INFLUENCE OF VEHICLE SANDWICH BUMPER BEAM ON CHILD VEHICLE OCCUPANT HEAD INJURIES IN FRONTAL CRASHES

I.A Rafukka [1,3], B.B Sahari[1] , A.A Nuraini[1], A. Manohar[2]

[1]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*

[2] *Department of Orthopedic Surgery, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*

[3]Department of Mechanical Engineering, Faculty of Engineering, Bayero University, PMB 3011, Kano, Nigeria

ABSTRACT: Background: *Though substantial literature studied the performance of light weight material in energy absorption and vehicle weight reduction, limited attention was given to how effective such materials are in reducing injury risk to vehicle occupants especially children.* ***Objective:*** *To study the effect of sandwich energy absorption bumper beam on minimizing the three year old (3YO) child occupant head injuries based on 48 km/h full frontal impact.* ***Results:*** *Head Injury Criteria (HIC) evaluated from child dummy finite element (FE) model was compared for the steel and sandwich bumper. HIC15 and HIC36 for steel bumper were respectively 43% and 49% above National Highway Traffic Safety Administration (NHTSA) limit. Significant reductions in head injury were obtained with sandwich bumper in which HIC15 and HIC36 were found to be 22% and 5% below the recommended limit. This study revealed that in addition to providing protection to pedestrians, the energy absorption bumpers have the potential of preventing child occupant injuries.* ***Conclusion:*** *Sandwich bumper material can reduce injury level to 3YO child occupant in frontal crashes at 48 Km/h due to increase in energy absorption. It is suggested that bumper energy absorption characteristics be included in design consideration for better child occupant safety.*

Keywords: *bumper beam, child occupant, energy absorption, finite element method, head injury criteria, sandwich material, vehicle crash,*

1. INTRODUCTION

Motor vehicle traffic crashes are the leading cause of death for children aged 4 and the second leading cause of death for children aged 3 and every age 5 through 14 in 2013 (NHTSA)[1]. Head injury is a disaster that leads to loss of lives of vehicle occupants of all age groups. Safety systems available for child protection in vehicle crash are still not optimum. Research on child injury prevention is focused on various perspectives: mainly on vehicle crashworthiness and child restraint system (CRS) improvement. Studies currently inclined towards energy absorption mechanisms that absorb more kinetic energy there by effectively minimizing child occupant injury.

Increased global emissions of greenhouse gases has made it necessary for automotive engineers to design high energy absorption, low weight vehicles that will consume less fuel, while maintaining the crashworthiness of the components for better occupant safety. On frontal collision, crush zone structures collapsed in a controlled way there by consuming more kinetic energy from impact and ensuring safety to the vehicle occupants. Bumper system is the first vehicle part to suffer crash. It absorbs substantial amount of kinetic energy through its plastic deformation. High energy absorption bumper can help in reducing vehicle deceleration thereby increasing the chance of survival of child vehicle occupants.

Research on vehicle energy absorption components focused on the evaluation of crashworthiness of light weight vehicle components without application of real dummies in order to determine how effective such materials are in reducing injury risk to vehicle occupants. The effect of light weight material of automotive side member on adult occupant protection has been studied by (Salwani, Sahari, Ali, & Nuraini, 2014)[2] in which it was found that aluminum provides significant weight reduction compared to steel with improved HIC and Chest Severity Index (CSI) values. Elmarakbi et al. (2013)[3] applied finite element simulations to study the influence of structural and material characteristics of road side pole on injury of 3YO child and focused on how to minimize child injury by improving energy absorption of traffic pole structures. It was found out that anchored base support system provides desirable crashworthy results, thus reducing fatalities and injuries resulting from vehicle impact. [4] develops sandwich frontal bumper for better kinetic energy absorption. It was reported that sandwich bumper absorbs more energy than steel bumper, and occupant injury parameters obtained using adult FE dummy model were found to be lower for sandwich bumper for 35 mph frontal impact test. Other works studied the effect of energy absorption materials on vehicle deceleration without relating it to occupant injuries (Abbasi, Kazemi, & Ghafari Nazari, 2011; Abdel-Nasser, 2013; Chen, Yang, & Wang, 2015)[5,6,7]. The aim of this work is to minimize child head injuries during frontal crashes by improving the energy absorption of bumper beam.

Head Injury Criteria (HIC)

HIC is the metric used in the assessment of head injury risk on impact. It is defined as the standardized maximum integral of resultant acceleration of head centre of gravity within a specified time windows. It is given by the equation:

$$HIC = \left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a_{result.} \cdot dt\right]^{2.5} \cdot (t_2 - t_1) \quad (1)$$

Where t_1 and t_2 are the time duration of crash in seconds and $a_{result.}$ is the resultant acceleration of the dummy head center of gravity in unit of acceleration of gravity (g). The maximum time interval is limited to 15ms or 36 ms which yields HIC15 and HIC36 respectively.

Finite element modeling

The child crash dummy FE model used in this study was a 3YO child model developed by the authors by morphing a six year old hybrid III dummy FE model produced by Livermore Software Technology Corporation (LSTC). The 3YO child model was validated using sled test results of physical hybrid III 3YO dummy (Turchi, Altenhof, Kapoor, & Howard, 2004). Head resultant acceleration and HIC were measured by the accelerometer located at the dummy head center of gravity as illustrated in Figure 1.

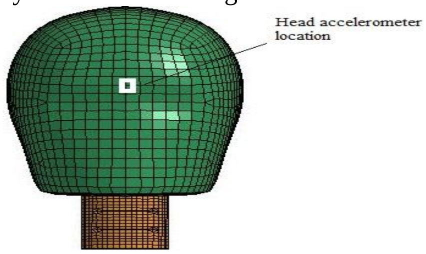

Figure 1 Accelerometer location in the 3YO child dummy FE model head

The CRS was modeled using rigid material model as it is assumed not deform under child weight. The seat and belt CAD model were first drawn and meshed using LS PREPOST. The seat contains 3552 nodes, 3436 quadrilateral and 32 triangular elements. Polypropylene material properties with Belytschko-Tsay shell elements were used for the seat. Fabric material (material type 34 in LS DYNA) with isotropic properties also with Belytschko-Tsay shell element

Table 2 Material properties of the composite bumper beam (T300/5208 Carbon/epoxy) (Naik et al., 2000)

$\rho(Kg/$	E_a $(MP$	E_b $(MP$	E_c $(MP$	PR_b	PR_c	PR_c	G_{ba} $(MP$	G_{bc} $(MP$	G_{ca} $(MP$
1554	15070	13300	13300	0.287	0.287	0.390	4900	4900	4800

The meaning of the variables mentioned in Table 2 is: E_a – young's modulus in a-direction,
E_b- young's modulus in b-direction, E_c- young's modulus in c-direction, PR_{ba}- Poison's ratio in ba direction,PR_{ca} -- Poison's ratio in ca direction, PR_{cb}- Poison's ratio in cb direction,G_{ba}-shear modulus in ba direction, G_{ca}- shear modulus in ca direction, G_{cb}-shear modulus in bc direction

Low density foam was attached to the composite bumper to form a sandwich beam. Addition of foam is expected to improve energy absorption of the composite bumper. Composite beam is considered as face sheet of the sandwich bumper that is stiff enough to resist in plane and bending loads. The sandwich core carries the shear load; it is flexible and therefore able to absorb impact energy by balancing it with strain energy.

The bumper foam was modeled using MAT_LOW_DENSITY_FOAM (material type 54 in LS DYNA) with material properties extracted from Taurus 2012 model sandwich bumper (NCAC, 2015)[8]. These include: mass density of 9.131×10^{-11} Kg/mm^3, elastic modulus of 30 MPa, and the hysteretic unloading and shape factors of 0.01 and 8 respectively. Stress-strain relationship used for the foam material model is as shown in Figure 2.

was applied for five point harness belt. Both the seat and belt was modeled using 2 mm thickness membrane elements. The material properties are presented in Table 1.

Table 1 material properties of child seat and belt (Kapoor, Altenhof, Wang, & Howard, 2006)

Parameters	Child seat	Five point harness
Density (Kg/m^3)	900	911.8
Elastic modulus (GPa)	1.2	6.27
Poisons ratio	0.3	0.3

The FE model of Ford Taurus car was developed by EASi Engineering through the process of reverse engineering for the NHTSA (NCAC, 2015)[8]. The vehicle model was validated against physical crash data by (Marzougui, Kan, & Bedewi, 1996)[9].

Bumper beam design

Steel bumper beam material properties of the vehicle model were substituted with carbon/epoxy composite properties reported in (Naik, Sekher, & Meduri, 2000)[10]. The fiber orientation used was taken to be $[0/60]_s$. MAT_COMPOSITE_DAMAGE (material type 22 in LS DYNA) was applied and material properties of the carbon/epoxy composite are as presented in Table 2.

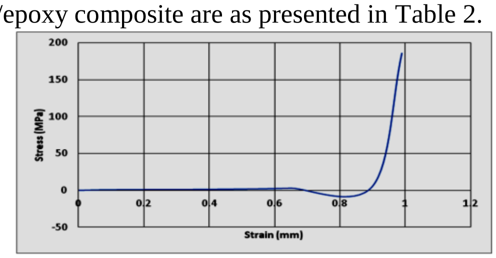

Figure 2 Engineering stress-strain curve of the low density foam used for sandwich bumper

The thickness of the foam was selected to be 100 mm considering limited space between the bumper beam and fascia. The foam was attached to the bumper beam by means of single surface contact as was done for the other parts of the car model. Its dimensions are: 1233 mm by 142 mm by 50 mm modeled using 384 solid elements applying constant stress solid element formulation (Type 2 in LS DYNA) option with reduced integration. The smallest and largest solid element edge length varies from 23.6mm to 24.5mm. Foam orientation was curved to follow the composite bumper beam as shown in Figure 3.

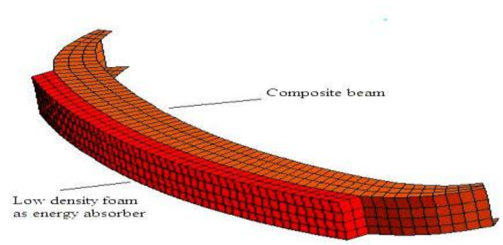

Figure 3 Sandwich bumper beam

Simulation setup

Finite element model of the child dummy, child seat and the vehicle were combined to simulate the crash test. A frontal impact test simulation was conducted at a speed of 48 Km/h (Nahum & Melvin, 2012)[11]. Crash speed was chosen based on Federal Motor Vehicle Safety Standard (FMVSS 208) which specify full frontal impact test to be carried out at 30 mph. The vehicle FE model was modeled with forward facing CRS attached to the vehicle body with rigid body constraint in the rear seating position as shown in Figure 4. Simulation was carried out using LS DYNA solver with 10 hours running time.

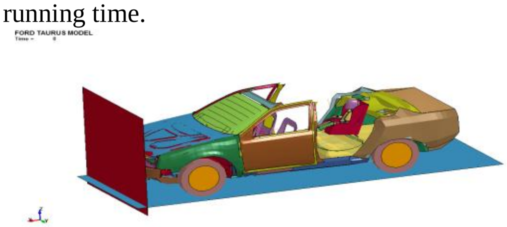

Figure 4 FE model of the child dummy restrained in CRS for frontal crash test

RESULTS AND DISCUSSIONS

Figure 5 presented the energy involved in the crash test simulation. Kinetic energy of the car on the impact was absorbed by the vehicle structures and this is confirmed by decreases in dynamic energy with increase in internal energy. The internal energy was about 93% of the kinetic energy and this indicates that energy balance was fairly good: because the hourglass energy and interfacial energy were only about 7% of the total energy as such they don't have a significant effect on the energy output results. The total energy was constant throughout the impact process.

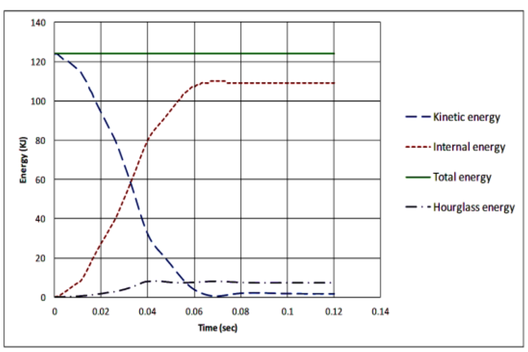

Figure 5 Energy balance of crash with original steel bumper

Crush force is vital for occupant safety and need to be minimized. Figure 6 indicates that the force reduced by 25% with the introduction of sandwich bumper.

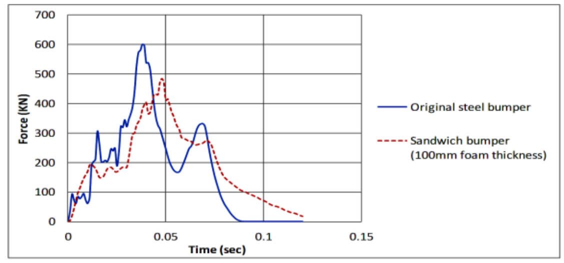

Figure 6 Crush force-time graph of steel and sandwich bumper

Figure 7 presents the deformation versus time history of the sandwich and the steel bumper. It is clear that the sandwich deform more than the steel bumper due to its strain energy absorption characteristics.

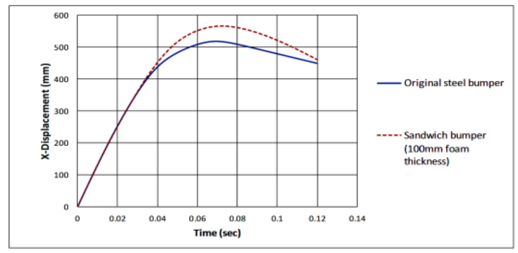

Figure 7 Deflection-time graphs of sandwich and steel bumper

The injuries sustained by the occupant during crash depend on the deceleration of the vehicle which is high due to sudden change in the vehicle velocity.

Injury parameters increase with increasing vehicle deceleration on impact. Figure 8 shows that the vehicle deceleration was high for steel bumper and this is because of high impact forces experienced by the vehicle on impacting rigid wall with steel bumper.

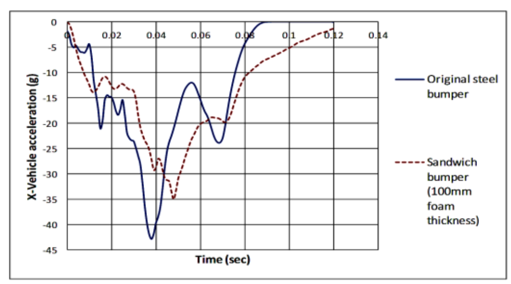

Figure 8 Vehicle deceleration comparisons for sandwich and steel bumper

As the impact forces reduced with application of energy absorbing material (sandwich) the deceleration also decreases and this lead to the lower impact forces to the occupant and of course lower injuries. Sandwich bumper reduces the deceleration by about 19%.

The head injury criteria that is used to predict the severity of injury to child head was also evaluated from 3YO child FE model for frontal impact. Figure 9 shows the HIC of 15 ms window for steel bumper. The peak resultant acceleration was about 100 g at 70 ms, which corresponds with the time of zero kinetic energy as seen in Figure 5. The HIC15 of 816.5 was about 43% higher than recommended values of NHTSA for 3YO child. This fact therefore revealed that the Taurus model with steel bumper beam was not safe for 3YO child at impact speed of 48 Km/h.

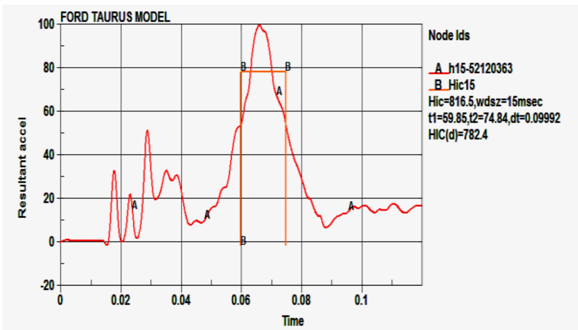

Figure 9 HIC15 of 3YO child for steel bumper

On substituting the steel bumper with sandwich, the severity of injury was reduced drastically as can be seen in Figure 10 where the HIC15 was 447.7, which is about 22% lower than the threshold values. This ensures the child survival on impact. Great reduction in head peak resultant acceleration was also achieved using sandwich bumper on which it was 70 g as compared to steel bumper having 100 g. This is because of the impact force that was absorbed by the sandwich bumper which causes lower HIC values. HIC is a function of head resultant acceleration as presented in equation (1).

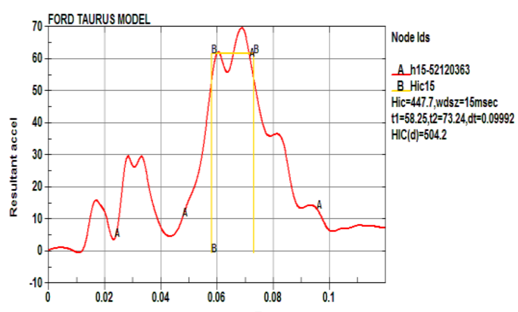

Figure 10 HIC15 of 3YO child for sandwich bumper

Figure 11 shows higher HIC36 values of 850.3 for steel bumper which was about 49% higher than NHTSA recommended value of 570. Significant reduction of HIC36 was also achieved with sandwich bumper, with value that is 5% below the NHTSA recommend limit as presented in Figure 12 and Table 3.

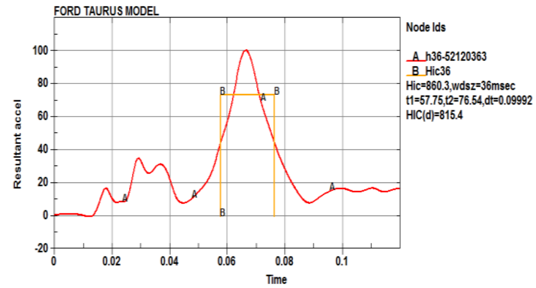

Figure 11 HIC36 of 3YO child for steel bumper

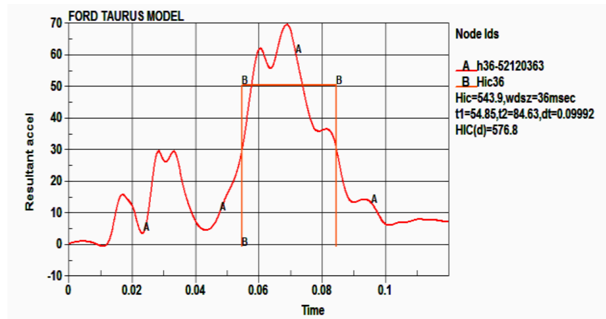

Figure 12 HIC36 of 3YO child for sandwich bumper

Table 3 Comparison of HIC values with NHTSA limits

	HIC15	HIC36
NHTSA Limit	570	570
Steel bumper	816.5	850.3
% of limit	143%	149%
Sandwich bumper	447.7	543.9
% of limit	78%	95%

CONCLUSIONS

This study reveals the ability of sandwich bumper to minimize head injuries sustained by 3YO child in 48 Km/h frontal crash using finite element simulations. The crash analysis results indicate that vehicle deceleration was higher for steel bumper than sandwich bumper which leads to higher HIC values. It was also shown that HIC values were higher than NHTSA limits by more than 40% for steel bumper, while for sandwich bumper, HIC values were drastically reduced below NHTSA regulation limits. This explains the ability of energy absorption crush zone structures to reduce injuries to vehicle occupants.

ACKNOWLEDGEMENT

The authors wish to thank Universiti Putra Malaysia for the facilities and Bayero University Kano, Nigeria for the financial support of the first author. In addition, this work was also supported by Fundamental Research Grant Scheme with Reference Number: FRGS/2/2013/TK01/UPM/01/1, vot 5524355, Ministry of Education (MOE), Malaysia, and was carried out in University Putra Malaysia (UPM). The authors therefore would like to record their thanks to the MOE and UPM for the supports.

REFERENCES

Abbasi, M., Kazemi, R., & Ghafari Nazari, A. (2011). Using a parametric method for investigating automotive crashworthiness. *Int J Automot Eng, 1*(3), 165-172.

Abdel-Nasser, Y. A. (2013). Frontal crash simulation of vehicles against lighting columns using FEM. *Alexandria Engineering Journal, 52*(3), 295-299.

Chen, H., Yang, Y., & Wang, L. (2015). Vehicle front structure energy absorbing optimization in frontal impact. *The Open Mechanical Engineering Journal, 9*(1)

Donga, A. (2011). *Application of sandwich beam in automobile front bumper for frontal crash analysis* (Master of Science).

Elmarakbi, A Krznaric, V Sennah, K Altenhof, W Chapman, M. (2013). Crashworthiness of vehicle-to-pole collisions using a hybrid III three-year-old child dummy. *International Journal of Vehicle Systems Modelling and Testing, 8*(1), 1-37.

Kapoor, T., Altenhof, W., Wang, Q., & Howard, A. (2006). Injury potential of a three-year-old hybrid III dummy in forward and rearward facing positions under CMVSS 208 testing conditions. *Accident Analysis and Prevention, 38*, 786-800. doi:10.1016/j.aap.2006.02.005

Marzougui, D., Kan, C., & Bedewi, N. E. (1996). Development and validation of an NCAP simulation using LS-DYNA3D. *FHWA/NHTSA National Crash Analysis Center, the George Washington University, Virginia Camnpus, Ashburn, Virginia, USA,*

Marzougui, D., Samaha, R. R., & Cing-Dao, C. C. K. (2012). *Extended validation of the finite element model for the 2001 ford taurus passenger sedan.* (No. NCAC 2012-W-004). Virginia: George Washington University.

Nahum, A. M., & Melvin, J. W. (2012). *Accidental injury: Biomechanics and prevention* Springer Science & Business Media.

Naik, N., Sekher, Y. C., & Meduri, S. (2000). Damage in woven-fabric composites subjected to low-velocity impact. *Composites Science and Technology, 60*(5), 731-744.

1. NCAC. (2015). Applications: Finite element model archive. Retrieved from http://www.ncac.gwu.edu/vml/models.html

NHTSA (2013). *Traffic Safety Facts*, Washington, DC.

Salwani, M. S., Sahari, B., Ali, A., & Nuraini, A. (2014). The effect of automotive side member filling on car frontal impact performance. *J Mech Eng Sci (JMES), 6*, 873-880.

Turchi, R., Altenhof, W., Kapoor, T., & Howard, A. (2004). An investigation into the head and neck injury potential of three-year-old children in forward and rearward facing child safety seats. *International Journal of Crashworthiness, 9*(4), 419-431. doi:10.1533/ijcr.2004.0300

Varadappa, S., Shyo, S., & Mani, A. (1993). *Development of a passenger vehicle finite element model.* (No. Final Report DOT HS 808 145). Washington DC: Department of Transportation.