



OPTIMIZATION OF SANDWICH BUMPER FOR THREE-YEAR-OLD CHILD NECK INJURY PREVENTION

I. A. Rafukka

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

*Corresponding author's email address: ibrahimrafukka@yahoo.com

ARTICLE INFORMATION ABSTRACT

Submitted 26 December, 2023
Revised 23 February, 2024
Accepted 25 February, 2024

Keywords:

crash dummy
frontal crash
neck moment
sandwich bumper

Impact energy absorption vehicle components play an important role in reducing severity of injury in vehicle crashes. Children being delicate are most vulnerable in vehicular collisions. The neck is the major body region after head that experiences a high moment when deceleration is transmitted to it. Bumper is one of the vehicle's frontal energy absorption components that reduce deceleration to the occupants. Sandwich bumper is an energy absorption component that could substitute a steel bumper. The geometry of the sandwich bumper affects its energy absorption capability on impact. This work applies an optimization technique to determine the sandwich bumper thicknesses that provides lower neck moments to child on impact at 48km/h in LS DYNA code. Finite element (FE) simulations using crash dummy models being the simplest method to reproduce accident was employed. The optimization results found the minimum neck moment of 25.4 Nm occurred at foam thickness (t_f) of 68.76 mm and bumper thickness (t_b) of 2 mm. The study provides designers with quantitative information on how the bumper performance affects child injury in vehicular frontal crashes. This will lead to design of safer vehicles for the children population.

1.0 Introduction

Road crashes have become a major cause of death in the last two decades in developing countries. Heads and necks are the body parts that experienced high acceleration on impact. Children are restrained in child seat to reduce the effect of decelerations. Light-weight materials are being explored to reduce fuel consumption of vehicles thereby minimizing the deleterious effect on the environment. Research recently focused on substituting steel vehicle frontal components with energy absorbing crashworthy materials to enhance crashworthiness and reduce occupant injuries (Navale et al., 2023). In addition to vehicle weight reduction, light-weight materials also provide occupants safety.

Head is known to be a major cause of fatality in children (Li et al., 2013). Head exerts inertial loads which make the neck experience flexion and extension. Neck loading on impact can also cause serious injuries. Neck response is necessary in assessing the safety performance of child seats. Head trajectory and loading conditions are determined by neck response on impact (Meijer et al., 2010). For child occupants, neck response governs head kinematics on head contact with the vehicle interior in a crash. Neck moment and forces must not exceed the threshold set by Federal Motor Vehicle Safety Standards (FMVSS) in the certification for the vehicle to be safe for child occupant. Designing a bumper with energy absorbing material is considered a suitable way of reducing injuries to occupants of all ages. Adult passengers have always been the target for the design in which adult crash dummies are used to evaluate the performance of such front components in vehicle crash (Salwani et al., 2014). Child crash

dummy FE models were also used in assessing the effect of road side poles on the injury of Three Year Old (3YO) children (Elmarakbi et al., 2013). Effect of sandwich bumper on occupant injury in vehicle crash has been studied by Donga (2011) and Rafukka et al. (2017). Sandwich bumper absorbs energy on crash and reduces decelerations depending on the geometry and thickness of the face sheet. The aim of this work is to use optimization to determine the sandwich bumper geometry that provides lower neck injuries to 3YO child in frontal impact using FE simulation in LS DYNA code.

2. Materials and Methods

2.1 Finite element modelling

Car FE model that is publically available for research purposes on the National Crash Analysis Centre (NCAC) website (National Crash Analysis Centre, 2015) was used to simulate a 48km/h crash test. The speed was chosen based on Federal Motor Vehicle Safety Standards (FMVSS 208) which requires full frontal impact test to be carried out at 30 mph (48 km/h). The car model has been validated against physical crash data by Marzougui et al., (1997). It is used in this work because of its low computation time. Vehicles subjected to frontal impact usually exhibit large deformation on the front-end, whereas the rear end hardly undergoes deformations. Taurus model front-end structures were developed with fine mesh, since it was meant for frontal impact assessment as shown in Figure 1.

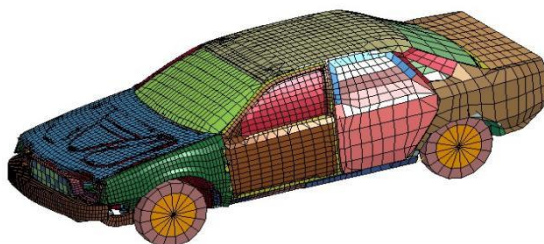


Figure 1: Ford Taurus finite element model

Validated 3YO child dummy model scaled from 6YO HIII dummy available on Livermore Software Technology Corporation (LSTC) website was used in this work. The dummy was positioned in the rear seat of the car model restrained in the Child Restraint Seat (CRS) FE model as shown in Figure 2.

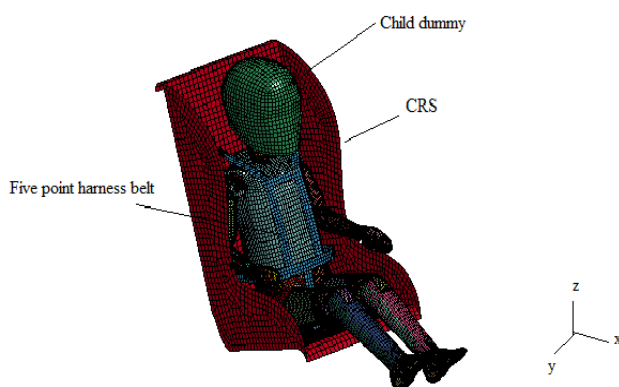


Figure 2: Child dummy model in CRS

The child model is equipped with an upper neck load cell located below the occipital that measures neck moment and forces. Moment about occipital condyle (M_{oc}), is reacted by shear force F_x , as shown in Figure 3:

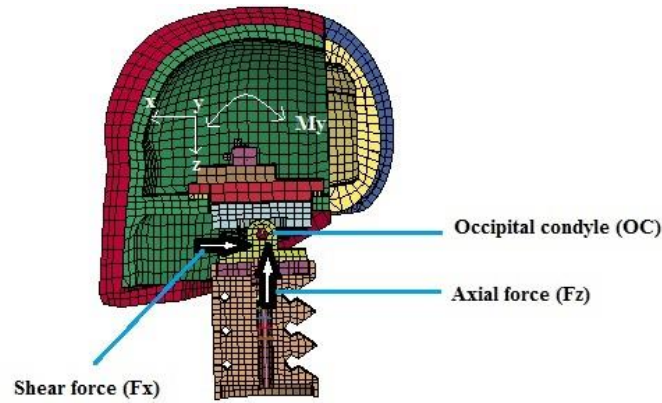


Figure 3: Free body diagram of moment and force acting at the dummy upper neck

Thus according to 6YO HIII manual, Moment about occipital condyle is expressed by equation [1] (Mahadevaiah et al., , 2013):

$$M_{OC} = M_y - 0.01778F_x \quad (1)$$

M_y = Neck moment in y-direction; tendency of head and neck to bend towards chest (flexion) or towards back (extension).

2.2 Bumper beam modelling

The steel material of the beam of the car was substituted by a carbon/epoxy composite with material properties as presented in Table I. The fibre orientation used was taken to be $[0/60]_s$. MAT_COMPOSITE DAMAGE (material type 22 in LS DYNA) was employed.

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

ρ (Kg/m ³)	E_a (MPa)	E_b (MPa)	E_c (MPa)	PR_{ba}	PR_{ca}	PR_{cb}	G_{ba} (MPa)	G_{bc} (MPa)	G_{ca} (MPa)
1554	15070	13300	13300	0.287	0.287	0.390	4900	4900	4800

The meaning of the variables mentioned in Table I 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.

The existing bumper of the Ford Taurus model was redesigned by introducing foam attached to the front composite bumper beam which was made to be the face sheet of the sandwich beam that is stiff enough to resist plane and bending loads. The core was made from a foam material that carries the shear load: it is flexible and therefore able to absorb impact energy by balancing it with strain energy. The foam was modelled using MAT_LOW_DENSITY_FOAM (material type 54 in LS DYNA). The Mass density and elastic modulus were $9.131 \times 10^{-11} \text{ Kg/mm}^3$ and 30 MPa respectively. The hysteretic unloading and shape factors were taken to be 0.01 and 8 respectively. These material properties were extracted from Taurus (2012) model sandwich bumper (National Crash Analysis Centre, 2015). The stress-strain relationship coupled to the material model is as shown in Figure 4.

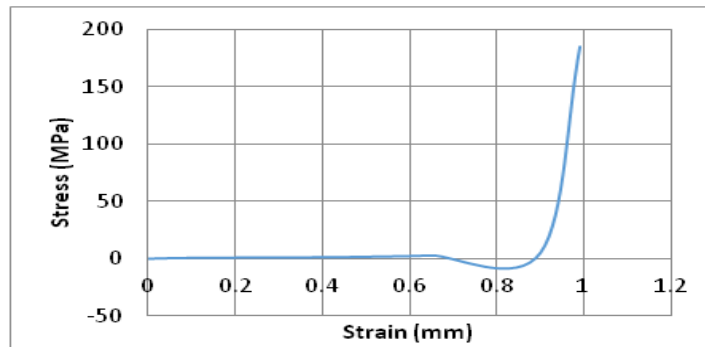


Figure 4: Engineering stress-strain relationship of the low density foam used for sandwich bumper (National Crash Analysis Centre, 2015)

The maximum thickness of the foam was taken to be 100 mm considering the limited space between the bumper beam and the facia. The foam was attached to the bumper beam using single surface contact as was done for the other parts of the car model. It was modelled with dimensions 1233 mm by 142 mm by 50 mm to cover the contact area of the bumper beam with a rigid barrier. The orientation of the foam was curved to follow the composite beam as shown in Figure 5. The foam was discretized using 384 solid elements which were modelled with 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.

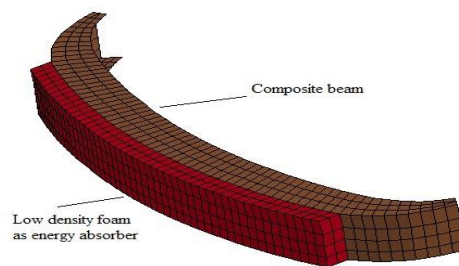


Figure 5: Sandwich bumper beam

2.3 Simulation setup

Crash simulation was conducted in LS DYNA at a speed of 48km/h chosen based on Federal Motor Vehicle Safety Standard (FMVSS 208) which requires a full frontal impact test to be carried out at 48 km/h. The calculation was carried out using LS DYNA solver with a running time of 10 hours. The simulation was carried out for 140ms time duration to allow for complete dummy response. The time step scaling factor was reduced from the default of 0.9 to 0.7 in *CONTROL_TIME_STEP card. Neck moment – time history was tabulated from the simulation for the various thicknesses of composite bumper beam and sandwich foam for optimisation.

Bumper design parameters are functions of shape, geometry, size and material properties. This study however, considers thickness as a design variable because other factors such as shape and geometry require vehicle model revisions. To determine the optimal safety design of the bumper, a set of designs was sampled from the sandwich bumper beam that gave better injury values. The composite bumper thickness (t_b) and foam thickness (t_f) were used as design variables and the injury parameter neck moment (NM) was considered as objective parameter. Objective optimization technique was applied to determine the t_b and t_f of the bumper that gives the lowest values of the injury parameter.

A full factorial design was applied using two variables; the foam thickness t_f varying for five levels and composite bumper thickness t_b varying for six steps making a total of 30 experiments. Optimization was carried out using MATLAB R2015a. Response models were developed and the polynomial with highest R^2 value and lowest RMSE was selected for the optimization.

3. Results and Discussion

3.1 Bumper Optimization

The arrangement of the optimization levels and simulation results obtained from the design samples are shown in Table 2.

Table 2: Design points and crash responses for sandwich bumper

Foam thickness (mm) (t_f)	Composite bumper thickness (mm) (t_b)	Neck Moment (Nm) (NM)
0	1	100.8
	1.2	96
	1.4	95
	1.6	84
	1.8	89.2
	2	81.5
25	1	48.8
	1.2	49.6
	1.4	55.7
	1.6	56.3
	1.8	48.6
	2	43.6
50	1	20
	1.2	18.8
	1.4	26.4
	1.6	26.8
	1.8	20.5
	2	26.1
75	1	33.6
	1.2	35.8
	1.4	34.1
	1.6	25.7
	1.8	25.7
	2	29.5
100	1	30
	1.2	37.2
	1.4	33.4
	1.6	27.5
	1.8	26.9
	2	28.1

3.1.1 Response Surface Model for Neck Moment (NM)

The response surface model parameters for the neck moment are shown in Table 3.

Table 3: Response surface parameters for neck moment

Response surface model	R ²	R ² -adj	RMSE
1 st	0.6368	0.6098	15.95
2 nd	0.9432	0.9314	6.69
3 rd	0.9636	0.9497	5.73

Thus, the response model polynomial function of cubic form having highest R² value and lowest RMSE as shown in Table 3 was chosen as the objective equation [2]

$$\begin{aligned}
 NM(t_f, t_b) = & 90.51 - 3.255t_f + 20.98 t_b + 0.03832 t_f^2 \\
 & + 0.3833t_f t_b - 12.67 t_b^2 - 0.0001129 t_f^3 \\
 & - 0.005433 t_f^2 t_b + 0.07857 t_f t_b^2
 \end{aligned} \quad [2]$$

Optimization of the neck moment was formulated as follows:-

Minimize $NM(t_f, t_b)$

$$\left\{ \begin{array}{l} \text{s.t. } 0 \leq t_f \leq 100 \\ 1 \leq t_b \leq 2 \end{array} \right.$$

The response surface is as shown in Figure 6:

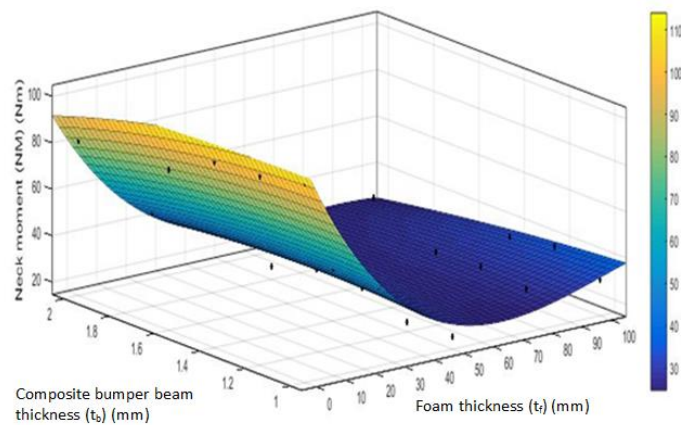


Figure 6: Response surface for neck moment

The composite bumper thickness seemed to have no effect on the neck moment as seen in Figure 6. Addition of foam to the composite beam decreases the neck moment experienced by the child's neck. A huge neck moment reduction can be noticed from about 90 Nm for 0 mm to about 25.4 Nm for 68.76 mm. Further increase in foam thickness to 100mm increases the neck moment to 38Nm which is still below the recommended limits of 68 Nm (Eppinger et al., 1999).

The optimization results found the minimum neck moment of 25.4 Nm occurs at t_f of 68.76 mm and t_b of 2 mm. A simulation was carried out using these values to assess the objective equation [2], and 21 Nm moment was obtained which is 16% less than the value estimated by the equation.

3.2 Parametric Analysis

To better explain the effect of the composite bumper and foam thickness on the injury level of 3YO child, an analysis was carried out to determine how bumper beam and foam thickness affect neck moment.

3.2.1 Effect of Composite Bumper Beam and Foam Thickness on Neck Moment

Figure 7 shows that, sandwich bumper beam drastically reduces high neck injuries. A Sandwich beam with about 50 mm foam thickness reduces the neck moment to below 30 Nm. Though there is little increase in the moment with foam thickness above 60 mm due to decrease in energy absorption of thick foam at densification stage, the moments were all low and within an acceptable range. Neck moments for all foam and composite bumper thickness were below the NHTSA specified limits of 68Nm for three-year-olds.

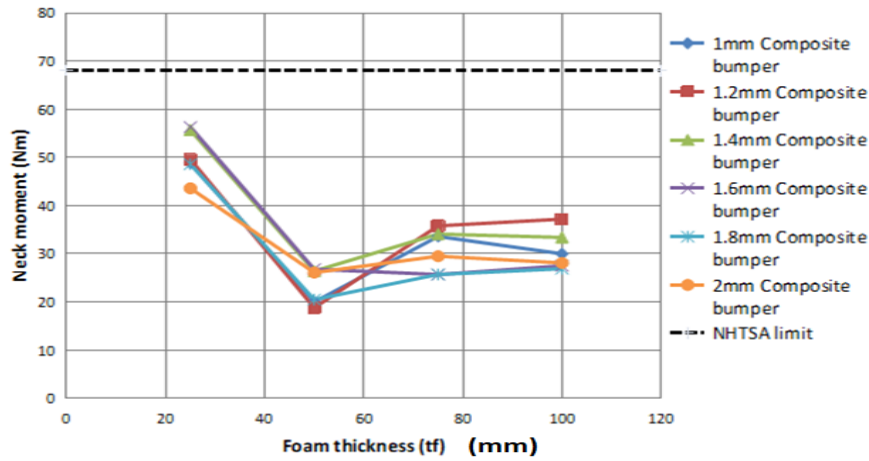


Figure 7: Effect of foam thickness on neck moment of 3YO child occupant for various composite bumper thicknesses

The injuries sustained by child occupant during crash depend on the magnitude of peak crushing force which determines vehicle deceleration transmitted to the occupant.

3.2.2 Effect of Foam Thickness on Crushing Force

As a basis for explaining the capability of sandwich bumper in reducing the crushing force on impact, a 1 mm composite bumper thickness (t_b) was selected, because it is considered to have the low neck moment. Figure 8 shows the variation of crush force with time for foam of different thicknesses. It demonstrates that energy absorption (related to area under the graph) of foam leads to a decrease in crushing force. As an example, taking 50 mm of foam to a composite beam reduces the peak force by 12%, and this lowers the severe injury condition to the child occupant as confirmed by the NM values shown in Figure 7. The first peak in the force-time curve was a result of first crushing contact of the foam part of the bumper with rigid wall and this is the reason for the noisy signals appearing on part of the curve just before the end of first peak as seen in Figure 8.

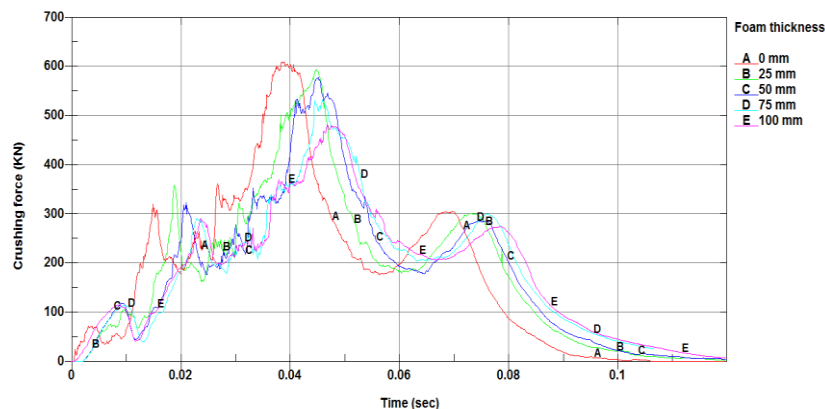


Figure 8: Crushing force – time histories of 1mm composite bumper for various foam thicknesses

4.0 Conclusions

This work investigates the effect of sandwich bumper thickness on child occupant injuries. 3YO child dummy was used in crash simulations using the car FE model in LS DYNA code. Neck moment was evaluated for various t_b and t_f . Objective functions were determined using curve fitting for NM which were in turn used in the optimization. The optimization was successful in determining the t_b and t_f that minimizes injuries potential to child occupants. Optimum design of sandwich bumper that yield lower neck moment of 25.4 Nm was 68.76 t_f and 2 mm t_b . Optimized sandwich bumper is useful in improving child occupant's safety in addition to CRS.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgement

The authors would like to acknowledge Bayero University, Kano, Nigeria for the supports in works related to this paper.

References

- Donga, A. 2011. Application of Sandwich Beam in Automobile Front Bumper for Frontal Crash Analysis. Unpublished Doctoral Dissertation, Wichita State University, College of Engineering, Department of Mechanical Engineering
- Elmarakbi, A., Krznicaric, V., Sennah, K., Altenhof, W. and 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.
- Eppinger, RH., Sun, E., Bandak, F., Haffner, M., Khaewpong, N., Maltese, M., Kuppa., S., Nguyen, T., Takhounts. E., Tannous, R., Zhang, A. and Saul, R. 1999. Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems - II (Docket No. NHTSA-1999-6407-0005). National Highway Traffic Safety Administration, Washington, D.C.
- Li, Z., Zhang, J. and Hu, J. 2013. Surface material effects on fall-induced paediatric head injuries: a combined approach of testing, modelling and optimisation. *International Journal of Crashworthiness*, 18(January 2015): 371–384. <http://doi.org/10.1080/13588265.2013.801291>
- Mahadevaiah, U., Burger., M. and Maurath., C. 2013. LSTC Hybrid III 6 year old Finite Element Model Documentation. Livermore Software Technology Corporation, United States.
- Marzougui, D., Kan, CD. and Bedewi, NE. 1997. Development and validation of an NCAP simulation using LS-DYNA3D, *National Crash Analysis Center Paper*, 12(3): 23–29.
- Meijer, R., Wisgerhof, R., Wismans, J. and Been, B. 2010. Scaling head-neck response data and derivation of 5th percentile female side-impact dummy head-neck response requirements in NBDL test conditions. *International Journal of Crashworthiness*, 15(1): 115–115. <http://doi.org/10.1080/13588261003611903>
- Naik, NK., Chandra Sekher, Y. and Meduri, S. 2000. Damage in woven-fabric composites subjected to low-velocity impact. *Composites Science and Technology*, 60(5):731–744
- Navale, AB., Chippa, SP., Chougule, DA. and Raut, PM. 2021. Crashworthiness aspects of electric vehicle design, *International Journal of Crashworthiness*, 26(4): 368-387.
- National Crash Analysis Centre .2015. Application: Finite element model archive. Retrieved from <http://www.ncac.gwu.edu/vml/models.html>.
- Rafukka, IA., Sahari, BB., Nuraini, AA. and Manohar, A. 2017. Influence of Vehicle Sandwich Bumper Beam on Child Vehicle Occupant Head Injuries in Frontal Crashes. *Science. International Journal Lahore*, 29(1): 109–113.
- Salwani, MS., Sahari, BB., Ali, A. and Nuraini, AA. 2014. The Effect of Automotive Side Member Filling on Car Frontal Impact Performance. *Journal of Mechanical Engineering and Sciences*, 6: 873–880.