. Comparison of hexagonal tube deformation between simulation and experiment

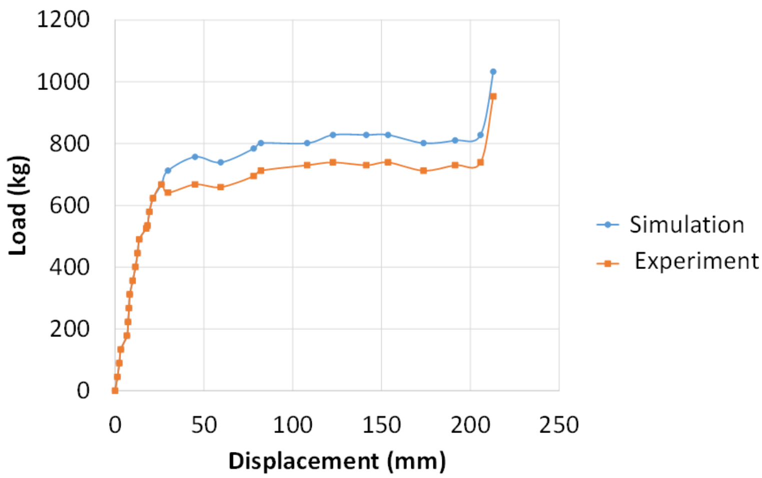

Figure 6. Comparison of load-displacement of *Tube C* between simulation and experiment

4.2. Effect of hexagonal tube geometry.

Using the same FE simulation procedure, the effect of various geometry of the hexagonal tube on the deformation profile was investigated, in which, the diameter and the thickness were varied. Figures 7a, b and c shows load-displacement with respect to different thicknesses (t) for *Tube A* (d_o = 165 mm), *Tube B* (d_o = 195 mm) and *Tube C* (d_o = 219 mm), respectively. It can be seen that for a given tube diameter, the tube shows higher deformation strength with the increase of thickness. This is quite obvious that higher thickness means more rigidness of the tube, which requires larger force to deform. Also, as the tube diameter increases, the amount of force requires deforming the tube increases. This will eventually increase the energy absorption capacity of the tube. It can be noticed from figure 7 that *Tube C* shows the highest deformation strength among all. Further, it appears that *Tube C* with thickness of 4 mm can absorb the highest energy and can be chosen as a potential candidate for buffer design. In particular, as is seen from figure 7c, when thickness is increased from 3mm to 4 mm, the deformation strength of *Tube C* increases significantly, i.e. the large force is needed for a small amount of deformation. It is often recommended that larger diameters may be used to take up high impact loading in the event of vehicles hitting objects at high speeds, e.g. 80-100 km/h. However, it must be noted that other thicknesses may be considered and the final decision in selecting an appropriate geometry would be based on the analysis of feasibility in terms of the number of tubes and the associated costs incurred to the buffer designs. In general, for a given buffer size, tubes with less energy absorbing capability will increase the number of tubes required for the buffer, which will definitely increase fabrication and handling costs.

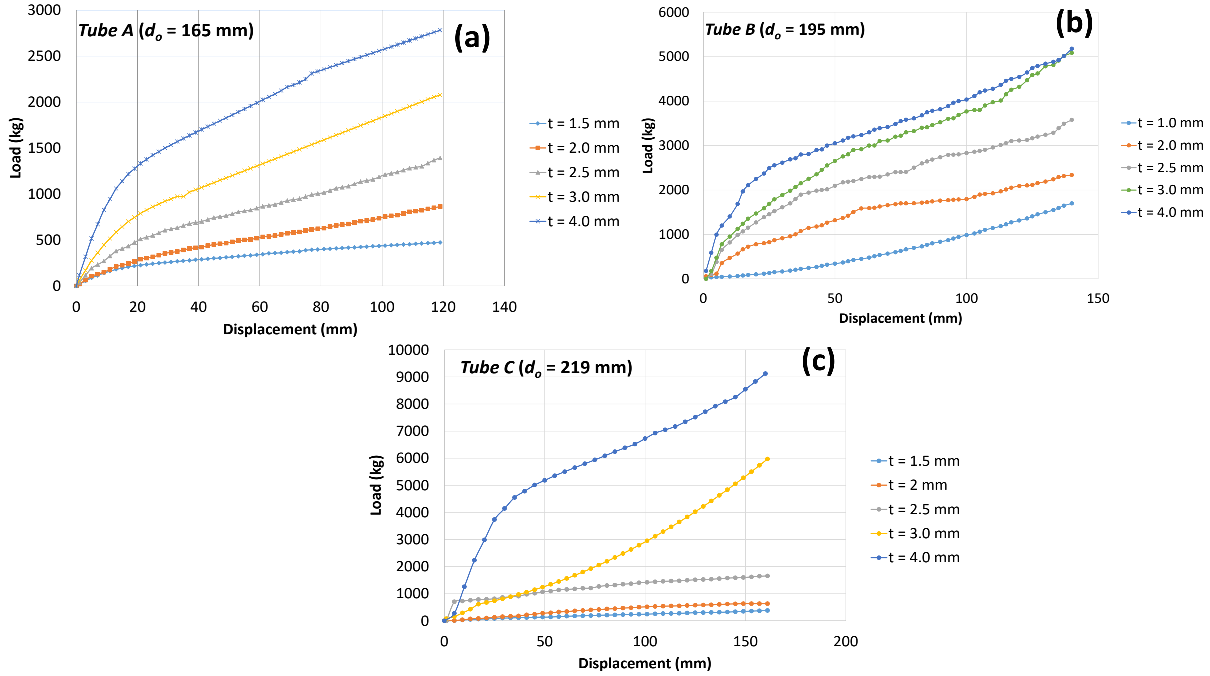

Figure 7. Load-displacement plot with respect to thickness for (a) *Tube A,* (b) *Tube B* and (c) *Tube C*

4.3. Comparison between hexagonal and existing tube designs.

In order to validate the performance of hexagonal shape, we further performed a comparison of the deformation of hexagonal *Tube C* (d_o = 219 mm and t = 4 mm) with existing tubes –cylindrical and octagonal. In this regard, following the same procedure, FE simulation was performed to estimate load-displacement results of tubes. During simulation, we have considered tubes with the same diameter and thickness for the sake of a balanced performance comparison. Energy absorption capacity is another indicator to measure the deformation ability of the tubes. We have estimated energy absorbed by the tubes, where, the energy is estimated as the area under the load-displacement curve. Figure 8 shows comparison of energy absorption capability between hexagonal, octagonal and cylindrical tubes. Hexagonal tube exhibits the highest energy absorption capacity among all. Octagonal shape shows the second highest deformation ability. The underlying reasons for difference in deformation capacity would be simply the inherent geometric variation due to their shapes. The results clearly show that hexagonal tubes can be used for buffer designs for high speed impacts. As can further be seen from figure 8, the hexagonal tube (*Tube C*, d_o= 219 mm, t =4 mm) has the energy absorption capacity of about 23.5 kJ at its 75% deformation. For instance, a vehicle with mass of 2000 kg travelling at 80 km/h possesses the kinetic energy of 94 kJ. It is expected that this energy will be equally absorbed by the buffer and the vehicle structure. Therefore, the buffer to be designed will absorb energy of 247 kJ. Thus, the number of tubes required for the buffer to absorb energy can be estimated by dividing the total energy by the energy absorption capacity of an individual tube (= 247 kJ/23.5 kJ), which is about 11 tubes. Accordingly, it can be easily predicted that buffers made of octagonal and cylindrical tubes will require 14 and 18 tubes, respectively. The results imply that hexagonal tube based buffers will be much more compact and cost-effective. However, to make a comprehensive conclusion of this, a detailed analysis in terms of arrangement of tubes within the buffer, fabrication, handling and maintenance cost of the tubes and buffers must be conducted. This has been left for our future work.

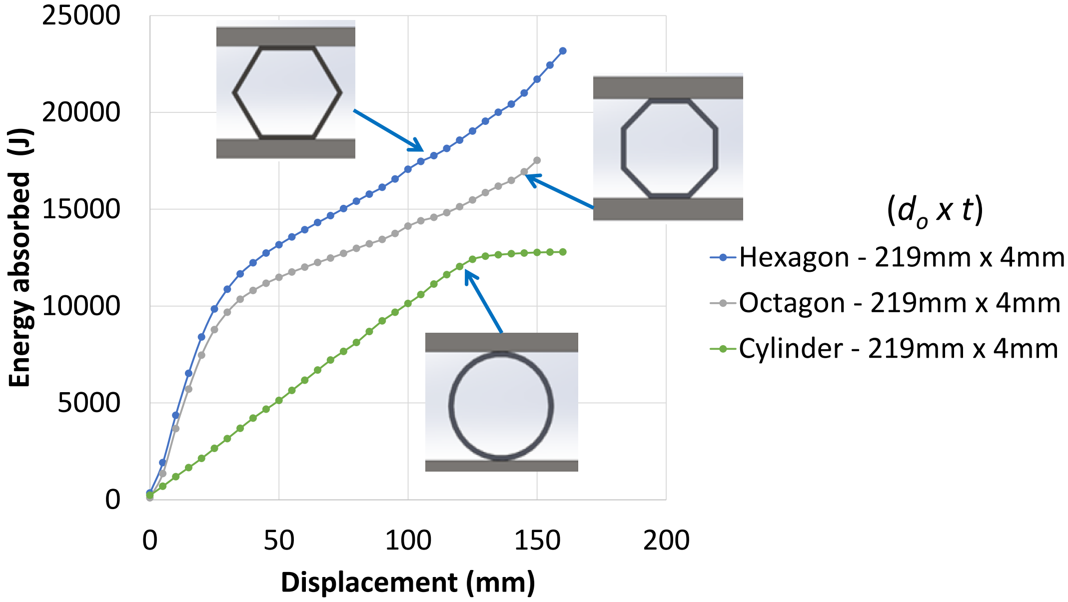

Figure 8. Comparison of energy absorption capacity among hexagonal, octagonal and cylindrical tubes

5. Conclusion

This paper studied new hexagonal hollow tube based energy absorbing crash buffers for roadside fixed objects. A FE simulation was performed to investigate the effect of different geometry on deformation and energy absorbing capacity of individual tubes. Experiments were conducted to verify FE simulation. The key conclusions drawn out of the study are as follows.

- FE simulation matched with experimental results, indicating that the FE model proposed is accurate enough to estimate deformation of the tubes.
- Parametric study showed that larger diameter and larger thickness increases the deformation strength of the tubes.
- For a given diameter and thickness, the hexagonal tube was found to show the highest energy absorption capacity and hence can be regarded as potential candidate for buffer designs.

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