



Effect of Crush Zone Components Materials on Injury of Child Passenger in Vehicle Frontal Crashes

Rafukka, I. A.

Department of Mechanical Engineering,
Bayero University, Kano,
Kano State

ABSTRACT

There is concern about child injury severity in vehicle crashes. Automotive engineers devise ways to reduce the injury levels to child occupant. Energy absorption crush zone components are known to reduce injuries in frontal crash. This study presents the effects of energy absorption of bumper and side member to Head Injury Criteria (HIC), Chest Severity Index (CSI) and Neck Moment (NM) of Three Year Old (3YO) child in finite element (FE) simulations. Crash simulation was conducted at 48km/h in accordance to Federal Motor Vehicle Safety Standards (FMVSS) using restrained three year old child FE model seated in the rear seat of Ford Taurus FE model in LS DYNA software with composite bumper and with traditional steel bumper of the car and injury values were recorded. Another crash test was carried out using steel side member and with aluminum side member. Composite bumper greatly reduces HIC36, CSI and NM by 24.4 %, 12% and 19% respectively when compared to steel bumper. Aluminum side member showed little effect on HIC36 but it minimizes CSI and NM by 14% and 8.2% lower than values obtained using steel side member. This is in addition to weight reduction imparted by the composite bumper and aluminum side member compared to steel. Crashworthy energy absorption bumper and side member could help in minimizing child fatalities while reducing vehicle weight and fuel consumption.

ARTICLE INFO

Article History

Received: September, 2023

Received in revised form: October, 2023

Accepted: February, 2024

Published online: June, 2024

KEYWORDS

Crash Dummy, Frontal Crash, Energy Absorption, Side Member

INTRODUCTION

Car crash has been killing vehicle occupant every day especially in the low-and medium-income countries. Designing vehicles that reduce injuries during crash will assist in minimizing road crash fatalities. Crush zone components such as bumper and side members have been studied with particular attention to the effect of materials and geometry on the energy absorption (Molla & Abuye, 2020; Yeshanew et al., 2023).

Child restraint system has been a major passive safety system for children. Using crush zone material that absorbs energy to save children is another way of reducing severity of injury on crash. Chassis side member and

bumper are two components that absorb impact energy by deforming in frontal collision. Studies are centered on optimizing the energy absorption capability of different materials (Salwani, Sahari, Ali, & Nuraini, 2014). Very few studies investigated the effect of energy absorption to injury out comes especially to children during frontal car crash, which is one of the most common impact situations. The front rails represent the main deformable components designed to dissipate the kinetic energy of the vehicle in a stable and well-controlled manner (Ahmad, 2009).

Steel is a traditional material for side member construction. Yeshanew et al., (2023) found that, carbon polyamide bumper enhanced

Corresponding author: Rafukka, I. A.

✉ bakarihenny341@gmail.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University.

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved



the crashworthiness of the existing automobile bumper and minimize crash injuries and weight. The study did not relate the crashworthiness characteristics of the occupants to injury outcome using crash dummy. In frontal crash, energy is transferred first to the bumper and to the chassis via side member before being transferred to the passenger compartment (Salwani, Sahari, Ali, & Nuraini, 2014). Numerical simulations are used in this work to determine the potential of composite and aluminium as bumper and side member materials in reducing child occupant injuries in frontal crashes when compared to traditional steel components.

THEORY

Injury in the head can cause brain concussion or affect some sensory organs (Ji, 2015). HIC is the main criteria used in assessing the head injury risk on impact. It is the standardized maximum integral of head acceleration measured at the centre of gravity within a specified time windows. It is calculated based on the equation (Bois, Chou, Fileta, King, & Mahmood, 2004; Henn, 1998):

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

Where t_1 and t_2 are the initial and final times of intervals within which HIC reaches a maximum value (Liu et al., 2016). Acceleration is measured in unit of acceleration of gravity (g) and time in seconds.

The resultant acceleration of the dummy model is measured by accelerometer located at the head centre of gravity which provides the components of acceleration in x , y , and z directions and the resultant acceleration is evaluated as:

$$a_{result.} = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (2)$$

The maximum time interval can be limited to 36ms or 15ms which yields HIC_{36} and HIC_{15} respectively.

Chest severity index gives the degree of chest injuries. It is determined same way as HIC, only that the accelerometer used to measure chest resultant acceleration is located in the dummy spine. This parameter though can be determined using finite element software such as LS-DYNA, it is not being considered in current certification standards.

It is important to note that, N_{ij} is not currently being used in the NHTSA specifications for three year old child dummy, instead, the peak values of neck moment and forces are used

The moment about occipital condyle, M_{yc} is given by:

$$M_{yc} = M_y - (D \cdot F_x) \quad (3)$$

Where, M_{yc} = Total moment about occipital condyle in y-direction

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

D = Distance between the load cell axis and the condyle axis

F_x = Neck force in x-direction

It is important to note that, N_{ij} is not currently being used in the NHTSA specifications for three year olds child dummy, instead, the peak values of neck moment and forces are used.

Finite element modelling

Ford Taurus vehicle finite element model publicly available for research purposes in National Crash Analysis Centre (NCAC) website (NCAC, 2015) was used. This model has been validated against physical crash test data by Marzougui et al. (1997). Taurus model front end structures were meshed with fine mesh because it is used for frontal impact assessment. The rear portion was meshed with coarse elements so as

Corresponding author: Rafukka, I. A.

✉ bakarihenny341@gmail.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University.

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved

to reduce computation time without affecting the simulation results quality.

Most parts of the vehicle were modelled mainly using shell elements of quadrilateral and triangular sections and with piecewise linear plasticity material model. The parts were joined using rigid body and spot-weld constraints.

Hybrid III 6 year old Finite Element Model Version: LST0.104.BETA, available on LSTC website, which is currently the latest child model, was selected as the baseline model in this study. The dummy was scaled to 3YO child anthropometry. It was developed by LSTC in cooperation with NCAC and made available to LS-DYNA users. The model was validated based

FORD TAURUS MODEL
 Time = 0

on the certification tests contained in the Code of Federal Regulations, Title 49, Part 572, Sub-part N. contains 199,102 nodes, 127,154 solid elements, 45,032 shell elements and 142 beam elements (LSTC, 2013). LS-DYNA specific "History" beam elements and nodes are positioned in some specific locations of the body in order to provide value of response required for the extraction of occupant injury criteria.

The vehicle FE model was modelled with forward facing CRS attached to the vehicle body with *CONSTRAINT RIGID BODIES OPTION, in the rear seating position. Child dummy was positioned on the CRS restrained with belt as shown in Figure 1.

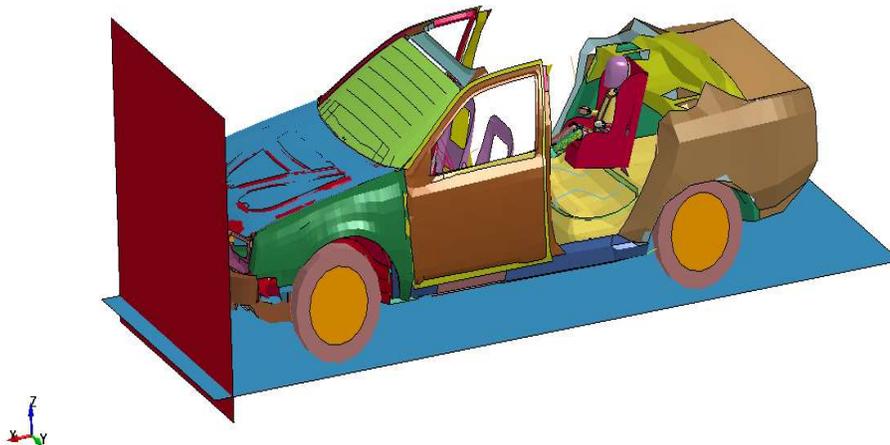


Figure 1 Child FE model restrained in CRS involved in frontal impact test in car FE model

Carbon/epoxy composite with material properties as presented in Table 1 was used. The fibre orientation used was taken to be $[0/60]_s$. MAT_COMPOSITE DAMAGE (material

type 22 in LS DYNA) was employed. The material properties of the Aluminium used for side member is shown in Table 2.

Table 1: Material properties of the composite bumper beam (T300/5208 carbon/epoxy) (Naik et al., 2000)

$\rho(Kg/m^3)$	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

Corresponding author: Rafukka, I. A.

bakarihenny341@gmail.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University.

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved



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.

Table 2 Mechanical Properties of AA 6060 T4

Material	E (N/mm ²)	v	ρ (kg/m ³)	σ _y (N/mm ²)
AA6060	66820	0.33	2700	175

E-Elastic modulus, v-Poisson’s ratio, ρ-Density, σ_y-Yield stress

Simulation setup

A frontal impact test was conducted at a speed of 48 km/h in accordance with the current speed limit on Nigerian highways of 100 km/h. This impact speed is also currently applied in full width frontal impact in Canada, Japan and Australia regulations (Crandall, Myers, & Meaney, 2012). The speed was also chosen based on FMVSS 208 which requires full frontal impact test to be carried out at 30 mph (48 km/h). The frontal impact test was simulated as shown in Figure 1.

The simulation was carried out for 140ms time duration. The control options are set according to 6YO HIII dummy manual. The time step scaling factor was reduced from default of 0.9 to 0.7 in *CONTROL_TIME_STEP card. This is because instabilities occurred using 0.9 scaling factor which led to the termination of the simulation prematurely. The total simulation time was 10 hrs. The injury parameters were evaluated from the dummy FE model for steel and for composite and aluminium for side member and bumper respectively.

RESULTS AND DISCUSSIONS

Injury Evaluation for Bumper Beam

The criterion used in assessing safety performance of vehicles is HIC, CSI and NM. These parameters must be kept within specified values that are acceptable for FMVS. Injury severity need to be minimized in designing crush zone with material that absorbs kinetic energy of the vehicle and reduce the deceleration transmitted to vehicle. Figure 2 shows acceleration time history of dummy head and HIC36 values as compared for steel and composite bumper. It can be noticed that the resultant acceleration curves have similar trend and peak values for steel bumper occur earlier than composite bumper. This is attributable to the fact that composite bumper takes little time to deform so as to get the peak acceleration, whereas steel bumper deform less and hence peak acceleration is reached earlier. Peak acceleration of steel bumper is higher than composite bumper which indicate higher HIC values. CSI plots also have same trend with peak resultant acceleration of steel bumper higher than composite member as shown in Figure 3. Neck moment plot with respect to time shown in Figure 4 indicates the time history of the dummy neck flexion during impact. Steel bumper imposes higher moment values than composite bumper. Negative sign of Nm is an indication of flexion moment as a result of the deceleration of the vehicle.

Corresponding author: Rafukka, I. A.

✉ bakarihenny341@gmail.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University.

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved

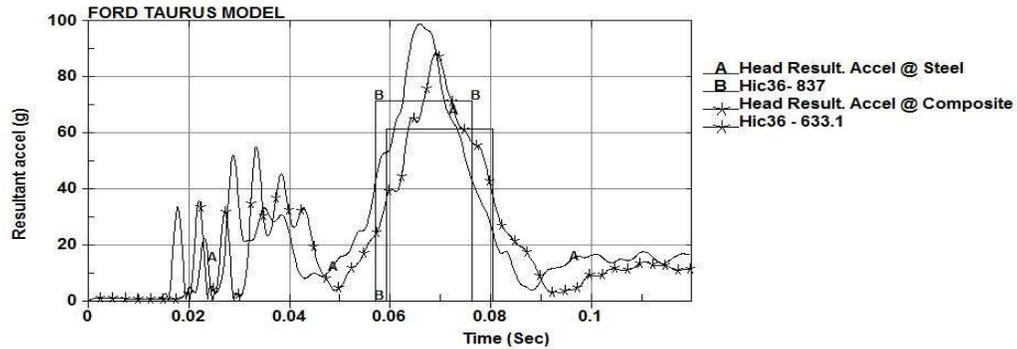


Figure 2 HIC36 for steel and composite bumper

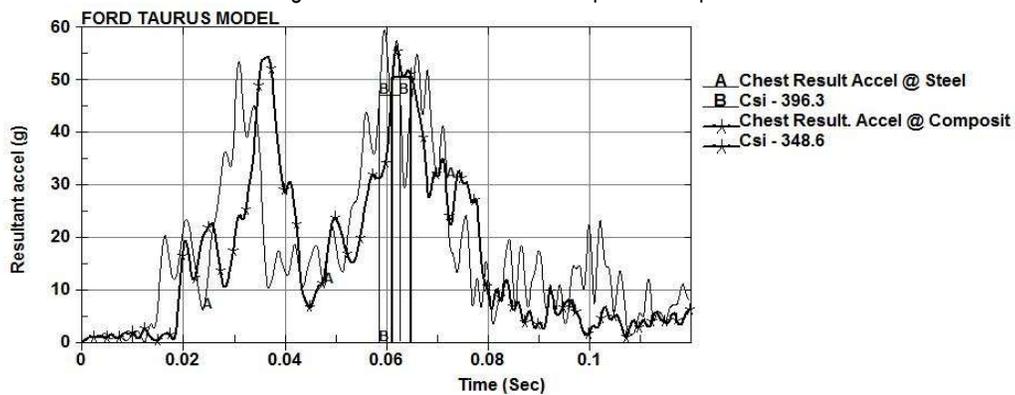


Figure 3 CSI for steel and composite bumper

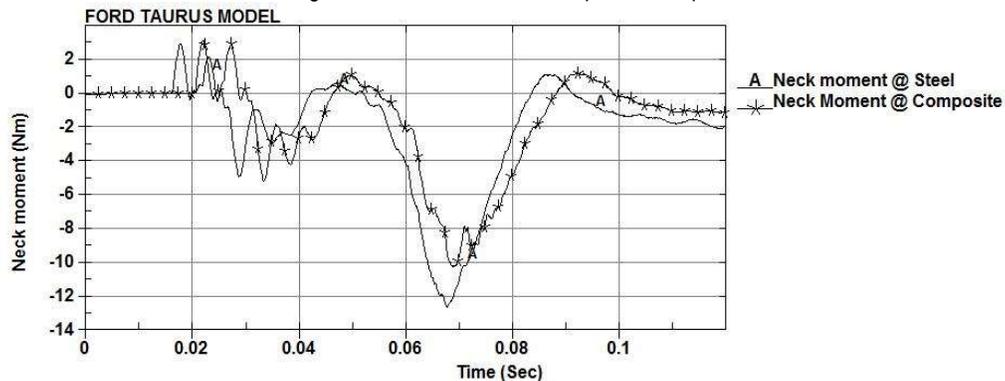


Figure 4 Neck moment for steel and composite bumper

Table 3 compares HIC and CSI and peak value of NM. For all the parameters compared, child dummy experienced lower injuries when bumper is produced with composite than steel. Composite bumper reduces about 25% of the HIC than steel which indicates

protection against head injuries which is the major cause of child fatalities in crash. CSI and NM were also minimized by composite bumper by 12% and 19% respectively for frontal impact. Steel bumper however increase the chances of high injury to 3YO child occupant

Corresponding author: Rafukka, I. A.

bakarihenny341@gmail.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University.

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved

Table 3 Comparison of injury values for steel and composite bumper.

Injury Parameters			3YO injury values using Steel Bumper	3YO injury values using Composite Bumper	% difference
Head Injury Criteria (HIC36)			837	633.1	24.4
Chest Severity Index (CSI)			396.3	348.6	12
Neck Moment (Nm)			-12.6	-10.21	19

Injury Evaluation for Side Member

HIC and CSI are shown in Figure 5 and 6. The curves show similar trend for steel and aluminium side member with peak values approximately same time. However peak acceleration of dummy with steel is higher for Hic and CSI than aluminium member which is an indication of low energy absorption for steel, thus

transmitting high acceleration. Dummy neck sustains high flexion moment for steel member in Figure 7. Peak values of the three parameters happens around 0.06 sec to 0.07 second in the simulation. This is evidenced in the dummy response in which maximum head flexion occur within this period.

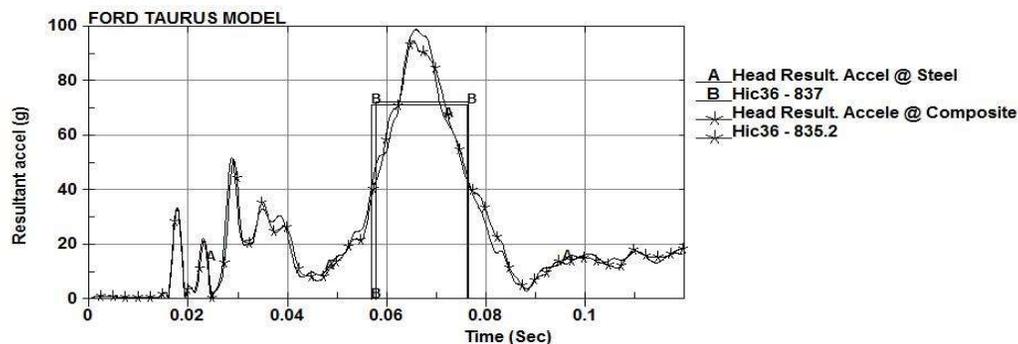


Figure 5 HIC36 for steel and composite side member

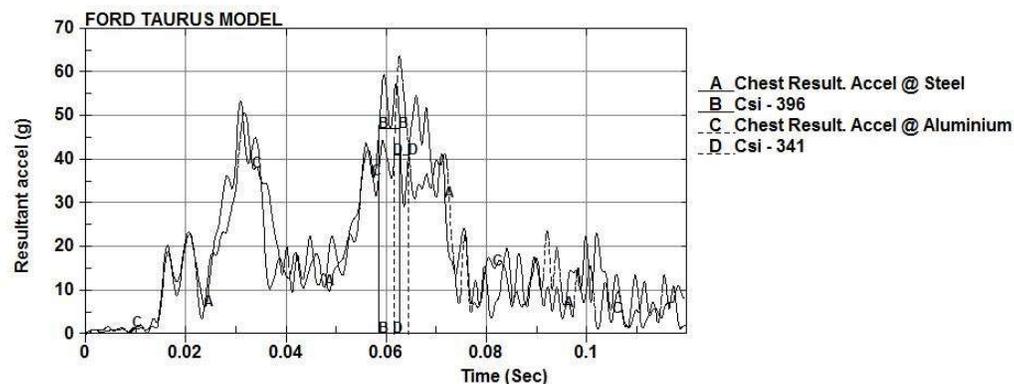


Figure 6 CSI for steel and Aluminium side member

Corresponding author: Rafukka, I. A.

bakarihenny341@gmail.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University.

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved

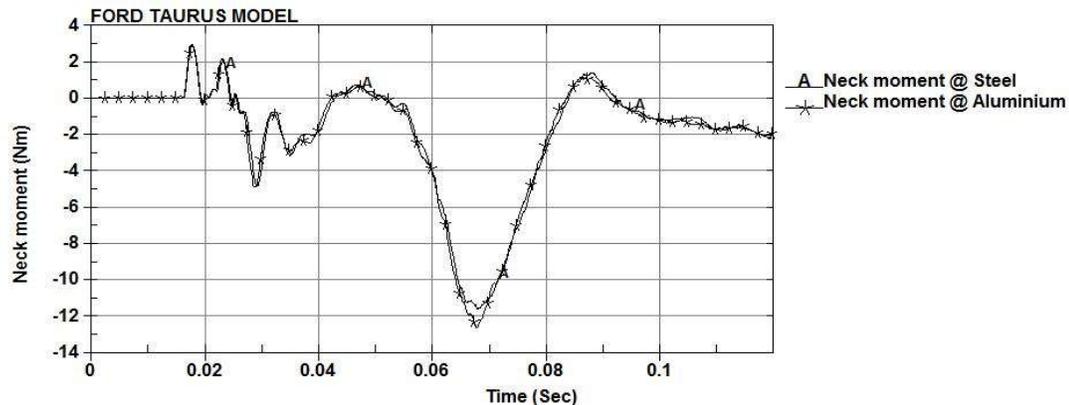


Figure 7 CSI for steel and composite side member

HIC36 values show little difference of 0.17% for steel and aluminium side member as shown in Table 4. Reduction in injury values are indicated in CSI and NM for aluminium member. The weight of composite bumper was found to be

392% lower than steel bumper while the aluminium side member is 189% lower than existing steel bumper. Reduction in vehicle weight means low energy consumption and fuel economy.

Table 4 Comparison injury values of steel and aluminium side member

Injury Parameters	3YO injury values using Steel Member	3YO injury values using Aluminium Side Member	% difference
Head Injury Criteria (HIC36)	837	835.6	0.17
Chest Severity Index (CSI)	396.3	341	14
Neck Moment (Nm)	-12.6	-11.57	8.2

CONCLUSION

In this work, the potential of composite bumper and aluminium side member in reducing head, neck and chest injuries in vehicle frontal crash has been presented for 3YO child. Results obtained showed slight reduction in HIC36 while CSI and NM were significantly minimized by the composite bumper and aluminium side member when compared to traditional steel components. The study further revealed that in addition to absorbing crash energy and reducing injury severity to child occupant, light weight composite and aluminium components reduced vehicle weight which led to less fuel consumption. Selecting energy absorbing material in the design of crush zone components of a car is crucial to

child injury severity reduction in automotive frontal crashes.

REFERENCES

- Ahmad, Z. (2009). *Impact and Energy Absorption of Empty and Foam-filled Conical Tubes*. Queensland University of Technology.
- Bois, P. Du, Chou, C. C., Fileta, B. B., King, A. I., & Mahmood, H. F. (2004). *Vehicle and Occupant Protection*. (P. Prasad & J. E. Belwafa, Eds.). American Iron and Steel Institute.
- Crandall, J. R., Myers, B. S., & Meaney, D. F. (2012). *Pediatric Injury Biomechanics: Archive & Textbook*. Springer Science & Business Media.

Corresponding author: Rafukka, I. A.

bakarihenny341@gmail.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University.

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved



- Henn, H. (1998). Crash Tests and the Head Injury Criterion. *Teaching Mathematics and Its Applications*, 17(4), 162–170.
- Ji, J. (2015). *Lightweight design of vehicle side door*. Politecnico di Torino.
- Liu, B., Xu, T., Xu, X., Wang, Y., Sun, Y., & Li, Y. (2016). Energy absorption mechanism of polyvinyl butyl laminated windshield subjected to head impact: Experiment and numerical simulations. *International Journal of Impact Engineering*, 90, 26–36. <http://doi.org/10.1016/j.ijimpeng.2015.11.010>
- LSTC. (2013). *LSTC Hybrid III 6 year old Finite Element Model Documentation*.
- Marzougui, D., Kan, C.-D., & Bedewi, N. E. (1997). Development and validation of an NCAP simulation using LS-DYNA3D. *NCAC Paper*, 12(3), 23–29.
- Molla, H., & Abuye, A. (2020). Automobile Bumper Beam Analysis to Improve Energy Absorption, 11(8), 1603–1612.
- Naik, N. K., 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
- NCAC. (2015). Application: Finite element model archive. Retrieved from <http://www.ncac.gwu.edu/vml/models.html>
- Salwani, M. S., Sahari, B. B., Ali, A., & Nuraini, A. A. (2014). The Effect of Automotive Side Member Filling on Car Frontal Impact Performance. *Journal of Mechanical Engineering and Sciences*, 6(JANUARY), 873–880.
- Yeshanew, E. S., Ahmed, G. M. S., Sinha, D. K., Badruddin, I. A., Kamangar, S., Alarifi, I. M., & Hadidi, H. M. (2023). Experimental investigation and crashworthiness analysis of 3D printed carbon PA automobile bumper to improve energy absorption by using LS-DYNA. *Advances in Mechanical Engineering*, 15(6), 1–23. <http://doi.org/10.1177/16878132231181058>

Corresponding author: Rafukka, I. A.

✉ bakarihenny341@gmail.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University.

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved