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A PARAMETRIC STUDY ON DESIGN OF HELMET TO MITIGATE BRAIN DAMAGE AND TO OPTIMIZE THE WEIGHT

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ABSTRACT

With the development of national highways for rapid transport system and also with the increase in the engine capacity of two wheeler to a great extent, there has been an increase in the rate of accidents on road. The Indian scenario in road safety is minimal and many accidents are either fatal or rider undergoes a traumatic brain injury. Helmet plays a vital role in the safety of the rider and hence it has to be designed with due consideration for stresses and deformations that cause brain damage thus effect the safety of the rider. In this paper, the effect of dynamic impact loads on the helmet and the effect of such impacts on skull and brain under high velocity of 30 m /sec which are the real time conditions were studied. In this parametric study after modeling the helmet the critical angle of impact was identified. The three layered helmet was analyzed for different material combinations. In the process of optimization, the DOE Table was generated using Central Composite Design method, by using input parameters i.e., the thicknesses of 3 layers and the mass of the helmet. From the design points generated in the above stage, the response surface graphs were generated for comparing the variation in output parameter for a given input variation. The optimal values for the helmet were finalized by using Multi Objective Genetic Algorithm method by taking constraints as allowable stresses for the brain, the skull, the material used with due consideration of factor of safety.

Keywords: helmet, brain, skull, optimization, impact, polycarbonate, ABS (Acrylonitrile Butadiene Styrene), response surface.

INTRODUCTION

Road traffic injuries are a major public health problem and a leading cause of death and injury around the world. Injuries to head and neck many times prove to be fatal or else it leads to coma or a severe trauma to the rider. To reduce the fatality rate and improve the safety, the designs of helmet become vital. A helmet works in three ways, firstly it reduces the deceleration of the skull, and hence the brain movement, by managing the impact. The soft material incorporated in the helmet absorbs some of the impact and therefore the head comes to a halt more slowly. This means that the brain does not hit the skull with such great force. Secondly it spreads the forces of the impact over a greater surface area so that they are not concentrated on particular areas of the skull. Thirdly it prevents direct contact between the skull and the impacting object by acting as a mechanical barrier between the head and the object.

Baumgartner B *et al*. [1] said that it is well known that helmets substantially reduce head injury, although the mechanism of this protection is neither well understood nor controlled. The helmet used in his study is a full face helmet with a polycarbonate thermoplastic shell and expanded polystyrene foam. After a validation with a head form FE model as used in the experimental normative tests, the helmet model was coupled with a previously developed finite element model of the human head. His approach consists to couple the human head with the helmet FE models in order to predict intra-cranial field parameters such as acceleration, pressure and Von Mises stress. G. Milne *et al*. [2] says that although cycling may be attractive for both economic and environmental reasons, cyclists are extremely vulnerable road users and subjected to falls or collisions with cars and in accordance with the EN 1078 standard, an experimental program has been carried out on an existing helmet by performing 90 normative impacts under three different types of conditionings. Mazdak Ghajari [3] has done Development and validation of the Finite Element (FE) model of a commercially available helmet in the LS-DYNA crash code. For the validation, drop tests were performed at front, rear and side of the helmet onto flat and kerbstone anvils according to the impact absorption test of the UNECE22.05 standard and the same impacts were simulated. Peter Halldin *et al*. [4] studied that Injury statistics show that accidents with a head impact often happen with an angle to the impacting object. An angled impact will result in a rotation of the head if the friction is high enough. Gaetano Davide [5] presented standards for evaluating the impact absorption performance of motorcycle helmets are described and compared. Remy Willinger [6] presented on original numerical human head FE models followed by its modal and temporal validation against human head vibration analysis in vivo and cadaver impact tests. Wilson [7] has given an overview of the state of scientific knowledge of blast induced Traumatic Brain Injury (TBI), as well as a review of the current helmet standards and various studies into physically modelling an impact to the head. Alexander R. Haley [8] to provide a forward-looking technological review and offer informed speculation on the future use of technology to improve the protection offered by ballistic helmets. Daniel Lanner [9] described both a numerical and an experimental approach to measuring the ballistic and blunt impact protection offered by military helmets. Ugo Galvanetto [10] investigated the modeling of a honeycomb reinforced helmet in LS- Dyna environment. The ECE 22.05 standard impact tests are simulated in the front, top and rear regions of the helmet, and the numerical outcomes are compared to experimental results.

Design considerations

The helmet must be designed to provide the user with the most lightweight object with firm fitting system, while meeting other system performance requirements. This can be achieved through a complete analysis of the system requirements. In this model, a new layer was introduced in order to accommodate metallic foam also to absorb the shock during an impact and designed model and cut section were as shown in Figure-1, and Figure-2, respectively.

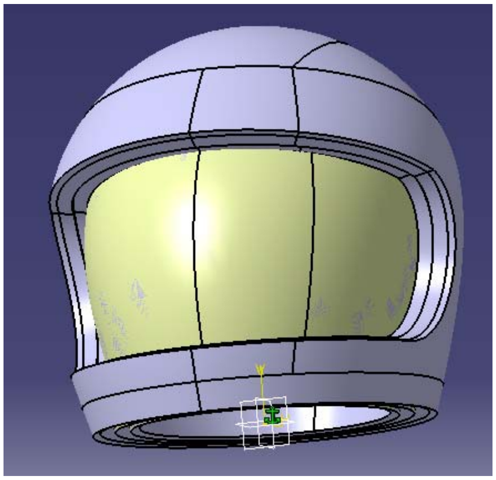

Figure-1. Assembled model.

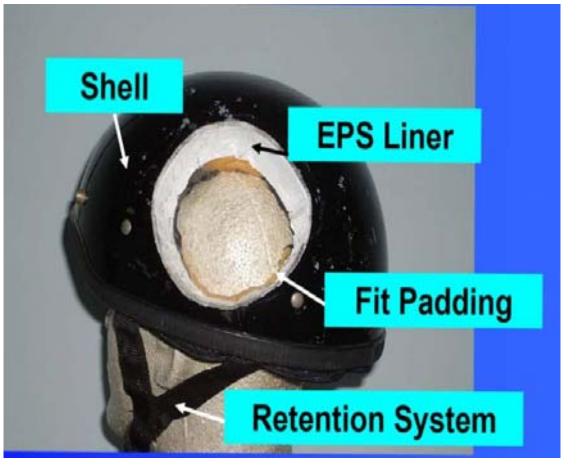

Figure-2. Components of a helmet.

The modeling was carried out by considering the helmet consisting of 3 layers outer shell made up of ABS / poly carbonate material, middle Aluminium sponge and inner foam. The head is modeled to consist of 2 layers only, i.e., the skull and the brain. The modeled helmet is tested in three different positions of impact i.e., in horizontal, vertical and inclined position. It is designed that the helmet to assumed to hit concrete surface. Stresses and deformations at all the positions are recorded and peak values are noted as shown in the Table-1 and Table-2.

Table-1. Analysis of impact load result: Skull.

Object name	**Total deformation - skull**	**Equivalent** (von-Mises) **stress - skull**	**Maximum shear stress - skull**
Vertical	9.8945e-004 m	7.3094e+006 Pa	3.7758e+006 Pa
Inclined at 45^0	9.65911e-004 m	7.233e+006 Pa	3.2752e+006 Pa
Horizontal	9.1055e-004 m	7.0323e+006 Pa	3.205e+006 Pa

Table-2. Analysis of impact load result: Brain.

Object name	**Total deformation-brain**	**Equivalent stress-brain**	**Maximum shear stress-brain**
Vertical	8.0658e-003 m	16469 Pa	9073.6 Pa
Inclined at 45^0	6.116e-003 m	13796 Pa	7858.4 Pa
Horizontal	5.6838e-003 m	10274 Pa	5881. Pa

By observation of the above results, the vertical impact is found to be critical. The Von-Mises stresses induced in the helmet components also show similar trend. For the outer layer the Von-mises stress are 1.97+07 Pa, 1.49 e+07 Pa and 1.02 e+07 Pa for the vertical, inclined at 45^0 and horizontal impacts respectively. For the middle layer they are 1.8398e+007 Pa, 9.839e+006 Pa and 6.503e+006 Pa respectively in the same order.

Since the stresses and deformation are very high compared to the other impacts, there is a need for the vertical impact to be analyzed further for different material of helmet. So in order to reduce these stresses and deformation in those particular direction two materials, Acrylonitrile Butadiene Styrene and Polycarbonate are used for analysis. The ABS as outer layer and the metallic foam as the second layer and with the foam as the third

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layer, has shown lesser stresses induced in brain and skull for given load conditions and dynamic impact when compared to Polycarbonate as outer layer as shown in Table-3.

Table-3. Analysis of impact load on skull and brain.

Object name	**Maximum shear stress in Pa**		**Total deformation - skull in m**		**Equivalent** (von-Mises) **stress - skull in Pa**	
	Skull	**Brain**	**Skull**	**Brain**	**Skull**	**Brain**
ABS	3.7758e+006	9073.6	9.8945e-004 m	8.0658e-003 m	7.3094e+006	16469
Poly Carbonate	4.7459e+006	11416	1.8167e-003 m	1.0626e-002 m	8.2839e+006	21300

Some of the diagrams showing Von-Mises stresses obtained in the skull, brain and the outer shell are shown in Figure-3, 4, 7, 8, 11 and 12 and their respective variation with time graphs are shown from Figure-5, 6, 9, 10, 13 and 14.

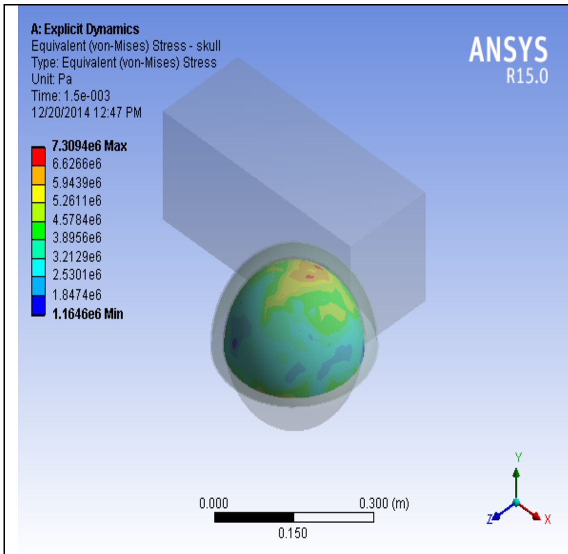

Figure-3. Von Mises stress on skull with Abs.

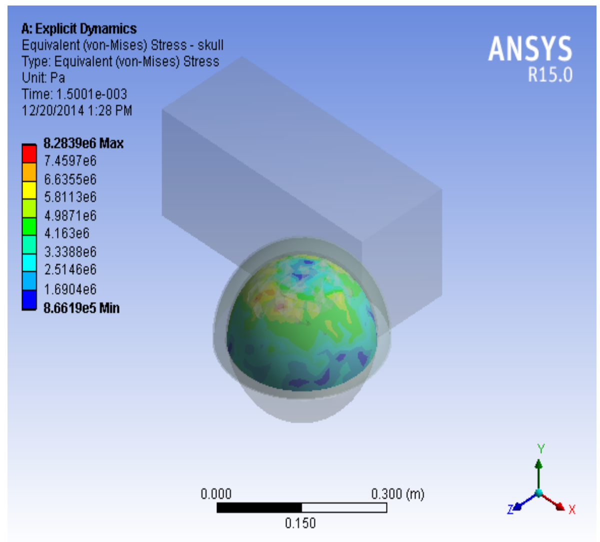

Figure-4. Von Mises stress on skull with Polycarbonate.

ARPN Journal of Engineering and Applied Sciences

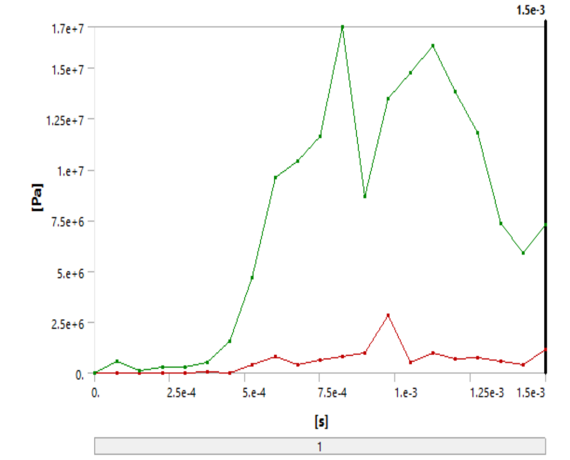

Figure-5. Max-Min Von-Mises stress in Skull vs Time ABS.

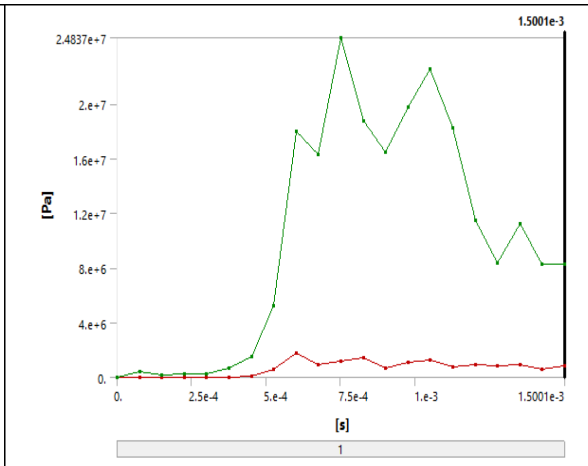

Figure-6. Max-Min Von-Mises stress in Skull vs Time Poly Carbonate.

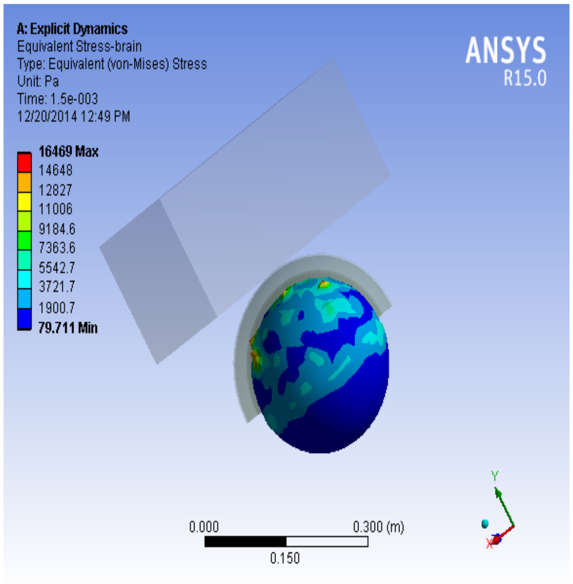

Figure-7. Von Mises stress on Brain with ABS.

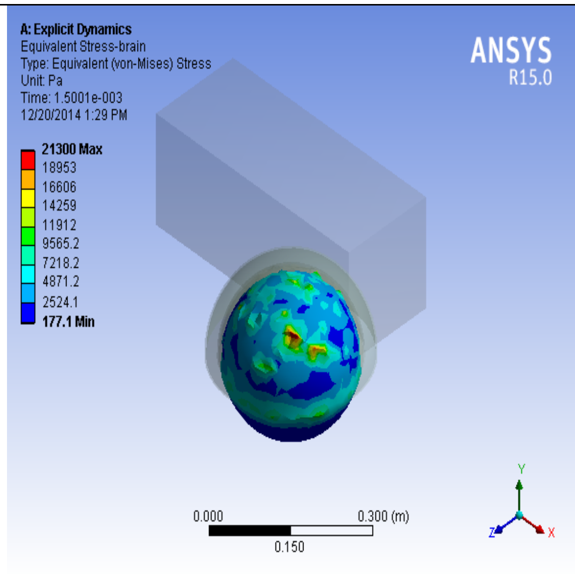

Figure-8. Von Mises stress on Brain with Polycarbonate.

VOL. 10, NO. 6, APRIL 2015 ISSN 1819-6608
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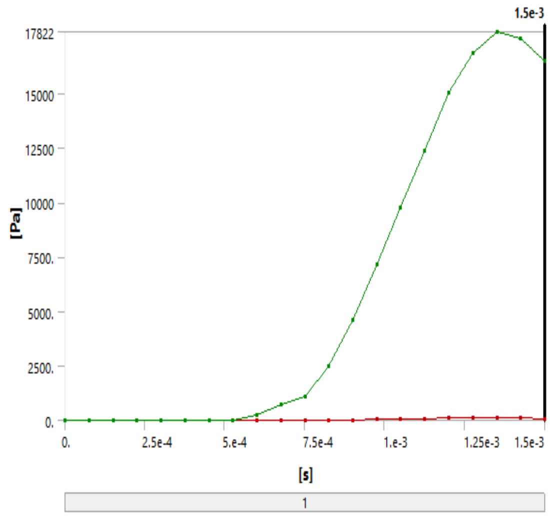

Figure-9. Max- Min Von Mises stress on Brain with ABS.

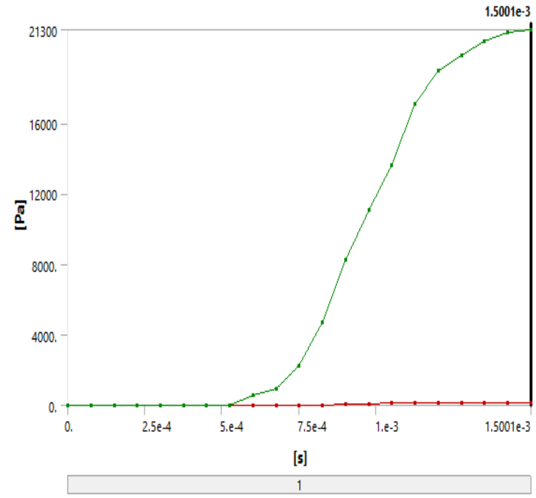

Figure-10. Max-Min Von Mises stress on Brain Polycarbonate.

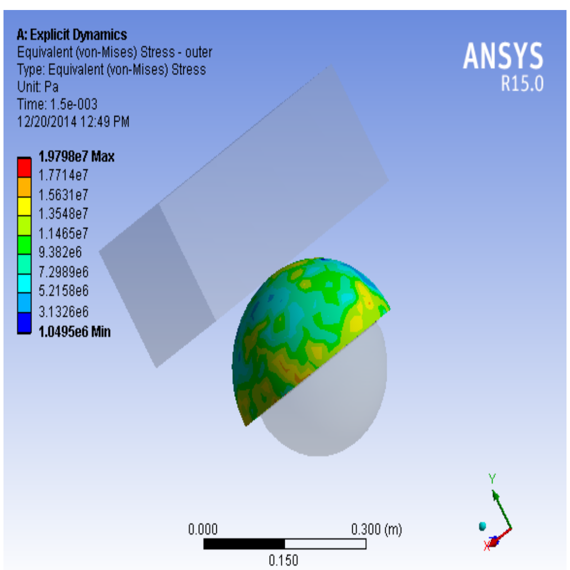

Figure-11. Von Mises stress on Shell with ABS.

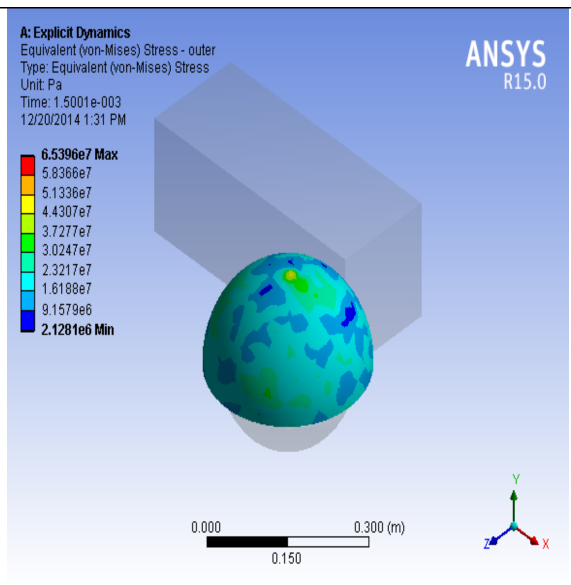

Figure-12. Von Mises stress on Shell with Polycarbonate.

VOL. 10, NO. 6, APRIL 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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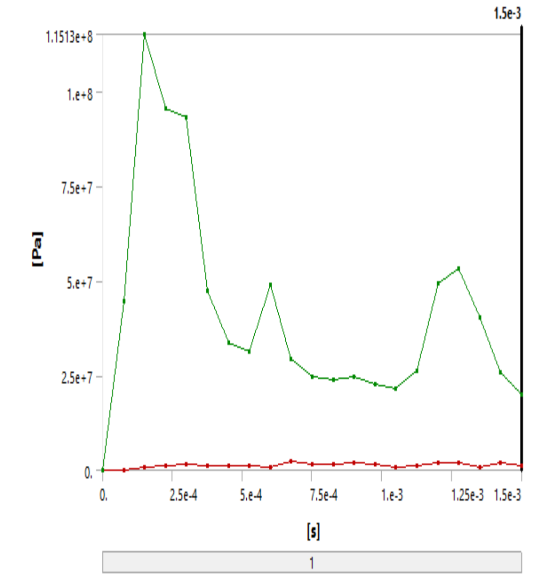

Figure-13. Max-Min Von Mises stress on Shell ABS.

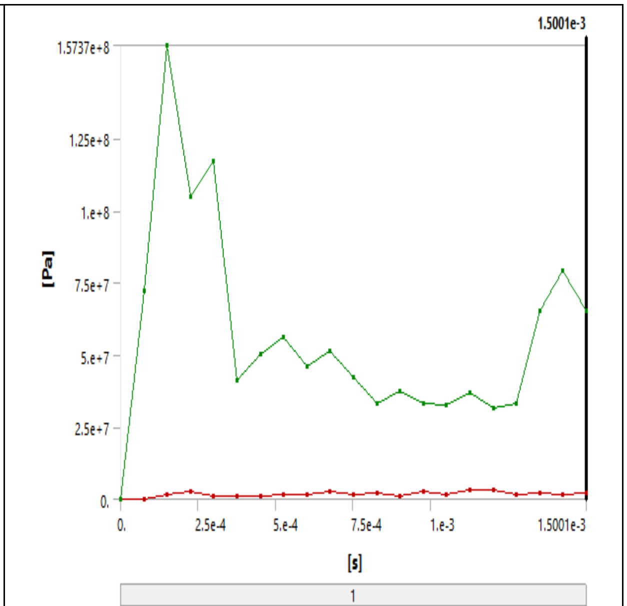

Figure-14. Von Mises stress on Shell with Polycarbonate.

All the output parameters like deformations and stresses are higher for Poly carbonate. The Poly carbonate helmet produces a shear stress of 11416 Pa and by considering a factor of safety of 2, at a speed of 30 m/sec the helmet will not satisfy the design requirement.

Though the stresses induced in both the models are within the ultimate stresses of the specific materials, using the polycarbonate results us the increase in weight of the helmet in order to provide safety but increase in weight is not a desirable quantity in our case. Since a better safety can be given at a lesser weight ABS with a combination of aluminum sponge is to be preferred.

The optimization of the various parameters will help identifying the optimum value of thicknesses that will give us the minimum amount of stresses. This is done by using ANSYS response surface optimization tool. The Design of Experiments by using Central Composite method and 15 critical points were generated with varied thickness of middle and outer layer of the helmet. The DOE was generated and analysis is done for both ABS and Polycarbonate materials.

The Response Surface is a meta-model built from the Design of Experiments for an efficient exploration of the design space. The response surface diagrams in 3-D graphs were generated for various parameters. The input parameters are the thickness of the outer shell and outer shell versus various parameters of the skull and the brain were drawn. The response diagram indicates the variations in various parameters as were generated by Design of Experiments. The response diagrams for the skull, brain and the outer shell are obtained and are shown in Figure-15 to Figure-17.

ARPN Journal of Engineering and Applied Sciences

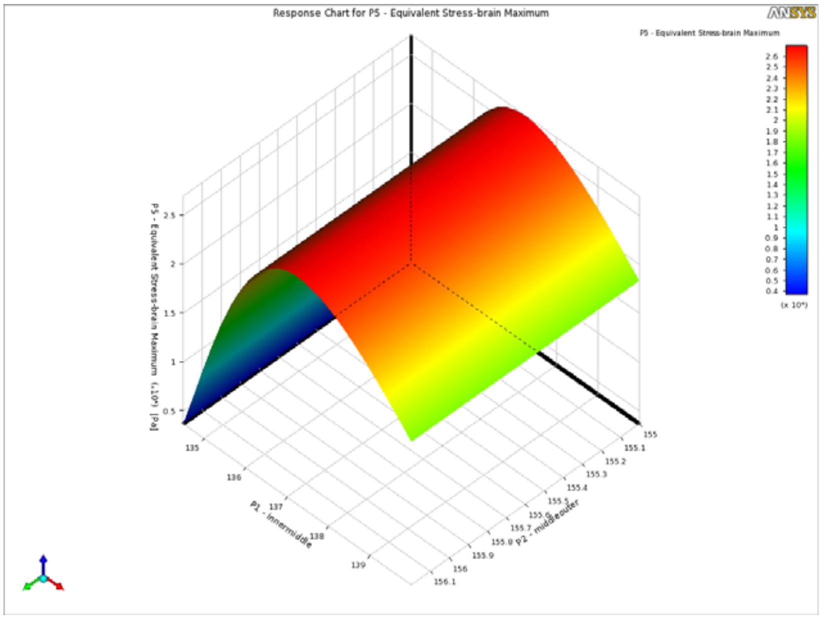

Figure-15. Von Mises stress on Brain with ABS Vs Thickness of middle and outer shell.

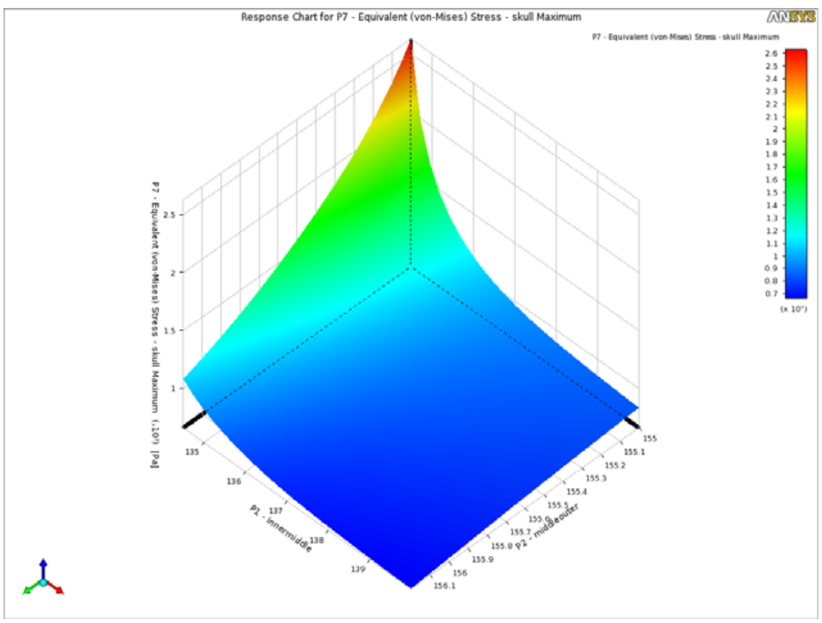

Figure-16. Von Mises stress on Skull with ABS Vs Thickness of middle and outer shell.

VOL. 10, NO. 6, APRIL 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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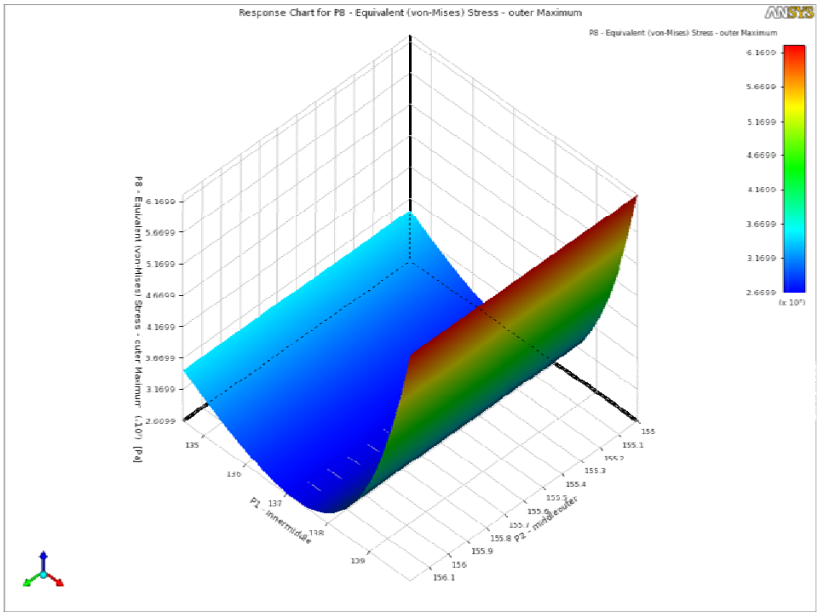

Figure-17. Von Mises stress on Ouetr shelll with ABS Vs Thickness of middle and outer shell.

The obtained values for different parameters are optimized using the Multi Objective Genetic Algorithm (MOGA) and the best 3 optimum values for the combinations with the thicknesses as well as the stresses are generated. The constraints for optimization are maximum shear stress is 10000Pa; maximum von mises stress 92000Pa for Brain. For skull the limiting stresses are for shear stress 1.83E+07 and for von mises stress 1E+09 Pa. The maximum limiting stress for the outer shell is 4E+07Pa.

In the DOE generated by using Central Composite Design method and subsequent optimization by using MOGA method duly considering a factor of safety as per DOT standards, the values obtained for ABS material are Von-Mises stress-8.328 kPa, shear stress-5.34 kPa and the total weight of the helmet is obtained as 0.5708 kg. This is 20% reduction when compared to the existing model of the helmet which is 0.6849 kg. But in case of Poly carbonate to meet the desired factor of safety and standards of design, the weight has to be enhanced by 8% as the initial value of mass of the helmet is 0.9775 kg and final value 1.0557 kg. Thus it is observed that for the optimal design of the helemt, the ABS material is preferred for safety and also comfort of the rider.

CONCLUSIONS

In this parametric study, the model was designed for 3 layers of helmet and the impact effects of dynamic load on 2 layers of human head i.e., skull and brain are considered. On testing the model in three different positions i.e., horizontal, vertical and inclined, the stresses at vertical impact are obtained as critical. Under vertical impact, the different obtained values for brain are the Von-Mises stress-16.469 kPa, shear stress-9.073 kPa, deformation-8.065e-3 are highest when compared to the other positions. Similarly for skull, the Von-Mises stress-7.309e6 Pa., shear stress 3.775e6 Pa., deformation-9.894e-4 are highest when compared to other positions. The reason is that the total load of the rider is also acting on the helmet along with the high velocity impact for this position. The above values are tested for Acrylonitrile Butadiene Styrene (ABS). For the same impact conditions the values obtained for Poly carbonate are the Von-Mises stress-21.3 kPa, shear stress-11.416 kPa, and deformation-10.62e-3.

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Thus it is concluded that the ABS material gives a better performance under the critical loading conditions when compared to the Poly carbonate. This reduces the scope for brain damage and ride comfort of the rider is also improved as the weight of the helmet is less.

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