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An Optimized Sandwich Bumper Beam for Child Occupant Head Injury Prevention

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ABSTRACT

Child fatalities from motor vehicle crashes are recently being considered as a global problem. Various mitigation systems have been proposed, but are still not optimum. Designing energy absorption vehicle front has been one of the methods used to minimize vehicle deceleration. This in addition to child restraint seat could help minimize child injuries especially to the most sensitive part of human body, the head. Sandwich bumper beam absorbs huge kinetic energy by plastic deformation and lead to reduction of vehicle deceleration and subsequent lower occupant injuries. In this work, optimization was carried out seeking for the optimum design of composite beam thickness (B_t) and foam thickness (F_t) of a sandwich bumper that will minimize Head Injury Criteria (HIC_{15} and HIC_{36}) to child occupant at 48 km/h frontal impact. Sampling design of the bumper and beam thickness applying design of experiment and finite element (FE) crash simulations using LS DYNA was applied to evaluate the three year old (3YO) child model head injury responses. Optimization models were developed which were in turn used in optimization process. The optimization was carried out using polynomial Response Surface Method (RSM) for HIC_{15} and HIC_{36}. The bumper beam and foam thickness that gives a minimum HIC_{15} and HIC_{36} of 386.6 and 311.5 respectively are 100 mm F_t with 1 mm B_t. Lastly, the work, suggested the need for employing the relationship that exist between child occupant response and bumper material and thickness in design considerations.

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1. INTRODUCTION

Road traffic accident claimed about 1.2 million lives annually worldwide: hence it is considered to have high impact on the health and development of any society (WHO, 2013). In developed countries it was reported to be the most common cause of fatalities to children[1]. Head has the highest percentage of injury in motor vehicle crashes. About 50% of the injuries sustained by child occupants in crash events are on the head [2]. It is well agreed by researchers that head is the body region that need extra protection for children of all ages [3]. High energy absorption vehicle crumple zone structures were considered to compliment the Child Restraint System (CRS) performance in minimizing child occupant injuries by absorbing more kinetic energy and transmitting lower decelerations to the occupant. Efforts have been made in improving child occupant protection by CRS design. studies on child occupant is focused on restrained system design [4][5][6]. Researches are now bending towards designing energy absorption components that will absorb more kinetic energy and thus minimizing the injuries to occupants[7], [8] . Well validated finite element computer models are suitable for studying the crashworthiness of car and biomechanical response of child in crash.

Crush zone of a vehicle are the frontal structures consisting of bumper beam, energy absorber, side members and crash box etc that progressively deform during collision there by absorbing kinetic energy which lower vehicle deceleration. Bumper being in the forefront is the first component to receive the forces in frontal impacts. Studies on safety concerning bumper design inclined to the pedestrian collisions [9][10]. Other studies focused on the evaluation of vehicle deceleration without using the dummy model to evaluate the occupant injury parameters [11][12][13]. Though substantial literature studied the performance of light weight material in energy absorption and vehicle weight reduction, limited attention was given to the occupant safety.
Salwani et al (2014) [14] studied the effect of light weight material of automotive side member on adult occupant protection. It was found that aluminium provides significant reduction in vehicle weight compared to steel with improved HIC and Chest Severity Index (CSI) values. Elmarkabi et al (2013) [15]used finite element simulations to study the influence of structural and material characteristics of road side pole on injury of 3YO children 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. Donga (2011) [16]develops sandwich frontal bumper for better kinetic energy absorption. It was shown that sandwich bumper absorbs more energy than steel bumper, and occupant injury parameters evaluated using adult FE dummy model were found to be lower for sandwich bumper for 35 mph frontal impact test. Few works studied the effect of vehicle energy absorption structures on the occupant injury, particularly involving children. Sandwich bumper was found to have potential in reducing head injury to vehicles occupants [17] The aim of this study is therefore to determine the optimum design of sandwich bumper that will minimize head injury to 3YO child vehicle occupant using FE simulations.

1.1 Head Injury Criteria (HIC)

Injury in head can cause brain concussion or affect some sensory organs. 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:

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

Where t_1 and t_2 are the time duration of crash within which the head acceleration was maximum. 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 center of gravity which provides the components of acceleration in x, y, and z direction. The resultant acceleration is evaluated as:

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

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

2. RESEARCH METHOD

2.1 Vehicle and child occupant modelling

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The vehicle finite element model of Ford Taurus car was developed by EASi Engineering through the process of reverse engineering for National Highway Traffic Safety Administration (NHTSA) [18]. The vehicle model shown in Figure 1, is publically available for research purposes in National Crash Analysis Center (NCAC) website [19]. This model has been validated against physical crash data by (Marzougui, Kan, & Bedewi, 1996). Vehicles subjected to frontal impact usually exhibit large deformation on the front end, where as the rear end hardly undergoes deformations, Taurus model front end structures were developed with fine mesh, since it was meant for frontal impact assessment.

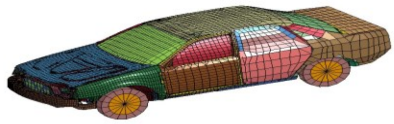

Figure 1 Ford Taurus finite element model

The child crash dummy used in this study was a 3YO child FE model scaled by the author from 6YO HIII dummy FE model using morphing technique. The biomechanical response of the morphed model was compared with sled test result from literature [20]. The child model is equipped with accelerometer at the head center of gravity to record the acceleration and HIC in crash simulations. Child restraint seat was modelled using rigid material model as it is assumed not deform under child weight. The seat and belt CAD models were first drawn and meshed using LS PREPOST. It 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 was applied for five point harness belt. Both the seat and belt were modelled using 2 mm thickness membrane elements. The material properties are presented in Table 1.

***Table 1** Material properties of child seat and belt* [21]

Parameter	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

2.2 Bumper beam modelling

The steel material of the beam was substituted by a carbon/epoxy composite with material properties as presented in Table 2. The fibre orientation used was taken to be $[0/60]_s$. MAT_COMPOSITE DAMAGE (material type 22 in LS DYNA) was employed.

Table 2 Material properties of the composite bumper beam (T300/5208 carbon/epoxy) [22]

$\rho(Kg/m^3)$	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

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.*

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 in plane and bending loads. The core was made from a foam material which 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 9.131×10^{-11} 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 [19]. The stress-strain relationship coupled to the material model is as shown in Figure 2

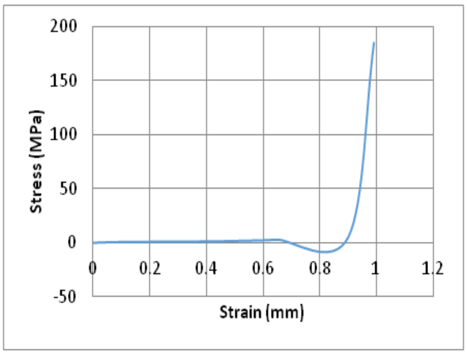

Figure 2 Engineering stress-strain relationship of the low density foam used for sandwich bumper

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 by means of single surface contact as was done for the other parts of the car model. It was modelled with dimension 1233 mm by 142 mm by 50 mm to cover the contact area of bumper beam with rigid barrier. The orientation of the foam was curved to follow the composite beam as shown in Figure 3. 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.

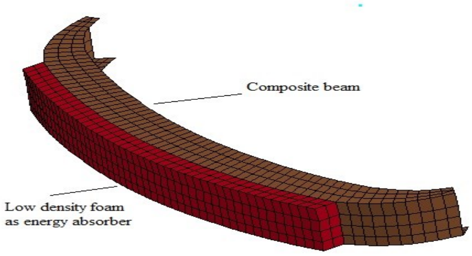

Figure 3 Sandwich bumper beam

2.3 Simulation setup

Crash analysis was conducted using FE model of Ford Taurus vehicle, 3YO child dummy model and CRS. The speed was chosen based on Federal Motor Vehicle Safety Standard (FMVSS 208) which requires full frontal impact test to be carried out at 48 km/h. The vehicle FE model was modelled with forward facing CRS accommodating 3YO child dummy attached to the vehicle body with *CONSTRAINT RIGID BODIES OPTION, in the rear seating position, and the frontal impact test was simulated as shown in Figure 4. The constrained option can allow integrating the dummy to the vehicle model in the absence of rear seat back.
The simulation was carried out for 140 ms time duration. 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 lead to the termination of the simulation prematurely. The calculation was carried out using LS DYNA solver with a running time of 10 hours.

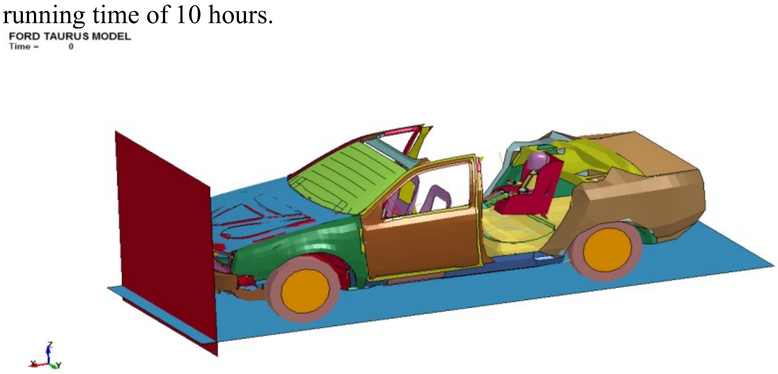

Figure 4 Restrained three year old child FE model in vehicle FE model for frontal crash test

3. RESULTS AND DISCUSSIONS

3.1 Mathematical modelling and optimization

Design samples were constructed by selecting a series of design sample points from the design domain. Foam thickness (F_t) sample points are: 25 mm, 50 mm, 75 mm and 100 mm, and the composite bumper beam thickness (B_t) was varied from 1 mm to 2 mm in step of 0.2. These two parameters were selected based on previous studies in which it was shown that increasing thickness improves the bumper beam strength. A total of 30 simulations were conducted on this design samples in order to provide the crash injury response observations.

A full factorial design was applied using five levels and two variables; the foam thickness F_t, and bumper beam thickness B_t, with beam thickness varying for six steps making a total of 30 experiments. The design variables and levels used for the experiment. The arrangement of the optimization levels are shown in Table 2.

Table 2 Design points and crash responses for sandwich beams

Foam thickness (mm)(F_t)	Bumper thickness (mm) (B_t)	HIC_{15}	HIC_{35}
0	1	563	590
	1.2	590	633
	1.4	586	596
	1.6	474	541
	1.8	472	566
	2	358	502
25	1	483.4	597.7
	1.2	468.8	505.5
	1.4	494.3	553.7
	1.6	480.2	529
	1.8	409.2	535.5
	2	378.3	547.3
50	1	370	478.2
	1.2	363.3	466.3
	1.4	500	516
	1.6	522.4	596
	1.8	402.7	564.4
	2	473.9	638.6
75	1	338.9	450.2
	1.2	426	491.6
	1.4	401	444.5
	1.6	423	511
	1.8	500.5	608.6
	2	574.7	687.1
100	1	311.5	386.6
	1.2	417.4	465.7
	1.4	420.4	475.8
	1.6	445	542.1
	1.8	457.6	581.5
	2	522.5	665.2

Response Surface Method (RSM) was applied to approximately model the sandwich bumper capability to reduce HIC to 3YO child. The foam and bumper beam thickness only vary between lower and upper limits. The response variables are the HIC_{15} and HIC_{36}. RSM programming was performed using MATLAB R2015a.

3.1.1 Response surface model for HIC_{15}

Best fitness was found in the cubic model because of its larger R^2, R^2 −adj and RMSE values and it is thus selected as multi objective function for the optimization. The response model polynomial function of cubic form was obtained as:

$$HIC_{15}\ (F_t, B_t) = -939.5 - 9.427F_t + 3123B_t + 0.1243{F_t}^2 - 1.483F_tB_t - 1978{B_t}^2 - 0.0003275{F_t}^3 - 0.04259{F_t}^2B_t + 3.348F_t{B_t}^2 + 370.3{B_t}^3 \quad \text{-----------(3)}$$

The response surface graph is as shown in Figure 5:

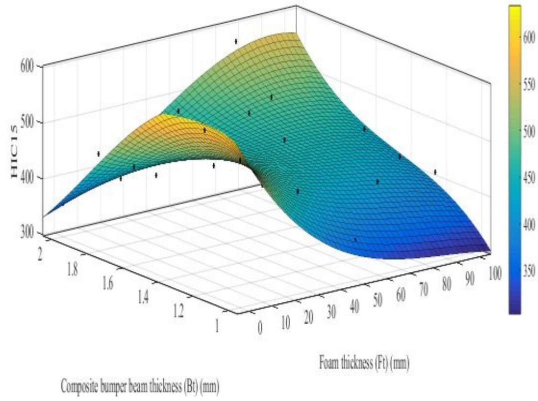

Figure 5 Response surface for HIC15

Optimal design was obtained by using constrained multi linear multivariable optimization algorithm (fmincon). The problem was formulated as:

$Minimize\ \ HIC_{15}\ (F_t, B_t)$

s.t. $0 \le F_t \le 100$

$1 \le B_t \le 2$

Though, the HIC_{15} decreases with increase in B_t because of increase in energy absorption, addition of 100 mm foam thickness reduced HIC_{15} to about 300 which was lower than 350 achieved by 2mm thickness of the composite bumper. Thus considering the weight and cost advantage of foam coupled with lower HIC_{15} value, 100 mm foam with 1 mm B_t is the best design for minimizing head injury risk to 3YO children at a speed of 48 km/hr. Increasing B_t to thicker foam adversely increases the HIC_{15} value. As seen in figure 5, the 2 mm B_t with 100 mm foam yield a HIC_{15} greater than 500. This combination considered worst in terms of weight, cost and HIC_{15} and therefore should be avoided. Though HIC_{15} of 500 was within the recommended value of 570 for 3YO child, it indicates the vulnerability of child to be exposed to higher HIC_{15} values closer to the specified limit which is unwanted.

Optimization was carried out using MATLAB from which the minimum HIC_{15} value was found at 100 mm foam thickness and 1 mm composite bumper thickness and the corresponding HIC_{15} value at that point was 311.5 in FE simulation. From response surface equation, however, the HIC15 was evaluated as 327.2 which is 5% different from simulation results. This proved the capability of the model to effectively predict the foam and bumper beam thickness that provides lower values of HIC_{15}.

3.1.2 Response surface model for HIC_{36}

Quadratic and quartic functions were first generated from curve fitting but R^2 and R^2-adj does not seem to justify their selection over cubic response model and hence polynomial function of cubic form was selected as:

$$HIC_{36}(F_t, B_t) = 644.9 - 6.226\ F_t + 79.1\ \ B_t + 0.06124\ F_t^2 - 0.3722F_tB_t - 118.8B_t^2\ - 0.000142\ \ \mathrm{F_t^3} - 0.02525\ \mathrm{F_t^2\ B_t}\ +\ 2.26\mathrm{F_tB_t^2} +\ 22.64\ \mathrm{B_t^3} \quad \text{-------------- (4)}$$

The response surface graph is as illustrated in Figure 6:

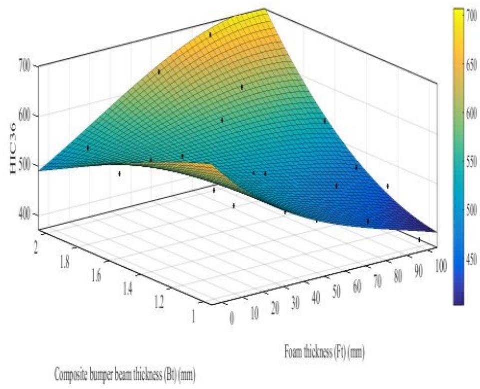

Figure 6 Response surface for HIC_{36}

Optimization of the HIC_{36} was formulated as:
$Minimize \quad HIC_{36}\,(F_t, B_t)$
s.t. $0 \le F_t \le 100$
$1 \le B_t \le 2$

The HIC_{36} response surface curve shown in Figure 6, depicts similar trend with that of HIC_{15} presented in Figure 5. Increase in foam thickness on composite bumper improved the HIC_{36} value below 400, for 100 mm F_t and 1 mm B_t. This is attributable to the strain energy of the sandwich material, as 1 mm B_t will deform more, and this coupled with large deformation of 100 mm foam leads to large strain energy and time of zero velocity increases there by lowering the sudden deceleration transmitted to the child. Vehicle passenger decelerated slowly due to crumple zone long time collapse which leads to large change in velocity and thereby reducing injury severity to occupants
Reduction in $HIC_{36}$is achieved with increase in both F_t and B_t, but HIC_{36} achieved with 100 mm F_t was about 100 lower than the HIC36 for 2 mm B_t. Severe HIC_{36} values that are beyond the specified limits are evidenced by combining thicker composite bumper with thicker foam as shown in Figure 6. This may be due to decrease in strain energy absorption of composite bumper and foam because of higher combined thickness.
The minimum value of HIC_{36} from simulation results was 386.6 achieved at 100 mm F_t and 1 mm B_t. The HIC_{36} value evaluated from multi objective equation was 384.3 which describe high prediction ability of the developed model.

4. CONCLUSION

In this work, sandwich bumper beam effect on minimizing child head injuries in frontal motor vehicle crashes has been studied. Response surface models for HIC_{15} and HIC_{36} as a function of foam and bumper beam thickness have been developed using polynomial RSM which was in turn used in the optimization to determine the B_t and F_t that minimizes head injury potential to child occupants in 48 km/h frontal crashes. Optimum design of sandwich bumper has been determined which is useful in design for child safety. Sandwich bumper obtained by combining 1 mm composite beam and 100 mm foam thickness yields lowest HIC values. This study provides designers with quantitative information on how their judgement affects performance of bumper beam on child occupant head injury.

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