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Design and analysis of energy absorbing crash buffers for fixed objects in high speed roadways

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Abstract: Road fatalities as a result of collisions of vehicles with fixed objects on roadways are of paramount concerns across the world. This paper aims to design cost effective and high energy absorbing buffer systems for high speed roadways. The proposed buffer design is based on the assembly of a series of steel cylindrical hollow tubes (cells). The idea is that during collisions, the kinetic energy of the errant vehicles will be absorbed by the progressive deformation of the cells, allowing a comfortable ride-down deceleration of the vehicle's occupants, and hence minimizing fatality and damage to the vehicle.

As the cell was the fundamental unit of the buffer design, three cells with different geometry were studied to understand the underlying deformation of the cells. Nonlinear quasi-static tests using three dimensional (3D) finite element (FE) and experimental methods were performed to evaluate the deformation and the energy absorption capacity of the cells. Based on experimental results of single cells, potential buffer systems were designed for 80 km/h speed roadways. Results indicated that buffers with larger diameter cells are favourable to be used in high speed zone. They are found to reduce the overall size of buffers, hence minimizing cost associated with materials and fabrication. Depending on the nature and available space of the roadways, the designed buffers can potentially be adopted to reduce the vehicle crashes with the fixed objects.

Keywords: Collisions with fixed objects, energy absorbing crash buffers, cylindrical hollow cells, finite element method

1 Introduction

It has been reported that road crashes in Australia costs about $15 billion annually, representing approximately 1.4% of Australia's gross national product [1]. Among them, a large amount of road fatalities occurs as a result of collisions with fixed objects on roadways. These types of collisions, often involving trees and poles, are particularly severe due to the narrow shape and rigidness of such objects. This has been an ongoing problem for a number of years. For instance, about 36% of the fatal road crashes in South Australia from 2000 to 2011 involved collisions with the fixed objects [2].

While improved vehicle and road design has decreased the overall fatality rate, a similar percentage of people are still being killed or injured in collisions with fixed objects every year [2, 3]. The costs to the community both economically and through personal loss are significant [4]. In order to minimize the consequences of such crashes, a 'buffer system', also commonly known as an 'impact attenuator' or 'crash cushion', is generally used. A buffer system is a form of road safety hardware designed to absorb the kinetic energy of an errant vehicle [5]. The main objective is to protect vehicle occupants from fixed roadside objects that cannot be removed, relocated or made breakaway [6]. By absorbing the energy of an out of control vehicle in a controlled manner, a buffer system can greatly reduce the severity of a crash from which would take place if the vehicle hits the unshielded object.

While there exists a number of solutions to the threat caused by poles/trees and other roadside hazards, they are not always suitable for high speed roadways or financially viable for the particular situation. For instances, to be noted are Universal TAU-II crash cushion designed by Lindsay Corp. [8], QuadGuard by Baylon Group [9] and Absorb 350 Crash Cushion by RMS Solutions [10]. While each of these impact attenuators is effective energy absorbing devices for protection from fixed objects, they are continuous, indiscrete and non-flexible, making them only suitable for open roads. They may not be applied to the closed roads, in which, fixed objects such as trees, poles are commonly found. The size of buffer systems is significantly large and increases with increase of speed zone where they will be installed. In addition, due to their complex design, build, and maintenance, the cost of these devices is relatively high. A more practical, flexible and cheaper alternative would mean the number of hazards along the road network could be greatly reduced, creating a more forgiving roadside environment. The aim of the current study is to design and analyse of cost effective and high energy absorbing buffers, which are capable of absorbing the impact energy of an out of control vehicle in a high speed zone.

2 Rationale for buffer design for high speed zones

Design of a buffer system involves consideration of a number of important parameters. Generally, at the impact of collision, the energy is absorbed through the elasto-plastic deformation of each individual cell within the buffer system. Given that the total amount of impact energy to be absorbed at a certain stopping distance is known, it is possible to determine the size of the buffer system by modifying important geometric parameters of the individual cells.

After the impact, the stopping distance of the vehicle is crucial to determine how quickly or smoothly the vehicle comes to rest position without posing any threat to the occupants. The larger the stopping distance, the more smooth and gradual absorption of energy and the less impact onto the vehicle's occupants. One way to allow for greater stopping distance is to increase the size of the buffer. The significance of this can be clearly observed by Eq. (1), which shows the average deceleration (a) is inversely proportional to the stoping distance (h).

$$a = \frac{v^2}{2h} \tag{1}$$

The increase in length can be achieved by the addition of more cells in the buffer. However, the larger length means more cells need to be added, which may increase costs associated with fabrication, setup, installation and maintenance. An alternative to adding more cells to increase the length is increasing the size of the individual cells, i.e. increasing the diameter of the cells. Increasing the size of the individual buffer cells could potentially lead to several significant benefits. These include greater ease of assembly of the cells and allow much greater accessibility. This is particularly true for the buffers with higher speed zones, where more cells are needed.

5 Materials and method

5.1 Modified cell design

This paper focuses on design of modified cell geometry over the previous buffer cell designed by Zivkovic [11], with an aim to (1) reduce the number of cells, (2) increase energy absorption capacity and (3) reduce manufacturing and handing cost.

The previous cell design contains 114.3mm outside diameter with a wall thickness of 4.5mm. If four of these cells are attached in series to form a buffer, it will give a width of 457.2mm. Figure 1 shows the geometric definition of the cell including slots around it. It would be preferable to replace these four cells with either two or three cells, which would result in the overall width of the buffer remaining relatively similar. Note that width of a buffer is defined as the product of the number of cells and outer diameter of a cell.

With this aim, three different cell geometries with larger outer diameters were considered, as shown in Table 1. Outer diameter of Cells B and C is the same except for thickness. For instance, three-cell assembly made of Cell A design would give a width of 495.3mm, while two-cell assembly made of Cell B or C design would give a width of 438.2mm. The width of both assemblies is close to that of the previous design (which is foul-cell assembly) and would be considered acceptable size.

It must be noted that although it is likely that other geometry of cell would be preferred for the buffer, only geometries available from the local supplier were considered, for the sake of the justification of the proposed design modification. The performance of these three geometries was tested using both finite element simulations and experiments to find which cell geometry provides a cost effective and high energy absorbing buffer system for high speed zones.

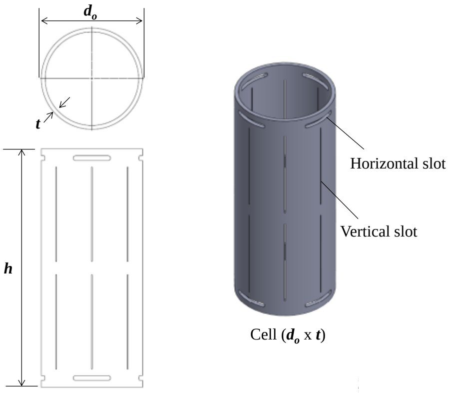


Figure 1: Geometric definition of a cell

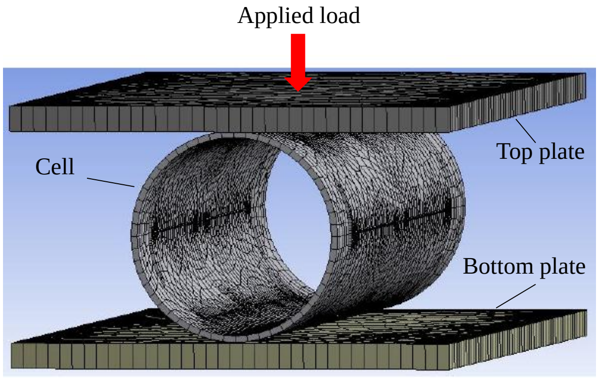


Figure 2: FE model of the cell

Table 1: Geometric dimension of the cell studied

Cell geometry	Outer diameter, d_o (mm)	Wall thickness, t (mm)	Cell height, h (mm)
Cell A	165.1	5.0	510
Cell B	219.1	6.4	510
Cell C	219.1	8.2	510

5.2 Simulations

A nonlinear quasi-static simulation using FE technique was conducted to estimate deformation and energy absorption capacity of the cells under the given impact load. For the sake of simplicity and being computationally effective, FE analysis was initially applied on single cell geometry. Figure 2 shows the FE model of a cell.

The FE model consists of a cell placed between a top and bottom plate. 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 cell to be compressed laterally. This would replicate a push plate attached to a hydraulic cylinder during real life experimentation (see 'Experiments' section). A reaction force probe was applied to the bottom surface of the top plate to estimate the force against the displacement of the cell. ANSYS, a commercially available finite element code [17], was applied to solve the contact problem between the cell and the top and bottom plates. Eight-node solid elements were used to mesh the simulation model.

The material of the cells studied was mild steel. The data for multi-linear isotropic hardening stress strain curve for the material was obtained from experimental study [11]. Figure 3 shows the stress-strain data curve for mild steel, which is feed into the material library of the software during simulation. The effect of frictional contact between the cell and the top and bottom plates was studied. Results showed that friction had a negligible effect on the deformation pattern and magnitude of the cell. Hence, the contact was assigned as frictionless throughout simulation.

After each simulation, force and displacement data were estimated. This was used to calculate the amount of workdone and energy absorbed by the cells. The results were plotted and analysed to design potential buffer systems.

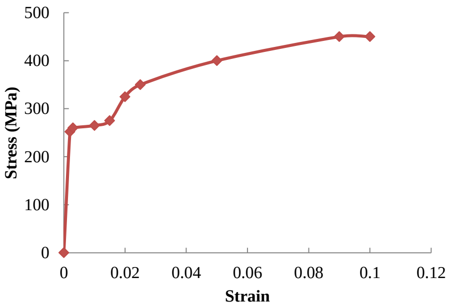


Figure 3: Nonlinear stress-strain data curve for mild steel

5.3 Experiments

Experiments involving lateral compression were conducted in order to investigate the deformation of the individual cells. The aim was to replicate as closely as possible the FE simulations or quasi-static tests. The tests involved the deformation of a cell 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 cell was deformed in a controlled way that would enable the reaction force acting on the top plate to be recorded for each of the desired displacements. Figure 4 shows the experimental setup for the cell deformation. At a certain interval of displacement, applied loads and displacements were measured by using a hydraulic pressure gauge and a linear encoder, respectively. During the tests, the deformation of the cell was allowed to 75% of its total capacity. Results of load-displacements and energy absorption were plotted and used to compare with those from FE simulations.

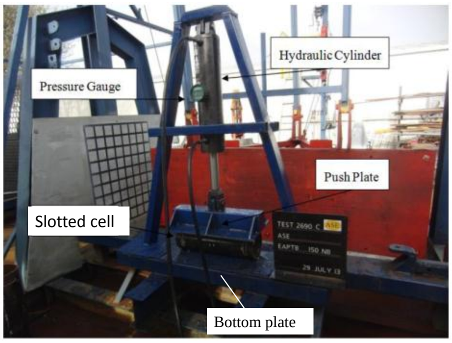


Figure 4: Experimental setup for the cell deformation

5.4 Potential buffer designs

Based on the experimental and simulation results and data obtained for individual cell geometries, potential buffers were designed. Energy absorption data for the individual cells obtained from the experiments were used to design the size of the buffer system as they were assumed to be the most reliable. The idea is that by knowing the amount of kinetic energy that a vehicle will have in any speed zones and the amount of the energy a cell can absorb, one can determine the number of cells that will be arranged in series to form the buffer system that will be able to absorb the desired amount of the energy.

It is assumed that during an impact, half of the total kinetic energy of the vehicle is absorbed by the vehicle itself. Therefore, the aim of the buffer system is to be able to absorb the rest half of total kinetic energy through the deformation of the individual cells.

Assume that a vehicle of mass, $m_{vehicle}$ travelling at a velocity of v hits a fixed object. The total kinetic energy of the vehicle can be estimated as:

$$K.E._{total} = \frac{1}{2} m_{vehicle} v^2 \tag{2}$$

Hence, the kinetic energy to be absorbed by the buffer system can be calculated as:

$$K.E._{buffer} = \frac{1}{2} K.E._{total} \tag{3}$$

Let’s assume that the buffer system comprises a series of rows of the cells attached to together. The kinetic energy is absorbed through the continuous deformation of the cells. Figure 5 shows an example arrangement of cells in a buffer design. If the energy absorption capacity of an individual cell at its 75% deformation, $K.E._{cell}$ and the number of cells in a row m, are known, the number of rows, N that will form the buffer system can be estimated as:

$$N = \frac{K.E._{buffer}}{K.E._{cell} m} \tag{4}$$

Accordingly, for the given cell geometry (i.e. outer diameter of a cell d_o), the size of the buffer system can be estimated as:

The width of the buffer, W = number of cells in a row*outer diameter of a cell = $m * d_o$ (5)

The length of the buffer, L = number of rows in a buffer * outer diameter of a cell = $N * d_o$ (6)

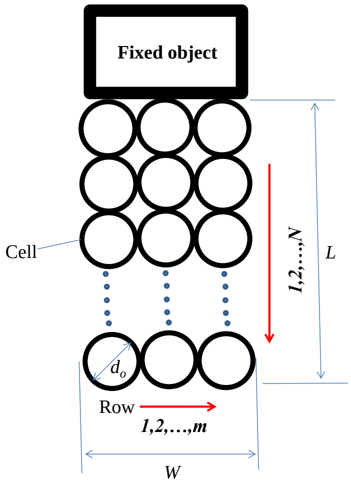


Figure 5: Example iillustration of a potential buffer design

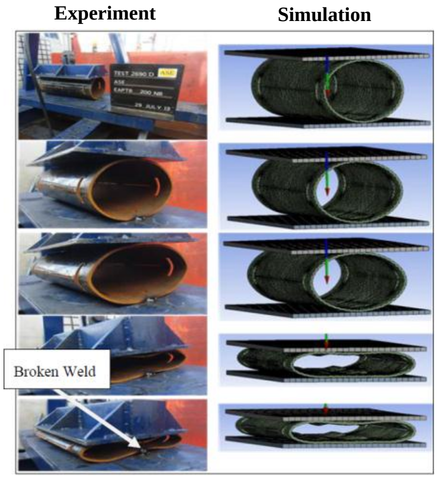


Figure 6: Comparison between experimental and simulated cell deformation

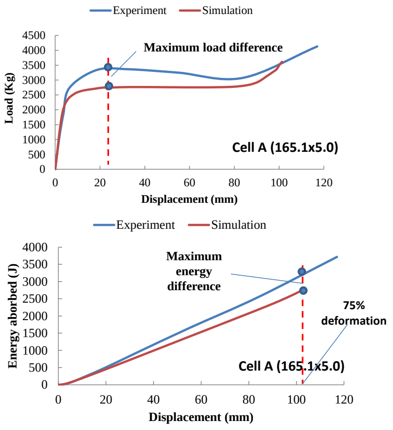
6 Results and discussion

6.1 Comparison between simulation and experiments for individual cell geometry

Figure 6 shows a comparison of cell deformation patterns obtained from experiment and simulation. Both experiment and simulation display exactly the same trend of the deformation until the cell reaches its maximum deformation level. The cell undergoes both elastic and plastic deformations, except for a broken weld spot observed at the contact between the cell and the bottom plate. Damage at the weld can be due to improper welding or unexpected lateral movement of the cell under experimental loading. Overall, the results for a single cell justify the accuracy of the current FE model, and indicate that the model would be able to accurately estimate the deformation of a buffer system consisting of a series of individual cells.

As a representative, Figure 7 illustrates a comparison of load-displacement and energy absorption patterns obtained from experiment and simulation for Cell A. The amount of energy absorption by the cell or workdone by the top (push) plate was estimated as the area under the load-displacement curve at a certain interval of displacement using the ‘trapezoidal rule’. This involved dividing the curve into a series of smaller trapezoids and summing up the areas of those trapezoids. The energy was estimated and plotted until 75% of the cell's maximum deformation level.

As can be seen in Figure 7, the load-displacement and energy absorption results are relatively similar. At early stage, the magnitude of experimental and simulation load to deform the cell is almost same. However, after initial elastic deformation of about 5-10mm, experimental load is higher than simulation, and this pretty much remains constant until the cell reaches its maximum deformation. On the other hand, the cumulative energy absorption capacity increases linearly with the deformation of the cell. For instance, for Cell A, the maximum error between experimental and simulated load was found to be 17.70% at about 22mm displacement while the maximum error in energy absorption was estimated to be 22.97% at 75% of the cell's maximum deformation (at about 113 mm displacement).



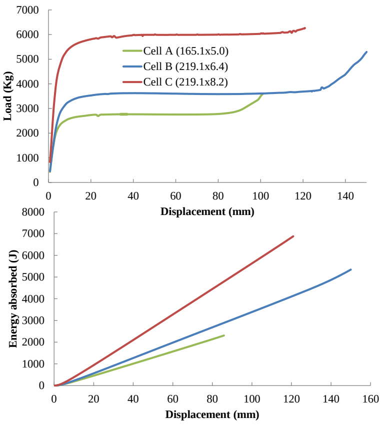


Figure 7: Load-displacement (top) and energy absorption capacity (bottom) of Cell A

Figure 8: Load-displacement (top) and energy absorption capacity (bottom) of three cells

The differences in the cell strength obtained from experiment and simulation can be believed to be the results of pre-stressed state of the cell used in experiments caused by the manufacturing processes. Material properties assigned to the cell in the FE simulation model may not exactly match with the actual mild steel properties of the cell itself. In addition, the contact between the cell and the top and bottom plates was assumed to be an ideal weld joint in simulation. However, a broken weld spot was observed during experiments (Figure 6).

Figure 8 shows the comparison of load-displacement and energy-displacement among three cell geometries. It can be seen that Cell C has the highest strength among all. This means that one needs a larger amount of load to deform the cell so that the energy is absorbed. This further indicates that Cell C is too hard and rigid. This is generally not desired in an energy absorbing buffer system as the main objective of a buffer is to absorb the impact energy through deformation of the cells as quickly as possible so that a smooth and comfortable ride-down deceleration is realised by the vehicle's occupant. On the other hand, Cell A and Cell B show almost the similar level of deformation and indicate more flexibility and are ready to absorb the energy. Therefore, in this study, we use Cell A and Cell B as base cell geometries to design potential buffer systems, which are discussed in the following section.

6.2 Potential buffer designs for 80 km/h speed

We assume that the mass of a vehicle, $m_{vehicle}$ of 1600 kg [11], travelling at a speed, v of 80 km/h. Using Eqs. (2-3), total kinetic energy of the vehicle is 395 kJ, and the energy to be absorbed by the buffer system would become 197.5 kJ. Given that the amount of energy a cell can absorb, $K.E._{cell}$ and the number of cells in a row, m, the number of rows, N and the number of cells, m_{total} that will form the size of the buffer can be estimated using Eqs. (4-6). The aim is to design possible buffer sizes that will be relatively shorter in length as compared to the commercially available buffer systems, and able to be used in different roadways to absorb the required energy for the vehicle travelling at 80 km/h.

Table 2: Buffer designs for 80 km/h speed

Buffer design	Energy absorbed by buffer, $K.E._{buffer}$ (kJ)	Energy absorbed by buffer, $K.E._{cell}$ (kJ)	No of rows, N	No of cells in a buffer, m_{total}	Width of buffer, W (mm)	Length, L (mm)
Cell A, m=3	197.5	3.7	18	54	495.3	2971
Cell A, m=4	197.5	3.7	14	56	660.4	2311
Cell B, m=2	197.5	6.25	16	32	438.2	3505
Cell B, m=3	197.5	6.25	11	33	657.3	2401

Table 2 summarizes the result of potential buffer designs for 80 km/h speed zone. For the given cell geometry, we vary the number of cells in a row to find different size of the buffer. Figure 9 shows the configuration of the designed buffers. Figure 10 shows the extrapolated load-displacement and energy absorption of the buffers at 75% of their maximum capacity, assuming that the buffer will follow the same deformation of a single cell. The extrapolation was performed based on the experimental deformation data for a single cell.

It is seen that the increase in the cell size and the number of cells in a row increases the width and decreases the length of the buffer. This similarly influences the load-displacement and energy absorption data curves. For example, as can be seen in Figure 10, the buffers with Cell A, m=4 and Cell B, m=3 show almost the same energy absorption capacity, but the buffer with larger cell, Cell B, m=3 contains significantly less number of cells. This will reduce the cost associated with the materials and manufacturing of the cells. This further indicates that the buffer with relatively large cells is cost effective, while it withstands high impact energy.

For all the buffer designs, the width and length were found to be quite less than 1,000 mm and 4000 mm, which are acceptable. The sizes of the buffers were significantly smaller than the available buffer sizes of QuadGuard, e.g. 4,910 mm – 8,290 mm in length for speed zone of 80 km/h [e.g. 13].

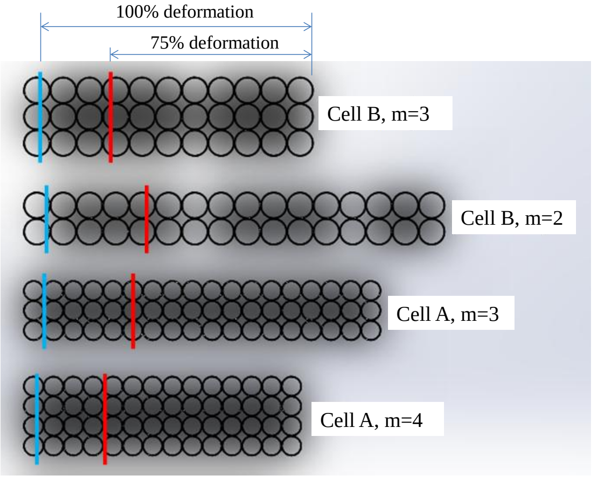


Figure 9: Buffer designs for 80 km/h speed

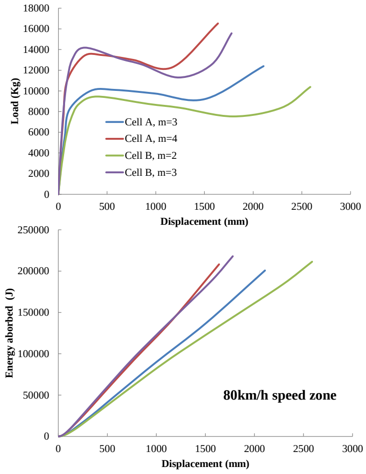


Figure 10: Load-displacement and energy absorption of the buffers for 80 km/h

There are a number of limitations that may hinder the performance of the FE model, and hence, impact the results and analysis. In this study, a quasi-static single cell deformation was tested using both simulation and experiment. However, dynamic FE and experimental testing is required to evaluate and justify the deformation and energy absorption capacity of the buffers. Uniform deformation of the cells under the impact is important to maximise the energy absorption. The slots on the cells provide the flexibility and enable the deformation. Therefore, size, location and orientation of the circular and vertical slots on the cells may need to be optimized so that the required energy is absorbed by the buffers with a comfortable stopping distance of the vehicle after the impact. These will be addressed in our future work.

8 Conclusions

This paper studied design and analysis of cost effective and high energy absorbing buffer systems for high speed roadways. Deformation and energy absorption capacity of the single cell with three different diameters and thicknesses were evaluated using quasi-static tests by FE simulation and experimental technique. Simulation results matched closely with experimental ones with relatively small errors (less than 30%), suggesting that the FE model presented in this paper was able to accurately estimate the deformation of cells. Based on experimental results of single cells, a number of potential buffer systems were designed for 80 km/h speed. Results indicate that the buffers with larger diameter cells, e.g. Cell B, m=3, Cell B, m=5 are favourable to be used in high speed zone as they reduce the overall size of buffers and contain less number of cells, while being able to absorb the required amount of impact energy at the given speed. All the buffer designs are relatively shorter than commercially available buffers used in roadways. Consequently, they will potentially result in a reduced cost associated with materials and fabrication. In addition, depending on the nature and available space of the roadways, the designed buffers can potentially be used to reduce the vehicle crash with the fixed objects.

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