FINITE ELEMENT STUDY OF EFFECTIVENESS OF MODIFIED FRONT-END STRUCTURE WITH ALUMINIUM FOAM IN REDUCING PEDESTRIAN INJURY

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ABSTRACT

Pedestrians are vulnerable road users. Unlike Occupant in cars, they do not have protection equipment and are often involved in serious accidents leading to fatalities. The reduction of pedestrian injuries has recently become one of the most important road traffic accident priorities. For the bonnet type of vehicle, leg and head injuries are the most prevalent type of injury associated with car-to-pedestrian collision. The possible reduction of leg and head injuries can be done through the design of vehicle bumper structure. Strong and stiff front structure of vehicle usually leads to severe injury to pedestrians in the accident. The use of new class of material like aluminium foam as part of bumper structure can provide better energy absorption capability and hence reduction of impact force to pedestrians. However, in order to design or modify the front structure to be safer for pedestrians, it is necessary to understand kinematics and injury mechanisms of car-pedestrian collisions, which are usually analyzed through costly full scale crash tests of a dummy or a cadaver. Finite element simulations with a human body model are an alternative mean, which offers information of post-crash kinematics and injury mechanisms. This paper has therefore employed the finite element model of pedestrian-city car collisions to study the effectiveness of the modified front-end bumper with aluminium foam in reducing the level of pedestrian injuries. The front bumper structure has preliminary been modified to include the aluminium foam as part of energy absorber. Two relative densities of aluminium foam were selected. The lower density one gave a better injury reduction performance. It was used to simulate a crash with THUMS to study detail injuries of pedestrian. The modified bumper model showed improved performance of injury reduction. The results exhibited the potential use of low density Al-foam in minimizing pedestrian injury and the benefit of using the human body finite element model which provides detailed injury information to help in the design and development of vehicle for pedestrian safety with cheaper cost compared to the actual full-scale crash tests.

INTRODUCTION

Road traffic injuries are a significant global public health problem around the world. Accidents which involve pedestrians mostly result in severe injury or death. Most of car manufacturers have given less priority to pedestrian safety. This is due to the fact that many countries in particularly developing countries have no such regulations. However, many regional New Car Assessment Programs (NCAP) have included pedestrian safety assessment into their car-rating system. This has encouraged many car manufacturers to develop cars with better pedestrian protection. NCAP has assessed pedestrian safety through the impact tests of the front structure with legform and headform since the front structure of vehicle is the part that mostly hits pedestrians. Strong and stiff front structure of vehicle usually leads to severe injury to pedestrians in the accident. Impactor crash test is poor in giving information about the injury mechanisms and kinematics of the pedestrian during crash. Car manufacturers have lately begun to use design principles that have proved successful in protecting car occupants to develop vehicle design concepts that reduce the likelihood of injuries to pedestrians in the event of a car-pedestrian crash. There is a possibility to protect a pedestrian lower limbs during impact by introducing an appropriate cushion and support of the lower extremities for example the bumper energy absorber. Aluminium foam is a material which has excellent energy absorption capacity. It has been recently introduced to automotive industry to make a crashbox for crashworthiness design [1]. This paper aims at introducing aluminium foam to the front-end structure of a passenger car to study its potential in reducing pedestrian injury level. For purpose of vehicle development, full-scale crash tests are required. However, the actual crash tests are costly compared to alternative computer simulations. Finite element (FE) analysis has been employed widely in vehicle components design and optimization. It is therefore, introduced in this work to simulate pedestrian-car collisions. By firstly, simplified the vehicle model to include only necessary components to reduce computation time. The simplified vehicle model was validated against the actual crash test. The front-end structure of this simplified model was modified by introducing aluminium foam with two relative densities aiming to minimise the pedestrian injury level. The modified bumper structure with two relative densities were numerically assessed with legform impactor. The best safety performance one was selected for car-to-pedestrian simulation. The dynamic responses and injury level were compared with those obtained from the original front-end structure.

SIMPLIFIED FE MODEL OF A PASSENGER CAR

A passenger car finite element model was taken from the National Crash Analysis Center (NCAC) [2]. In the present study, only frontal collision with a pedestrian was considered. Therefore, some unnecessary components were deleted to simplify the car model. The main body in white structure were kept upto the B-pillar. The doors were removed. All components below the hood were kept in place. Since some components and structures were removed, extra mass needed to be added and distributed correctly to obtain the same mass and Centre of Gravity (C.G.) location as in the actual car. Figure 1 shows the simplified FE vehicle model and comparisons of mass and C.G. location with the complete vehicle model. All extra nodes that carried extra mass were constrained to the C.G. of the car. All nodes at area A and B in figure 1 were not allowed to translate in y and z directions also not to rotate around x and z axes. The mass and the C.G. of the simplified model were almost identical to the complete model. In order to validate the simplified car model, a full frontal wall crash was simulated and compared the results with the actual crash test data of NHTSA [3]. The car model was set to impact a rigid wall at 56 km/h. The overall global deformation of the actual car was very similar to the actual crash test as shown in figure 2. The acceleration response taken from the engine top and bottom were compared as shown in figure 3. Reasonably good agreement can be seen.

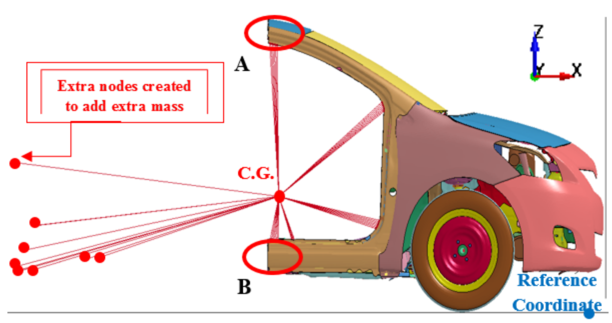
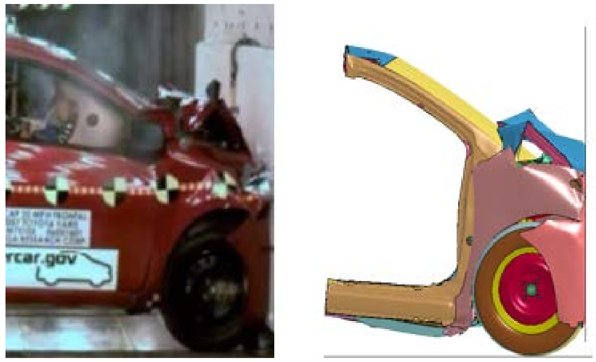


Figure 1. Simplified finite element model of Toyota Yaris sedan

FRONT-BUMPER MODIFICATION TO IMPROVE PEDESTRIAN

For the bonnet-type vehicle, leg and head are body regions that have high risk of severe injuries. The proposed design modification aims at illustrating the potential application of aluminium foam (Al-foam) together with add-on stiffeners to primarily reduce lower extremity injury. Three components made of Al-foam were attached to the front-end of the car as shown in figure 3. They were upper and lower stiffeners as well as a cushion part attached in front of the bumper beam. Two relative densities of Al-foam were used. Material behaviour of Al-foam was required for finite element implementation. The Crushable Foam material model in LSDYNA [4] was employed for this purpose. It requires mass density, Young’s modulus, Poisson’s ratio and stress-strain curve. Compression tests of Al-foam were conducted for relative densities of 0.051 and 0.185.



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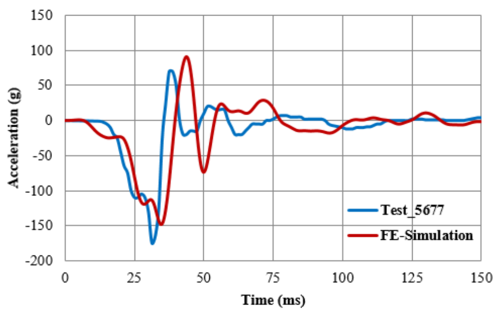

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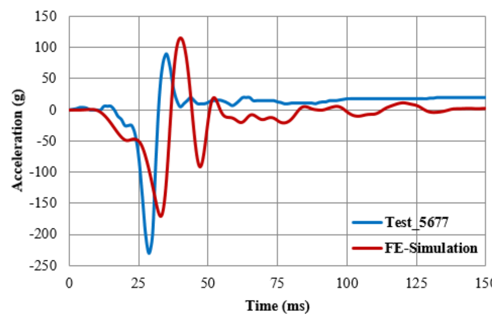


c)

Figure 2. Comparisons of a) global deformation b) engine top acceleration c) engine bottom acceleration.

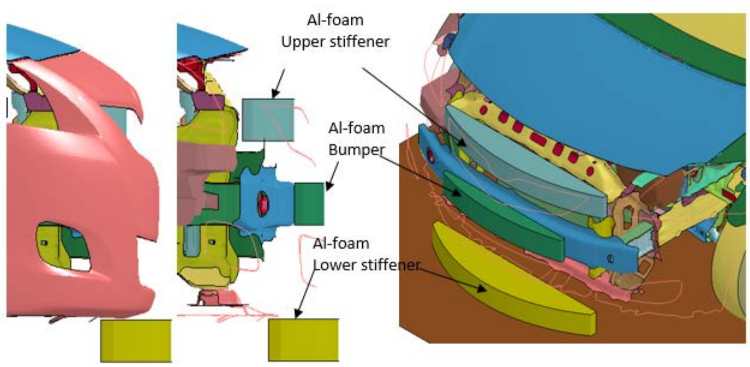


Figure 3. Front bumper modification with aluminium foam parts.

PEDESTRIAN CRASH FINITE ELEMENT MODEL SET UP

Two configurations of crash tests were simulated in this paper. One was legform-car impact test, the other was car-to-pedestrian crash test. A 50 percentile Total Human Body Model for Safety (THUMS) was employed for pedestrian model in this paper. THUMS model is capable of predicting detail injury of brain ligament, bones and internal organs. The set-up of both configurations are shown in figure 5. The legform-to-car model was set up according to the Euro NCAP protocol [5]. The legform was set to move towards the centre of the car bumper at a speed of 40km/hr. For the car-to-pedestrian model, the human body model was initially positioned in front of the car centerline. The car was set to impact the pedestrian from the right side at a speed of 40 km/hr. The contact friction coefficient between THUMS and the car was 0.3 and the ground friction coefficient was 0.9. Both the car and THUMS were placed in the acceleration field of gravity.

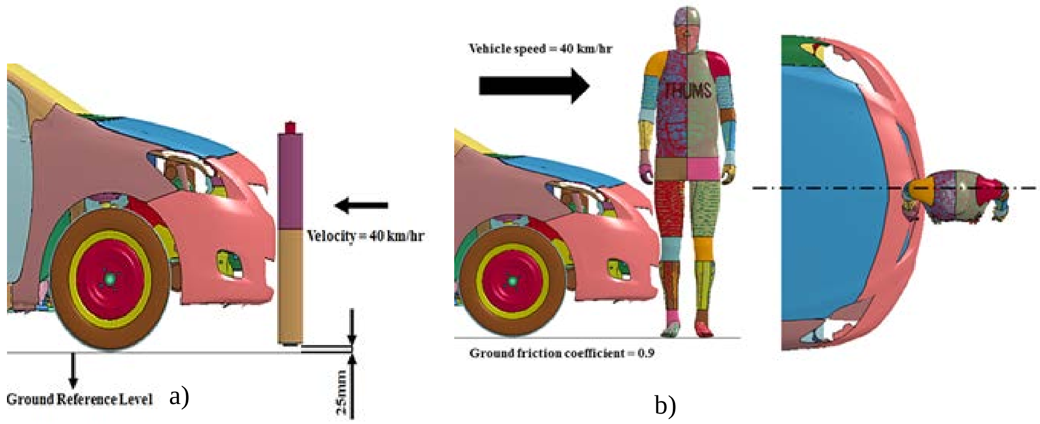


Figure 4. FE model of a) Car-to-Legform impact set-up b) Car-to-Pedestrian collision set-up.

SIMULATION RESULTS

Two set of simulation results are presented. The first set was from the car-to-legform impact test which was employed to assess performance of the original bumper structure and the modified bumper structure with two relative densities of Al-foam. The best performance among the two relative densities was selected to crash with THUMS for detail injury analysis which provided the second set of simulation results.

Legform-car impact simulations

Three cases were conducted. According to the Euro-NCAP protocol [5], three injury parameters including the upper tibia acceleration, the knee shearing displacement, the knee bending angle were used to assess the pedestrian protection performance of the front-end bumper. The maximum value of each injury parameter for each cases are given in table 1. It is obvious that the modified structure with 0.051 relative density Al-foam has all values of injury parameters below the limit specified by Euro NCAP.

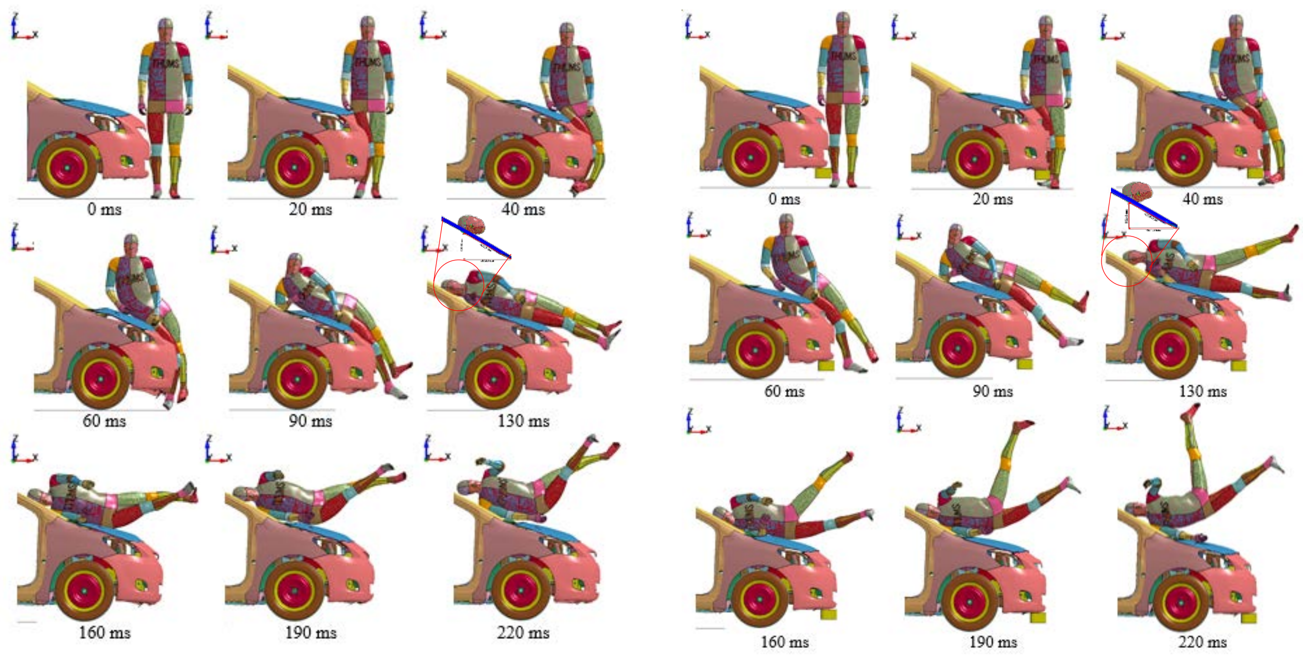
Table 1.
The maximum value of each injury parameters for each simulation cases.

Injury parameters	Euro NCAP limit [5]	Original structure	Modified structure with 0.051 relative density al-foam	Modified structure with 0.185 relative density al-foam
Tibia acceleration (g)	150	228	117.7	208.08
Knee shear displacement (mm)	6	-4.8	-1.54	-2.47
Knee bending angle (degree)	15	30	12.06	20.36

Car-to-pedestrian simulations

Two cases were simulated. The first one used the original structure of the car to hit with THUMS in order to obtain the baseline results. The second one used the modified structure with 0.051 relative density al-foam to hit with THUMS. The detail injury were compared and analysed.

Post-crash kinematics behaviour and dynamic responses Figure 5 shows a comparison of kinematics behaviour of pedestrian crashed by the car with original front-end structure and with modified front-end structure. For both cases, the knee was firstly struck by the bumper followed by the thigh and the tibia almost at the same time. The front bumper deformed and the lower extremities bent along the car frontal contour. The upper body rotated around the vehicle front area leading to the pelvis collision with the bonnet leading edge. The elbow were collided with the lower windshield portion. The chest and shoulder collided with the windshield portion at the back end of the hood. Since the neck behaved like a joint which allowed rotation degree of freedom, the head was angularly accelerated and made contact with the windshield. Finally the whole body bounced off the car. The differences can be seen clearly at 40ms, the simulation with the modified bumper model shows less knee bending angle than the original design. In addition, at 60 ms the left leg started to project away from the right leg. This was because the lower part of tibia was in contact with the lower stiffener which tried to resist the tibia movement. The left leg moved away from the car faster than the right leg because some of the right leg energy was absorbed by the lower stiffener aluminum foam. The time and location of head impact were also different. At 130 ms, the one with original bumper structure hit the windshield at 442 mm from the lower end of windshield where are the one with the modified bumper structure hit to the windshield at 410 mm.



a) b)

Figure 5. Pedestrian kinematics obtained a) original bumper model b) modified bumper model.

Figure 6 shows comparisons of dynamic responses. The patterns of contact force during collision were similar. The graphs consisted of 5 peak forces corresponding to the impact of plastic cover-leg, bumper beam-leg, elbow-lower part of windshield, chest-hood and head-windshield respectively. The highest peak force was when bumper beam in contact with the knee. The contact force obtained from simulation with the modified bumper was in overall less than those of the original bumper model except the highest peak. This was due to the introduction of the lower stiffener which tried to resist the movement of the lower part of the tibia causing the high contact force at the knee area. The introduction of bumper foam components slowed down the pedestrian body as observing from head and chest relative velocity graphs. The head impact acceleration was decreased from 175.7g to 150g. The HIC_{15} obtained from the simulation with original bumper model was 1059 which implied high risk of severe head injury with AIS3 50% injury risk [6]. The HIC_{15} was reduced to 913.8 for simulation with the modified bumper model, hence lower risk of head injury.

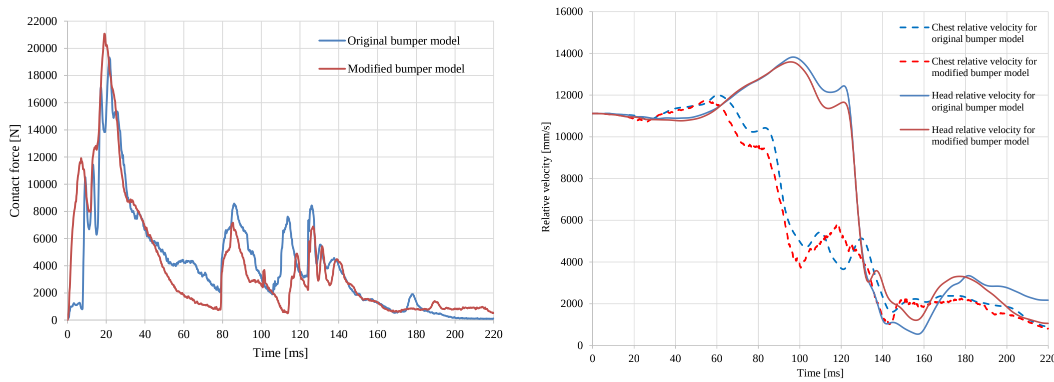


Figure 6. Dynamic response a) the contact reaction force during collision b)relative velocity.

<u>Pedestrian injuries</u> Figure 7 shows comparisons of bending moment and resultant force time histories at various height along the lower extremity. The threshold for 50% injury risk of AM50th was 447 Nm for femur [7-8] ,134 Nm for knee [7-8] and 340 Nm for tibia [9]. The patterns of bending moment were different. For the original bumper model, the maximum bending moment of the right lower extremity was the largest at the tibia height 400 mm above ground. It was 256.52 Nm but still within the tolerance limit of tibia for 50% injury risk of AIS2. While at the knee area with height of 500 mm above ground the maximum bending moment was 231.45 Nm. This value exceeded the tolerance limit of knee for 50% injury risk. The maximum bending moment of the femur was lower than that of tibia and knee. The values were still within the tolerance limit for 50% injury of AIS3. However, for the modified bumper model, the highest maximum bending moment of 400 Nm was shifted to the femur. This value was still within the limit of femur fracture. The knee and tibia bending moment taken from the modified bumper simulations had lower value than the original bumper model. They were all within the limit of bone fracture and knee joint damage.

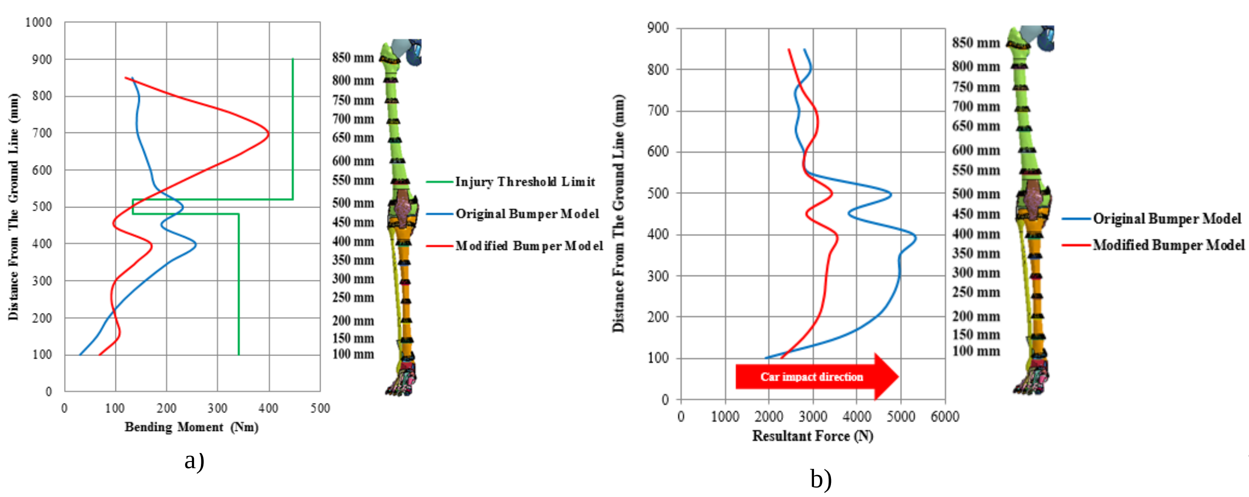


Figure 7 a) bending moment and b) resultant force along the right lower extremity.

Resultant force expressed the same trend as shown in figure 7 b). The resultant force obtained from the simulation with the modified bumper was less than those of the original bumper for every distance.

Apart from dynamic responses, the biofidelity of the human body model can also give detailed injuries of all parts of the pedestrian body. Figure 8 shows comparisons of stress and strain distributions on the extremities. For the original bumper design, high stress of 141 MPa occurred at the front fibula and tibia. However, the magnitude of the stress was still within the bone fracture stress threshold of 150 MPa [10-12]. It was found that stress distribution changed for the simulation with the modified bumper. High stress occurred on femur rather than on the tibia. The highest magnitude was 122.67 MPa which was still below the femur fracture limit of 150 MPa. However, the overall magnitude of stress within the lower extremities was reduced for the simulation with the modified bumper. The maximum strain on knee ligaments for the case of the original bumper was at 0.25 which was beyond the rupture strain limit of 0.16 [13]. The simulation with the modified bumper structure showed improvement of the strain value. The maximum strain value reduced to 0.18. Very high stress also found at the humerus (upper part of an arm) due to the impact of elbow to the lower part of the windshield. For the original bumper simulation case, the stress was 232.5 MPa which exceeded the bone fracture limit of 150 MPa. For the modified bumper case, the stress value was much lower. The modified bumper model helped reducing the injury risk of humerus fracture.

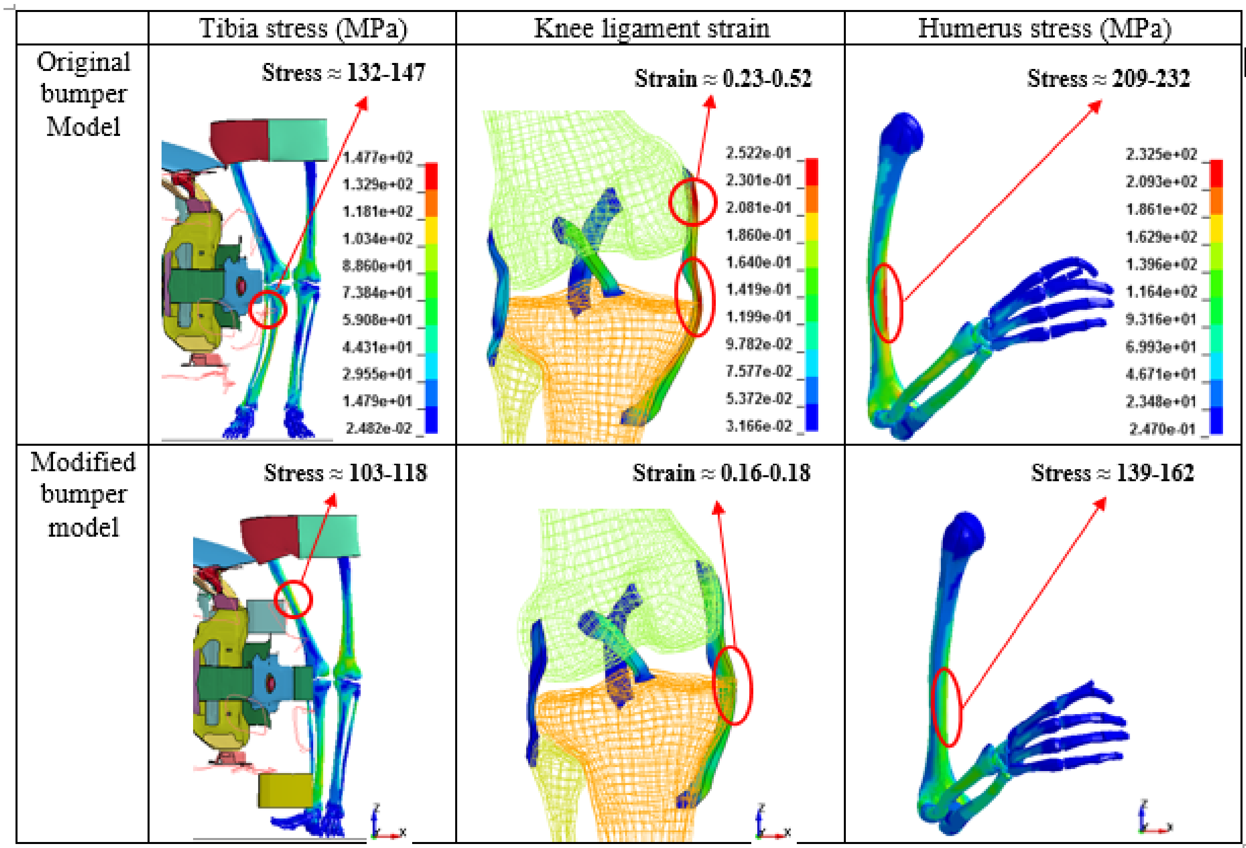


Figure 8. comparisons of stress and strain distributions on the extremities.

Figure 9 shows comparisons of detailed injury for the upper body. The thorax experienced high stress due to the impact of thorax to the back of the hood. For the original bumper model, two ribs, number 3 and 5 had quite high effective stress of around 149.2 MPa which was at the borderline for rib fractures. This impact also induced high pressure within the lung as shown in figure 9. The limit of human lung usually uses pressure to define threshold [12]. The limit is at ±10 kPa. From the simulation results, the red area represents the area that pressure exceeds 10kPa and the dark blue area represents area that pressure is less that -10kPa. The right lung showed damage as the pressure was greater than 10 kPa for almost all area of the right lung. With the modified bumper model, a drastically improvement was seen for the ribcage stress and the lung pressure. The maximum stress on rib number 5 reduced to 94 MPa which was much below the fracture limit. In addition, the pressure within the lung was also considerably reduced. However, when comparing strain on brain, it was found that the strain within the brain expressed advert effect. For the case with modified bumper, the strain increased to 0.52 which exceeded the limit value of 0.3 for soft tissue damage. This implied that the modified bumper structure induced brain contusion. Although, the head acceleration and HIC value were reduced, the brain strain did not follow the same trend. The argument is that the HIC is calculated from the translation acceleration. There have been some studies illustrating that the relational velocity and acceleration have effects on the brain injury [13-14]. Since post-crash kinematics of head were different, it could affect the strain pattern and magnitude

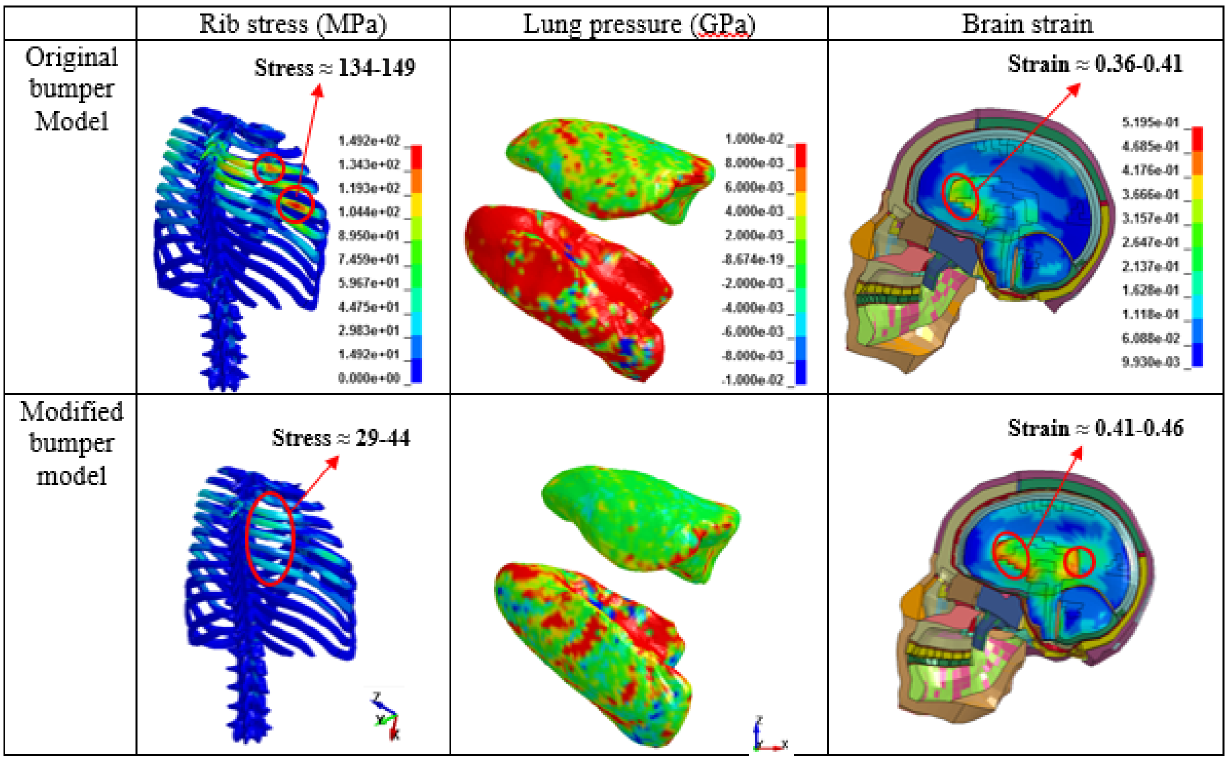


Figure 9. Comparisons of stress and strain distributions for upper body part.

CONCLUSIONS

This paper aimed at studying the potential use of aluminium foam as part of front-end structure to reduce pedestrian injury. The detail injury analysis was performed though the use of finite element human body model. A modification to the bumper structure was done but with limitation of the shape of the bumper cover of the existing car. Three components made of aluminium form were added to the front bumper structure as part of energy absorber. Two relative densities of aluminium foam, 0.051 and 0.185, were considered. The modified design with lower relative density of 0.051was selected based on the legform injury parameters performance. It was used to simulate a crash with THUMS in order to study detailed injuries of pedestrian. The post-crash kinematics showed some differences at the lower extremities and head. The dynamic responses and level of injury were improved with the modified front bumper using low density aluminium foam. However, when simulating car-to-THUMS collision, some detailed injury information showed that the modified bumper caused slight problem in brain area. The results illustrated that the low density aluminium foam could be employed in the design for pedestrian friendly vehicle. The design and development process needed to take into account the injury of other body regions also especially the brain which could not be simulated using a headform or a dummy. The current study also supported the benefit of using THUMS in the design development of pedestrian friendly bumper.

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