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Two Wheeler Helmets with Ventilation and Metal Foam

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ABSTRACT

Three different two wheeler helmets were studied to investigate their dynamic performance. First is helmet with ABS shell, second is helmet with metal foam, and third is helmet with single groove in the liner foam for providing ventilation. Front and side impact analyses were carried out at 10 m/s velocity by using LS-DYNA^{TM}. Forces on the helmet and on the head due to impact were studied with function of time. Pressure and stresses in the brain were investigated and found not to change significantly due to the presence of groove in the liner foam, which was provided to improve the ventilation in helmets. The dynamic performance of a helmet with outer shell as metal foam was examined and compared with ABS material.

Keywords: Impact dynamics, motorcycle helmets, human head, metal foam, CFD ventilation models

1. INTRODUCTION

Helmets are widely used by two wheeler riders to protect their head during the accidents or falls. In South Asia, excessive sweating and resulting discomfort due to hot and humid weather conditions discourages two wheeler riders from using helmets unless it is mandatory by law. To enhance the evaporation of sweat and minimising the discomfort, ventilation can be provided in helmet by grooves and holes. Fluid experiments and computational fluid dynamics analysis were carried out for different ventilation models in helmets however they are not presented here. Front and side impact simulations for impact velocities up to 10 m/s are performed to see if the presence of groove has a detrimental effect on the dynamic performance of the helmet. Lately, metal foams are being used in crash applications because of its light weight, high strength and energy absorption capabilities. The metal foams are expensive but much lighter than the ABS, which commonly used as material for shell. Dynamic simulations are carried out to investigate the behavior of helmet with head impact, in case metal foam is used as the shell material.

2. DYNAMICS OF TWO WHEELER HELMETS

In the past, the finite element analysis of drop test of helmet used a rigid head and results were reported in the form of head injury criterion (HIC) values and accelerations of the head form. Lately, finite element is also commonly used to model the head[1-3]. Generally, the models do not contain all the details of the head and are much simpler than the actual head. Horgan and Gilchrist[1] and Zong[4], *et al.* have also constructed 3-D finite element models of the human head. The former used it for simulating the pedestrian accidents whereas the latter authors use a structural intensity (SI) approach to study power flow distribution inside head in

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frontal, rear, and side impacts. The results using human head models are presented in the form of pressures and stresses in the brain although a clear relation between stresses and brain injury are still to be fully established. To investigate the biomechanical aspects of head injury under the helmet impact, it is essential to understand the behaviour of the components of helmet and head. To get the biomechanical response in terms of forces, pressures, and stresses, the human head was considered as deformable instead of rigid.

2.1 Crushable Foam and Outer Shell

In helmet, the energy-absorbing liner is made of expanded polystyrene (EPS) and outer shells are made from composite material, like fibre glass, carbon fibre and Kevlar, or a molded thermoplastic like acrylu-butadiene styrene (ABS) or polycarbonate. The outer shell is stiff and resists the penetration of any foreign object and distributes the impact load on a wider area, thus increasing the foam liner energy absorbing capacity. 4-noded shell elements with Belytschko-Tsay formulation were used to model the outer shell in the two wheeler helmet with 3 mm thickness. Material model 3 (*MAT_PLASTIC_KINEMATIC) available in LS-DYNA™ was used for outer shell in finite element analysis with ABS as material.

The liner foam used is of EPS foam with 30 mm thickness. When the closed-cell EPS foams are compressed, work is done in bending and stretching the cell walls and in compressing the gas within the cells. Figure 1 shows the stress-strain behaviour of EPS foam. The foam depicts linear elasticity at low stresses followed by a collapse plateau, truncated by a regime of densification in which the stress rises steeply. The longer the plateau region, more is the energy absorbed. Densification in the foam starts at 65 per cent strain and stresses rise sharply after that.

Material model 63 (*MAT_CRUSHABLE_FOAM) was used for liner foam. The model transforms the stresses into the principal stress space where the yield function is defined. If the principal stresses exceed the yield stress they are scaled back to the yield surface and transformed back to the original stress space. The yield surface and its evolution are defined by the equations:

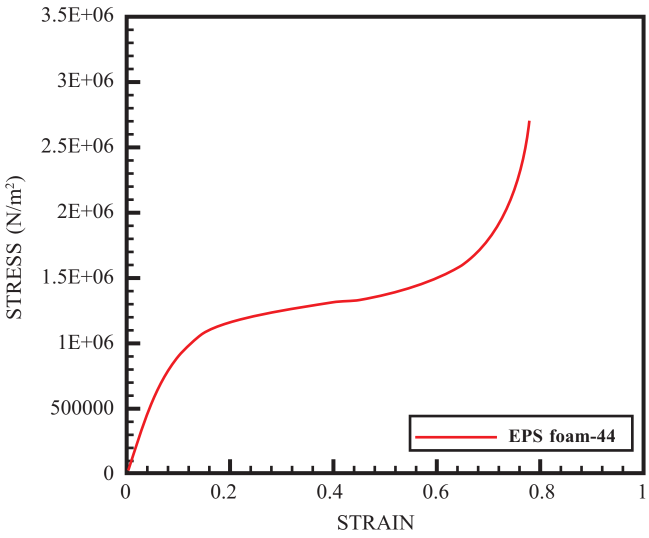

Figure 1. Stress-strain curve for EPS foam of 44 kg/m³ density under quasi-static loading.

Yield surface description

$$f_t = |\sigma_i| - \sigma_y = 0 \tag{1}$$

Hardening formulation

$$\sigma_y = \sigma_y^o + H(e_v) \tag{2}$$

$$\sigma_t = \sigma_t^0 \tag{3}$$

where, σ_y is the yield stress, σ_y^0 is initial compressive yield stress, σ_t is tensile cutoff stress, σ_i is the principal stresses and H is the strain hardening. Here e_v is the volumetric strain defined by natural logarithm of relative volume. An associative flow rule is assumed and the plastic strains are derived from

Flow of plastic strains

$$\dot{\varepsilon}_{ij}^{p} = \dot{\lambda}\frac{\partial F}{\partial \sigma_{ij}} \tag{4}$$

The flow surface is the same as the yield surface.

In LS-DYNA™, the data for stress versus volumetric strain for liner foam are given in tabular form and it fits the above equations to this curve. Quasi-static compression experiments, though they are not presented here, were carried out in strength of Materials Laboratory (Department of Applied Mechanics, IIT Delhi) with EPS foam of 20 kg/m^3 and 26 kg/m^3 density. But liner foams with these densities were bottomed out completely in dynamics at higher velocity impacts and the numerical simulation could not be completed. To study the helmet impact with head and metal foam at higher velocities (i.e., 10 m/s), the stress-strain curve for EPS foam of 44 kg/m^3 density under uniaxial loading was taken from Yettram[5]. A strap of 1 mm thick with nylon material was used as a restraint system to keep the head intact with the helmet. EPS foam and nylon strap were modeled with 8-noded brick elements in finite element analysis.

2.2 Metal Foams

The mechanical behaviour of polystyrene foams and metal foams is almost similar. The susceptibility of metal foam, which is aluminium foam here, to undergo gross plastic deformation at an almost constant load with large strokes makes it attractive for absorbing the energy of impact or impulsive loads in packaging and crash applications. In compression after yielding, strains will increase at almost constant stress, and once the foam is compressed (or densified), the stresses will start rising again. Figure 2 shows the stress-strain behaviour of aluminium foam for 300 kg.m^{-3} density.

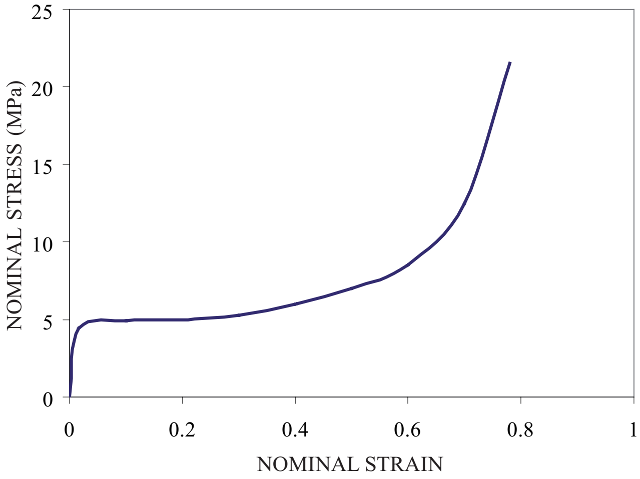

Figure 2. Stress-strain relation for aluminium foam of 300 kg.m^{-3} density.

Deshpande and Fleck[6] studied the isotropic and continuum-based metal foams and included a hydrostatic stress term in the yield function to take into account the volume changes in the foam.

Yield stress function Φ is defined by

$$\Phi = \sigma_e - \sigma_y \tag{5}$$

The equivalent stress σ_e is given by:

$$\sigma_e^2 = \frac{\sigma_{VM}^2 + \alpha^2 \sigma_m^2}{1 + (\alpha/3)^2} \tag{6}$$

where s_{VM} is the von Mises stress and s_m is mean stress. The parameter α controls the shape of the yield surface.

The yield stress α is expressed as suggested by Hanssen[7], *et al.*

$$\sigma_y = \sigma_p + \lambda \frac{e}{e_D} + \alpha_2 \ln\left(1/\left(1 - (e/e_D)^{\beta}\right)\right) \tag{7}$$

where, e is engineering strain and e_D is the densification strain, while σ, λ, and β are material parameters. The densification strain e_D is expressed as

$$e_D = -\ln\left(\frac{\rho_f}{\rho_{fo}}\right) \tag{8}$$

As aluminium foam is a typical filler material, solid elements with 8-node have been used in FE modelling. Material model 154 (*MAT_DESHPANDE_FLECK) was used for modelling metal foam and the properties have been taken from Hanssen[7]. The yield stress of aluminium foam, considered here, was 4.41 MPa. The thickness of the outer shell in two-wheeler helmets with aluminum foam was 7 mm.

2.3 Finite Element Model of Human Head

Three-dimensional finite element model of human head developed by Willinger[3], *et al.*, having skin, skull, CSF and brain, is used here. The FE model of head is of 4.5 kg with 11939 nodes and 13193 elements. The various layers of the head like other biological materials do not follow the constitutive relations for common engineering materials and these are generally nonhomogeneous, anisotropic, nonlinear, and viscoelastic. However, for modelling purposes here, these are assumed as homogeneous, isotropic, and linearly elastic, except for the brain, which is assumed as viscoelastic in nature. The shear characteristics of viscoelastic behaviour of the brain are expressed by

$$G(t) = G_\infty + (G_0 - G_\infty)\, e^{-\beta t} \tag{9}$$

Here G_∞ is the long-term shear modulus, G_0 is the short-term shear modulus and β is the decay factor. Material properties for helmet and head parts are given in Tables 1 and 2.

3. ANALYSIS OF HELMET-HEAD IMPACT

The experiments on helmets are conducted, normally, through drop technique, in which the dummy head along with helmet are dropped from certain height on to the anvil, which may be flat or hemispherical. The drop-test simulations were carried out by giving initial velocity to helmet-head, which impacts the flat rigid surface. Helmet was tied to the head by a nylon strap. The FE model of head by Willinger[3], *et al.*, mentioned above, was combined with a FE model of two-wheeler helmet to compare the forces experienced by the head during impact with a ventilated and non-ventilated helmet, and helmet with metal foam.

The full two-wheeler helmet model required input data like geometry, initial and boundary conditions, interface conditions, and material properties. Surface-to-surface contact interactions were used between the head and helmet and between the helmet and rigid surface to prevent interpenetration of these surfaces. Figure 3 shows FE models of helmet-head undergoing frontal impact and side impact with a flat rigid surface. One groove is made in central plane of the helmet foam from front to back. Numerical impact simulations were performed with helmet-head by considering helmet without groove, helmet with one groove in liner foam and with aluminium foam as outer shell.

Figure 4 shows the contact forces between rigid surface and outer shell for various helmet types during

Table 1. Material properties for helmet and head

Part	Density (Kg.m^{-3})	Elastic modulus (N.m^{-2})	Yield stress (N.m^{-2})	Poisson's ratio	Thickness (mm)
ABS shell	1200	2.0×10^9	34.3×10^6	0.37	3
Aluminium foam	300	1.5×10^9	$4.41\times10.^6$	0.05	7
Strap (nylon)	1100	3.0×10^9		0.42	1
Skin	1200	16.7×10^6		0.42	7
Skull (outer table)	1800	15.0×10^9		0.21	2
Skull (inner table)	1500	4.5×10^9		0.0	3
CSF	1040	12.0×10^3		0.49	
Face	3000	5.0×10^9		0.21	5
Faux	1140	31.5×10^6		0.23	2
Tentorium	1140	31.5×10^6		.23	1

Table 2. Material of brain

Part	Density (Kg.m^{-3})	Bulk modulus (N.m^{-2})	G_0 (N.m^{-2})	G_1 (N.m^{-2})	β (s^{-1})
Brain	1040	1.125×10^9	49.0×10^3	16.7×10^3	145

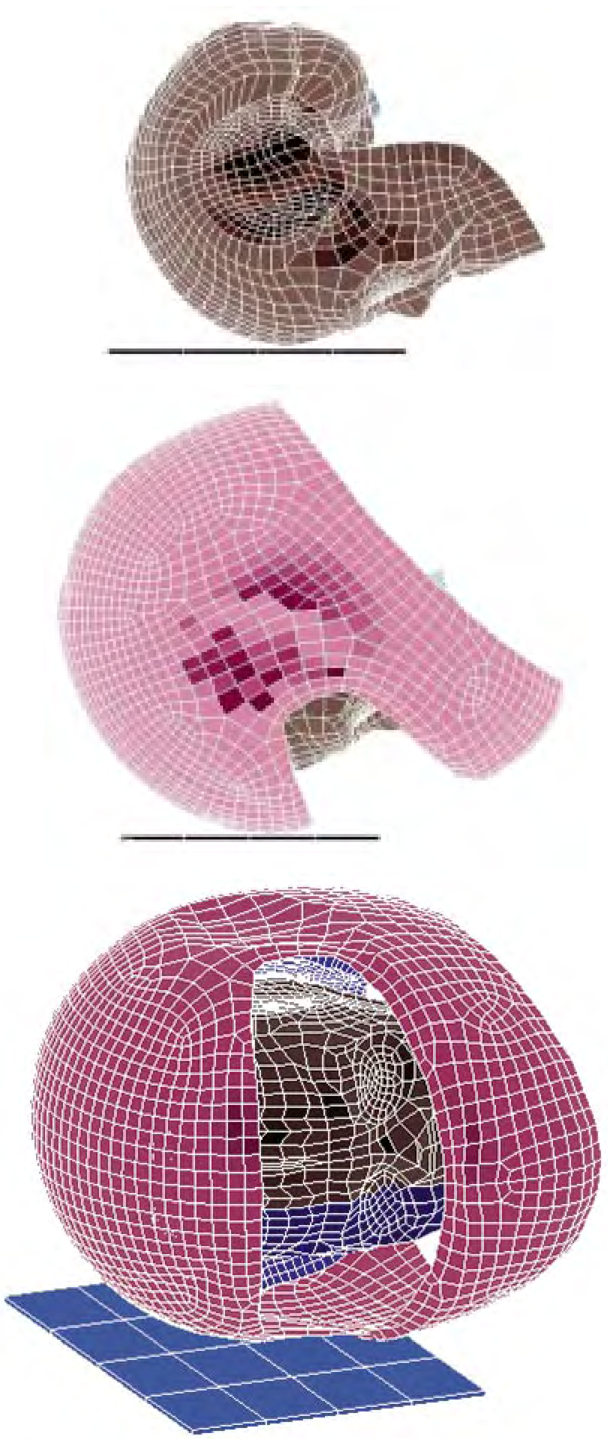

Figure 3. Finite element model of helmet-head in front and side impacts.

frontal impact. Forces on the helmet and head are raised till 5.3 ms and then dropped once these started bouncing back. The maximum force on helmet is 14700 N and 15100 N for ABS shell helmets without a groove and with a groove, respectively. With metal foam for outer shell, the maximum force on the helmet is 13800 N, which is approximately 900 N less compared to the ABS shell helmet. The lower forces in metal foam are probably due to its lower yield stress and flatter nature of the hardening curve. The weight of the outer shell has been reduced by 60 per cent with metal foam as compared to ABS material. However, more investigation are required as some regions of shell experienced tension and also tensile behaviour of metal foams is not clearly understood.

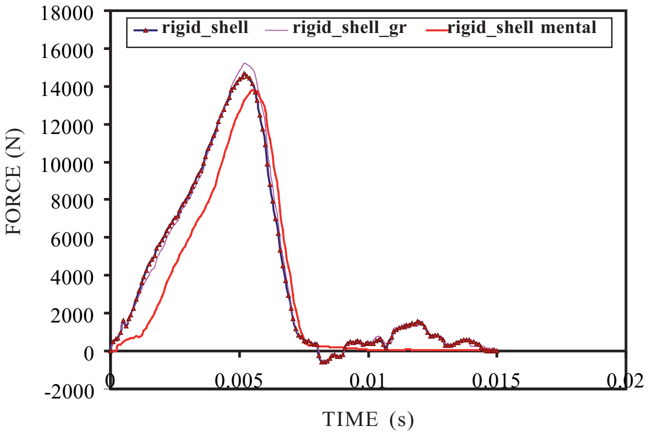

Figure 4. Forces between rigid surface and helmet shell in front impact at 10 m.s^{-1} velocity.

The helmet-head impact duration was almost the same in all these cases and was around 7 ms. The total force on the head (i.e., contact force between head and liner foam) due to helmet impact was approximately 13000 N for all the cases and is shown in Fig. 5. As brain is the most sensitive part in the head, pressure waves were studied in it as a function of time when the helmet-head impacts. The pressure was calculated by

$$P = -\frac{1}{3}(\sigma_{11} + \sigma_{22} + \sigma_{33}) \qquad (10)$$

where σ_{11}, σ_{22}, and σ_{33} are the normal stresses.

In Fig. 6, the intracranial pressures, which are considered in the brain, are shown at coup and contra-coup sites. Force on the head due to impact is creating the positive pressures at the coup site because of compression and negative pressures

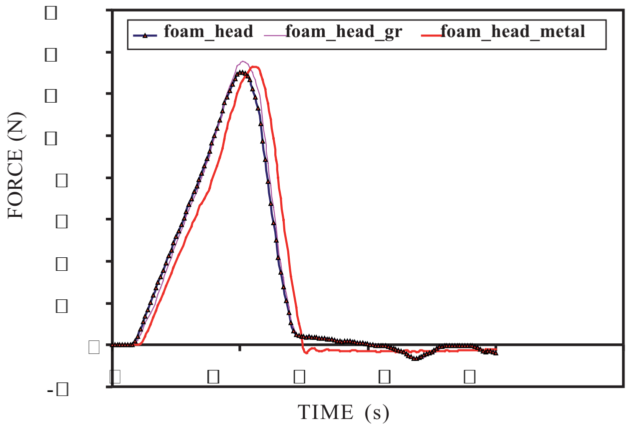

Figure 5. **Total forces on the head in front impact at 10 m.s^{-1} velocity.**

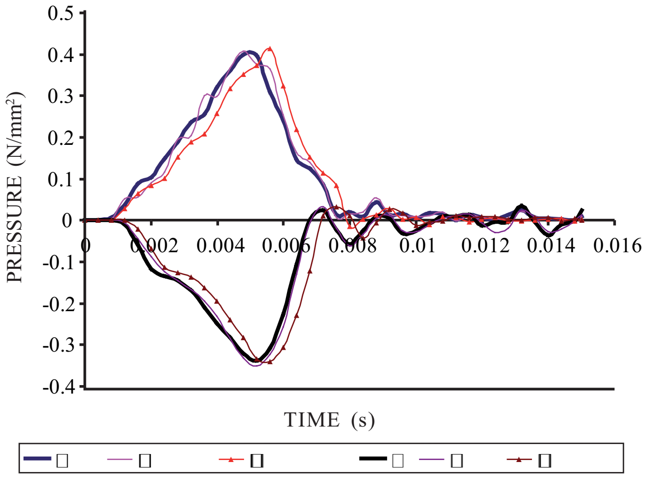

Figure 6. Intracranial pressures in front impact at velocity 10 m.s^{-1}.

are developed at contra-coup site because of tension. The trend of intracranial pressures is similar in all the cases which are 0.4 MPa at coup site and –0.35 MPa at contra-coup site. With the skull deformation under the head impact, brain also undergoes compression along with shear deformation, which can cause brain damage. Von Mises stresses are studied as it gives the overall magnitude of the stress tensor. Figure 7 shows the contours of von Mises stresses in the brain at 6.5 ms during the frontal impact of helmet with outer shell as metal foam. The highest von Mises stress in the brain was about 58 KPa and was observed in brain stem both in metal foam and ABS helmet, whereas in the grooved helmet, these stresses were slightly higher at 59.1 KPa.

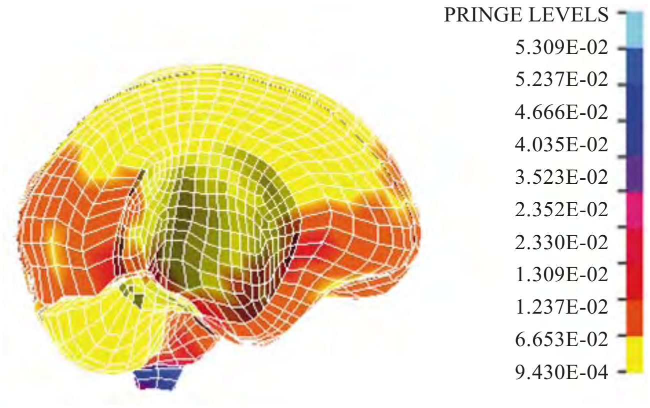

Figure 7. **Von Mises stresses in brain with metal foam helmet in front impact.**

Figure 8 shows the forces between different contact interfaces in the helmet (rigid surface-outer shell, outer shell-foam and foam-head) during the side impact at 10 m/s velocity. The maximum force on outer shell is 17000 N and the maximum force on the head is 14500 N. Side impact studies with grooved helmet showed similar results. Studies with metal foam are in progress.

The intracranial pressures for side impact in Fig. 9 illustrates for various helmet types (without groove, with groove, and with metal foam) and show similar trends in all the cases. The maximum pressure at coup site is increased but reduced at contra-coup though forces were increased in side impact.

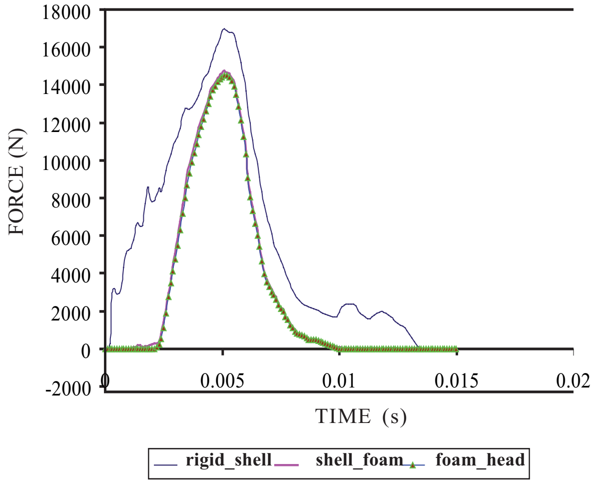

Figure 8. **Forces in the helmet-head in side impact at 10 m.s^{-1} velocity.**

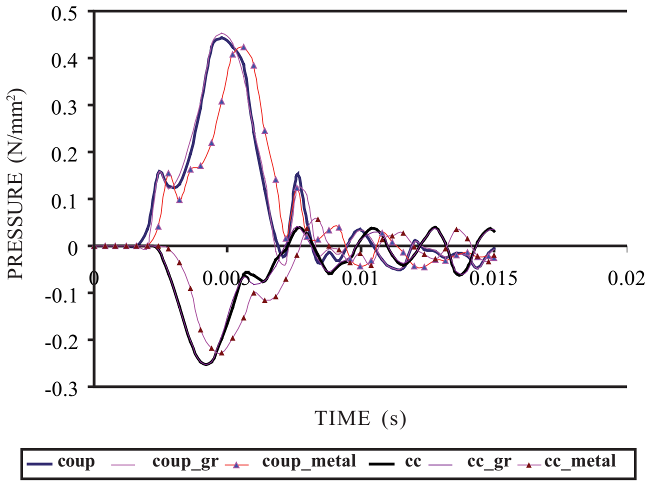

Figure 9. Intracranial pressures in side impact at 10 m.s^{-1} velocity.

The maximum pressure at coup site is 0.45 MPa and at contra-coup site is –0.25 MPa. Figure 10 shows the contours of von Mises stresses in the brain at 6.8 ms in the side impact of helmet with metal foam as outer shell. In side impact, the highest von Mises stress in the brain was about 58.6 KPa and was reached in brain stem with metal foam helmet whereas in conventional helmet and in grooved helmet with ABS shell, the stresses were higher at 66 KPa.

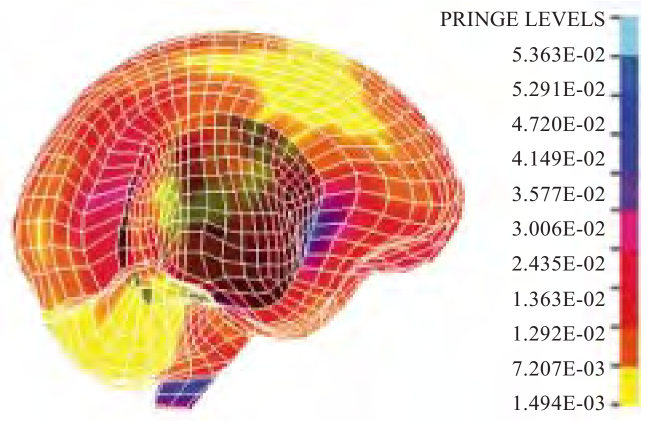

Figure 10. Von Mises stresses in the brain with metal foam helmet in side impact.

4. CONCLUSIONS

The study on frontal and side impact of helmet-head with rigid surface indicates that the provision of groove in liner foam is not detrimental to the dynamic performance of the two-wheeler helmet. The maximum pressures in the brain were not sensitive to the groove in helmet. The weight of the outer shell has been reduced by 60 per cent with metal foam as compared to ABS material and its dynamic performance was not impaired with this weight reduction.

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