New Design of Roadside Pole Structure: Crash Analysis of Different Longitudinal Tubes using LS-DYNA

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Summary:

This paper is an investigation into the design of an energy absorbing street pole, concerning the frontal impact of a vehicle. With design engineers now are looking at other ways to improve vehicle occupant safety by focusing on the advantages that can be achieved by improving the crashworthiness of street furniture. The study of axial crush behaviour of metal materials are investigated along with a number of variables such as cross-sectional shape, shell thickness, materials, as well as the velocity affects on tubes. Different simulations are carried out on the effects of bedded crumple initiators placed a various heights from the top of the tube, in determining the desired value of peak load reduction, along with the effect in energy absorption of the tube. With the conclusion of the desired variables for the design of an energy absorbing tube, the tubes are placed 90 degrees to that of the base of the model street pole to modify the pole design . Simulation of frontal impact of a vehicle and street pole are analysed and compared to that of the energy absorbing street pole concept. Studies are carried out by numerical simulation via the explicit finite element code LS-DYAN. Results compare the absorbed energy and the deflection of each variable, and recommend optimum design for the pole structure which improved vehicle crashworthiness.

Keywords:

Crashworthiness, vehicle–pole impact, energy absorption, thin tubes, finite element analysis.

1 Introduction

Currently within the UK there are many severe and often fatal crashes that result from vehicles colliding with street columns; column objects such as traffic light pole and street lamps can cause extremely high impact forces on such small area of the car.

In order for the occupants of the vehicle to survive a crash with a street pole it is necessary that the vehicle can absorb the energy created during the impact, which is achieved with the design of crumple zones. Although modern day cars are created with sophisticated composite materials that are used to transfer the energy during impact, the design of a energy absorbing shell that is to be used with street poles would dramatically reduce energy that the vehicle would have to absorb upon impact, thus resulting in a less aggressive drop in acceleration with respect to time.

Street poles have been created from a variety of materials such as wood, concrete, steel, aluminium and composite materials. Wooden and concrete poles show little deflection while impacted by a vehicle, whilst aluminium steel and composites show higher deflection thus absorbing more energy during impact. Although these materials show signs of deflection due to impact it is vitally important to prevent the pole from shearing or falling which would increase the risk to pedestrians. Current designs that are being used will be reviewed and tested showing the best results for material and shape during impact.

Statistics published by the department for transport highlight a demand for new energy absorbing street poles used to reduce the number of injuries and fatalities to vehicle occupiers. Recent statistics [1] show that over 9000 collisions are caused by vehicles colliding with roadside hardware such as lamp poles, traffic lights and road signs. Further research indicates how serious frontal collisions can be, showing that this type of impact accounts for over 1712 injuries and 378 fatalities. Although research shows concern over the high number of injuries and fatalities there are no official test procedures carried out by Euro-NCAP [2] for the testing of frontal impacts with poles, however in 2000 British standards released BS EN 12767:2000 [3] “Passive safety of support structures for road equipment, Requirements and test methods”. This explains in detail the different test methods and requirements for the design of roadside equipment.

With the increasing demands set by Euro NCAP [2], the safety performance of vehicles has increased dramatically over the last few years, improving vehicle crashworthiness. Although there may be scope for further improvement, focus is now directed on the greater gains that can be made by addressing issues with roadside hardware. Acknowledgment for improving roadside hardware has lead to new developments in street pole design. Technological advances enable poles to break away during impact or to deform, thus absorbing the energy of the impact during crash tests. These new designs demonstrate great performance characteristics; reducing the deformation of the vehicle upon impact and leading to less aggressive deceleration with respect to time for the vehicle occupier, thus showing the possibility of reducing injury and fatality rates.

Current designs of such energy absorbing poles are designed around basic key factors including, material and design structure. The choice of material to be used is vitally important, as each material can be thought of as having a set of attributes, each attribute chosen for different condition. Similarly for the design of a pole that will undergo deformation during impact it is important that adequate attributes are chosen for the situation.

A dearth of research has been implemented regarding the crashworthiness of crushing tubes. Witteman [4] studied the control of energy absorption for different collision situations under axial loads. This study looked into research regarding previously developed energy absorbent cross sections and concluded that much of this research reported on the mechanics of thin walled structures for which the variables of tube width, wall thickness and shape geometry determined the energy absorbing characteristics. Witteman further concluded that although a lot of research had been carried out on different crushing tubes, the experimental conditions of these studies differed.

Further research indicates the importance of material selection; including Yang [5]. He reviewed the dynamic progressive buckling of square tubes (Simulations of axial loading). In this study low velocity impact of thin walled tubes is observed. Results showed that aluminium tubes generally result in symmetric crushing, while mild-steel results in an extensional and mixed crushing modes.

Although research for this study has been carried out on various types of energy absorbing materials and shapes for the shell surrounding the street pole it is also necessary to consider the different types of street pole supports which could be adopted to increase energy absorption and reduce the risk of the street pole form shearing at the base. In a finite element analysis Elmarakbi et al. [6] carried out to determine and evaluate crashworthiness of motor vehicle and traffic light pole in frontal collisions. Within this study five different steel pole supports are reviewed, whereby energy absorption, acceleration and deformation of the street pole are concluded, after frontal collision with vehicle.

Elmarakbi et al. [6] developed five different support structures including a brake away base supported with anchor bolts fixed in a concrete surface; the second again with a brake away base but this time with springs between the nuts and buts on both sides of the steel plate. The third support similar to the previous two, however rubber dampers replace the springs. The fourth structure design consisting of a rubber cylinder, on which the street pole is anchored to. The fifth support is embedded directly into the soil of which two different types of soil material are used (clay and sand). Simulations are carried out via the FE software LS-DYNA, where set parameters are assigned to the street pole of 0.3 m diameter at base with a top diameter of 0.133 m. Two impact velocities of 48 and 64 km/h are carried out during the simulation, respectively.

Results from the various experiments carried out support the design of a street pole embedded into soil as opposed to the other four design concepts, for improved energy absorption. Various results presented in Elmarakbi's study indicate the strong link between the amount of energy absorbed by the pole and the acceleration (g) of the passenger compartment. Where high energy absorption by the pole embedded into the ground shows a more desired acceleration pulse for the passenger cabin. As expected the results also link to the deformation encored by the vehicles front end, thus higher street pole energy absorption resulting in reduced deformation. Elmarakbi then states the other advantage of the embedded pole as opposed to the fixed pole is that it is still standing after impact.

This paper aim to show how the use of a crumple zone surrounding a street pole can be used to reduce vehicle deformation, vehicle acceleration along with reducing the damage to main structure of the pole thus reducing the severity of injury during impact.

2 Energy Absorption Characteristics of Longitudinal Tubes

In order to obtain accurate and realistic results, the explicit finite element software LS-DYNA is used to carry out simulations. This paper is split into two sections; the first being the development and testing of various cross sectional shapes, material types, thickness and crumple initiators. With the concluded result on the most desirable properties for energy absorption, the concept design, in the second section, will then be taken forward and applied to a standard street pole, which has been embedded 1.8 m into clay soil. Simulations will be carried out to show a comparison between a standard street pole and that of a pole with added energy absorption tubes. Comparison between the standard and concept design will be simulated using a bogie vehicle supplied by NCAC [7] whereby body acceleration, front-end deformation, and energy absorption of the street pole will be compared. Each simulation will involve a frontal 35 mph impact between the bogie and street pole.

As the first stage of this paper is to determine the required shape, material, d/t ratio and crumple initiator that will be taken forward to the final testing process of the vehicle impacting with the street pole, the first stages are to create tubes that would act as energy absorbers fixed at a ninety degree angle to the base of the street pole.

In determining the most sufficient energy absorbing design, the first stage is to determine the required cross sectional shape to be taken forward for design, this is achieved by testing five different shapes which are octagon, hexagon, circle, rectangle and square. Each shape is given the same length of 350 mm and perimeter of 300 mm to ensure they all have the same mass per unit length therefore ensuring accurate results [4], with each shape undergoing simulation with the same impact velocity, thickness and material (as shown in Figure 1). In order to simulate the effects of a car impacting with the tube the initial parapets are applied to replicate the vehicle with a mass of 1100 kg and a velocity of 35 mph [4]. Unlike quasi-static loading of the tube, where studies show a velocity assigned to move downward until have the tube is deformed using the DEFINE_CURVE keyword card it is decided that a more realistic approach would be to assign the impactor with an initial velocity using the initial velocity card and applying the impactor with a mass. The initial velocity is given as -15.5 mm/ms with a negative value to simulate the impactor moving in a negative direction along the y-axis.

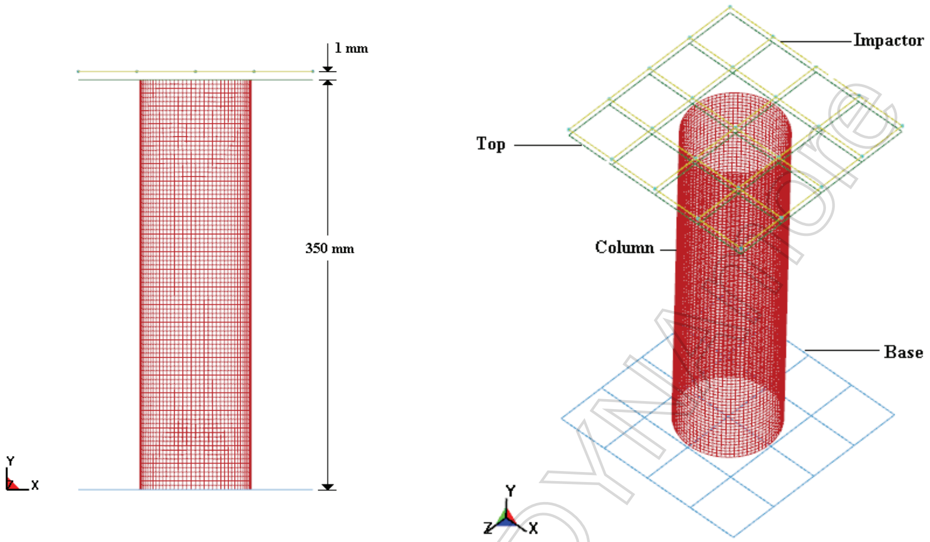

Figure 1: Longitudinal energy absorbing tube.

Along with the shape test other conditions are also carried out such as a material test, whereby steel and aluminium will be analysed for energy absorption, and deflection, each material test will be carried out on the same shape, thickness and impact velocity. The d/t ratio effect of the tube will be analysed at different thickness of 1 mm, 2 mm and 3 mm, respectively, simulated with same shape material and velocity. Simulations will also be carried out on the effect that velocity has on the energy absorption and displacement, tests of 25 mph, 35 mph and 45 mph, respectively, will be carried out with the same shape, material and thickness. As well as a numerical comparison between results a visual inspection of the fold numbers and fold types will be viewed, as bending or undesired collapse of the tube could prove problematic in the final stages of design.

Once the required simulations are carried on the various simulation conditions for the tubes the, desired parameters for energy absorption are taken forward and tested in a frontal collision using a FEA model of a bogie supplied by NCAC [7] . The FEA modelling of the street pole composes of four main components, first being the replication of the street pole embedded into the ground. To replicate the street pole in the ground, the pole length is set at 1.8 m and consisted of 144 shell elements, with a wall thickness of 3 mm. The lateral resistance of the soil is represented by using springs at each node level of the pole, allowing for various impact collision types. For replication of the friction resistance of soil eight vertical springs are applied to each node level. Model supplied by Elmarakbi et al [6].

The design of the pole above the ground is created using an octagonal shape to create a flat surface between the fixed tubes and the street pole, thus providing a larger surface area for the forces to be spread across, as opposed to a smaller surface area if a circular tube is used. The base of the pole is set at a diameter of 0.3 m and continued vertical for another 2 m, as this allows for the tubes to be flush with the street pole to cover the various differences in high of vehicles. The street pole is then taken from 2 m vertically to 10.4 m and taped to a diameter of 0.133 m. The street pole is made 3 mm thick and assigned the steel material. To ensure accurate results are obtained from each simulation, a study into various element sizes is applied to a 350 mm length tube of perimeter 300 mm. Deflection results of the various element sizes show that, element size 3.75 mm show the most accurate result.

With the created street pole the energy absorbing tubes designed for impact are then fixed ninety degrees to the base of the tube. Each tube had a diameter of 95 mm and a length of 100 mm. To reduce the contact force between the tubes and the street pole each tube is designed with a closed base, thus spreading the load and preventing the tubes from piercing the street pole. The final component of the street pole consists of an outer shell containing the tubes and base of the pole. Again, an octagonal shape is used in this case as it would allow for a flat surface to impact on the tubes, where as a circular shell would cause deformation of the corner of the tubes, thus reducing the energy absorbing potential of the tubes.

3 Results and Discussions

3.1 Longitudinal energy absorbing tubes

The variation in cross section shows that the circle, octagon and hexagon prove to be more sufficient in energy absorption than the square and rectangle. A prediction can also be made that the higher the number of folds, the better the energy absorption. Further tests are necessary to provide more accurate conclusions, which are discussed alongside the internal energy absorption and deflection results. As for material, it can be seen that aluminium and steel have similar fold numbers making them a possible variable to be taken to the final design stages. As predicted for wall thickness, the increase in thickness will have a linear relationship with the strength of the tube under axial impact, and therefore with increased wall thickness comes a reduced number in folds. In this case it can be predicted that reduction in wall thickness will also result in a reduction in peak loading needed to cause the crushing of the tube. An increase in velocity results in an increase in energy during the contact of the impactor and tube, thus leading to increase fold number over the same simulation time.

Figure 2 shows the results taken from the five different cross-sectional shapes, with initial conditions of a 35 mph impact with mass 1100 kg. It is clearly indicated that the circle, hexagon and octagon performed much better than the rectangle and square when compared. The circle and hexagon cross sections show similar values, with 25 KJ for the circle and 26.25KJ for the hexagon. Therefore it can be considered that the best cross sectional shapes to be taken forward for better energy absorption are the circle, hexagon and octagon.

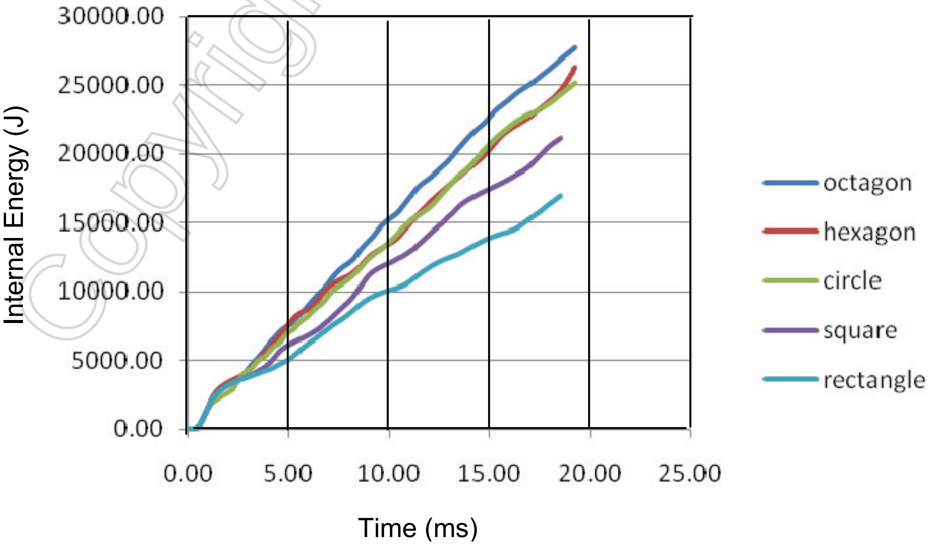

Figure 2: Internal energy absorption of different cross sections of the tubes.

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Following the results taken from the cross sectional shape demonstrating that the circle is more suitable for better energy absorption, the circular cross section is taken forward for comparison with different material type. The materials that are assigned for testing are mild steel (ρ = 7830 kg/m^3 , E = 207GPa, υ = 0.28, σ_y = 215 MPa) and aluminium (ρ = 2700 kg/m^3, E = 68.9 GPa, υ = 0.33, σ_y = 145 MPa). Each test is assigned the same simulation parameters of velocity 35 mph, impactor mass 1100 kg and tube thickness 2 mm. The results from the material test indicate that the steel material is capable of absorbing a much higher value than that of the aluminium, with steel resulting in a maximum value of 25 KJ and Aluminium 11.5 KJ.

At a velocity of 35 mph and circular cross sectional shape at length 350 mm of steel material, different wall thicknesses are simulated of 1 mm, 2 mm, and 3 mm, respectively. It observed that the increasing wall thickness causes an increase in the internal energy. The increment factor of 0.5 mm does not show the same increment increase in the internal energy, with an increment of 7.5 KJ where as the increment between the 2 mm and 3 mm thickness is 12 KJ. Also, the deflection of the variations in wall thickness is compared, the results demonstrating that with an increase in wall thickness, the deflection value is also increased. Results also indicate that the thicker the wall the later the deflection of the tube. Increasing tube strength from increased wall thickness, in turn, has an effect upon the peak loading values of the tube and thus results in a larger force value needed for the first fold. Although an increase of wall thickness to that of 3 mm results in increase energy absorption and deflection, the number of folds generated is reduced, which again could lead to bending or an undesired collapse during a frontal impact.

In addition, studies into the effects of velocity have been carried out on a circular cross section of length 350 mm with steel material. Results indicate that with increasing velocity the internal energy is increased due to the higher value of forces acting upon the tube. The increasing velocity value proves the same scenario for deflection as the greater the value of velocity the greater the deflection. With increased velocity, maximum deflection time of the tube is also reduced.

In order to reduce peak load reduction for better energy absorption, crumple initiators have been assigned to the tube. The tubes are tested using mild steel with circular cross section at a length of 350 mm and perimeter 300 mm. The crumple initiators, as shown in Figure 3, are placed at various heights from the top of the tube, which are 5 mm, 10 mm and 15 mm, respectively.

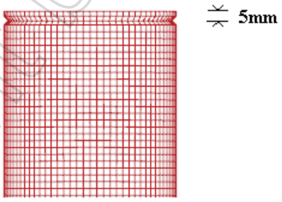

Figure 3: Crumple initiator positioned 5mm from the top of the tube.

Figure 4 shows the effect of placing the crumple initiator at various heights from the top of the tube with respect to the peak force. It is shown that initiators 15 mm and 10 mm from the top of the tube show similar results where as the 5 mm initiator shows a significant reduction in the first peak load. It is also visible that after the peak load has been reduced this has an effect on the how the rest of the tube is deformed, as each peak result after the initial peak result from impact shows reduced results i.e. not only does the initiator reduce the peak load but has an effect on the fold behaviour for the rest of the fold. Also, it is observed that the closer the initiator is positioned to the top of the tube, the greater the reduction in energy absorption. The values for the internal energy absorption by the cylinders show that 10 mm and 5 mm show similarly internal energy values.

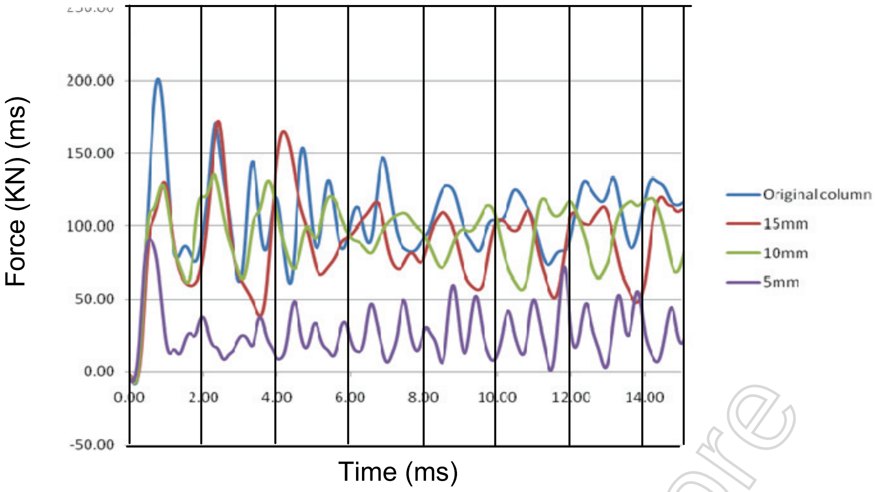

Figure 4: Peak force at different crumple initiators.

3.2 Modified street pole

In order to compare the modified street pole with positioned energy absorbing tubes, it is necessary to simulate the impact of a vehicle with an unmodified street pole. This simulation is carried out with a vehicle impact of 35 mph into a pole of thickness 3 mm with a steel material. After completion of the simulation results are gathered and analysed for vehicle bumper deformation, acceleration inside vehicle cabin, velocity of vehicle cabin, deformation of street pole, and the internal energy of the street pole.

With results gathered from impact testing with various tube simulations including material testing thickness velocity etc. The most desirable variables for energy absorption are taken foreword and fixed to the base of the street pole. Four energy absorbing tubes are attached to the pole and supported by an outer vertical shell cylinder. The energy absorbing tubes and outer cylinder are made of aluminium. Different shell thickness are considered as follows; tube thickness of 0.57-outer cylinder thickness of 3 mm; tube thickness of 1.75 mm-outer cylinder thickness of 3 mm; and tube thickness of 1.75 mm-outer cylinder thickness of 1 mm. To reduce the impact forces needed to deform the tubes upon impact the crumple initiators are placed 5 mm from the top of the tube. With the tubes fixed to the street pole the bogie is given an initial velocity of 35 mph as given in the previous simulation. Results of the vehicle collision with energy absorbing tubes are in comparison with the standard test. It is clear from Figures 5 and 6 that reduced rigidity of outer shell thickness and increased energy absorbing tube thickness result in a more desired deformation in the front end of the bogie and better acceleration pulse, experienced in the passenger compartment.

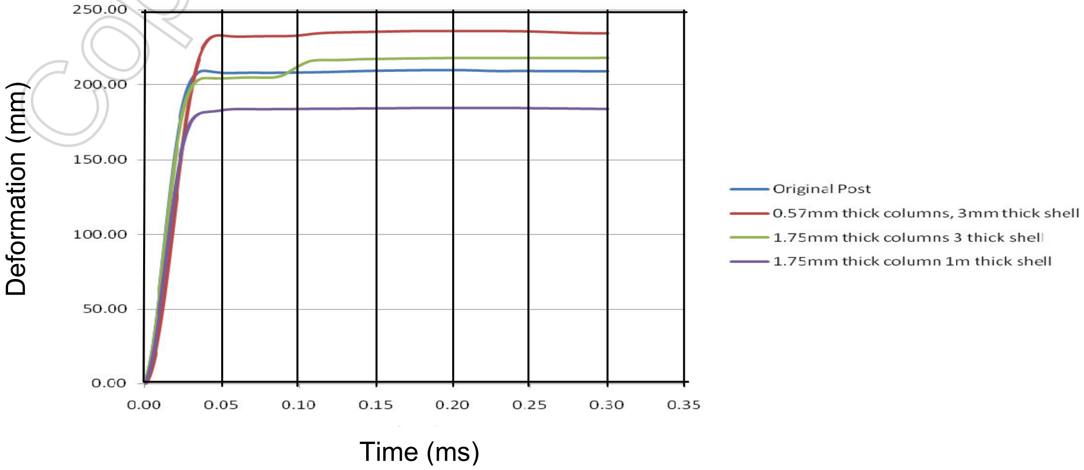

Figure 5: Deformation of the front-end.

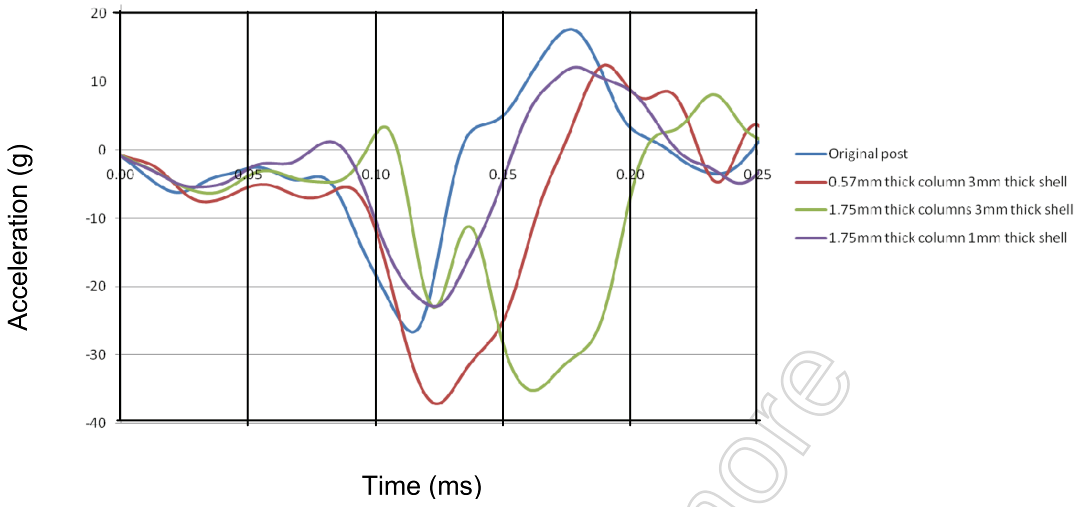

Figure 6: Body acceleration.

4 Conclusions

This paper comprises of two main sections. The first being the study of suitable cross-section, thickness and material for better energy absorption under axial load. Internal energy deflection and fold numbers have been studied. The addition of a bedded crumple initiator are applied to a circular shape cross section at 5 mm, 10 mm and 15 mm from the top of the tube. Studies identified that a circular cross sectional shape made with aluminium and a shell thickness of 2 mm have the greatest potential for energy absorption. The addition of crumple initiators allowed for a reduction of peak load force needed to start the first fold, with the initiator placed 5 mm from the top of the tube showing the highest reduction in peak force, and a stable folding pattern. The second stage of this paper is to compare the effects of front-end deformation and body acceleration of a vehicle impacting into a standard street pole and that of a modified street pole using energy absorbing tubes placed ninety degrease at the base of the street pole. Numerous studies are carried out to review the effects of tube thickness and outer shell thickness. The results obtained identified the minimum time required for maximum deformation of the street pole, and the required shell, and tube thickness for reduced bumper deformation and acceleration. This study identifies that for a reduction in front-end bumper deformation and body acceleration, it is recommended that deformation of the energy absorbing tubes occurs directly after the maximum deformation of the street pole.

5 Reference

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