MODELLING OF HEAD IMPACT ON LAMINATED GLASS WINDSHIELDS

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ABSTRACT

The windshield of a car is impacted by pedestrians and riders of two-wheeled vehicles (with or without helmets) in a large proportion of road traffic crashes. This paper reports work on development of a FEM model in PAMCRASH for head windshield impact from outside the car.. This includes a helmet mode and a windshield model. Helmet drop test data, impact data for a standard headform without helmet impacting a windshield and impact data for headform with helmet impacting the windshield is used to verify the model.

KEYWORDS

Windshield, Finite Element Method, Helmets,

THE WINDSHIELD OF A CAR is impacted by pedestrians and riders of two-wheeled vehicles in a large proportion of road traffic crashes. Acceleration history and the forces experienced by the head (head, with or without a helmet) are of significance in two-wheeler rider and pedestrian safety prediction. Although impact tests provide useful information, improvements in design can be more easily affected if a mathematical model could be created to simulate the impact experienced by the helmet and head during a crash. Also, various impact situations can be considered inexpensively and effect of design changes can be tested. The mathematical model should be validated against the data available from experiments. In this work we describe FEM simulation of windshield impact from outside the vehicle using PAMCRASH™, and its verification.

We have established a helmet model from CMM(Coordinate measuring Machine) data for the geometry and characterisation of static and dynamic material property of the shell and foam. Geometry of the windshield from CMM data, and standard material properties for float glass and PVP(Poly Vinyl Propelene) has been used to model the windshield. The standard properties have been tuned to match the simulation. Emphasis was on obtaining correct impactor motion rather than windshield deformation characteristics as we are primarily concerned with head acceleration. The model was analysed using repeated runs in PAMCRASH by perturbing geometric and material parameters. Using this information, we have arrived at a set of parameters that yield the right impact characteristics. Using the windshield model established through perturbation analysis and data for impact without helmet, we simulated the impact of headform with a helmet and find that to be conforming also.

HELMET MODEL

In this section, we present the finite element model for a helmet subjected to drop test. In a drop test, the head form and helmet have an approximate velocity of 10 m/s at impact. Gilchrist and Mills (1993,94,96) in a series of papers have done experimental measurements of shell deformation during the impact of a motorcycle helmet and compressive stress-strain relation of foam liner. The information was used to construct a computer model that allows the effects of different shell materials and foam densities to be predicted. The model is a lumped mass model and details such as different locations of impact or damage of helmet cannot be incorporated in such models. The authors have also used such models for helmet shell optimization. Zellmer (1993) performed drop tests of different types of helmets with different velocities and points of impact on the helmet. He found that shock absorption capacity of helmets in use was more affected by the thickness of the protective padding than by its energy absorption capacity. The effect of rotational acceleration on the head-form was also investigated. Miyari and Nagai (1995) conducted experiments on full face helmets and compared the safety and shock performance of helmets with different types of laminated shells. Brands et al (1996) used Finite element package MADYMO to study the full face motorcycle helmet mounted on head form. The model was validated against experiments. The impact simulation results were in close match with the experiments. However, it would be more useful if more realistic material properties and constitutive law for the liner was used. Some literature also exists on limiting performance of sports helmets for prevention of head injury. However, the models used are lumped parameter models. Lately, a Finite Element parametric study has also been done by Yettram et al. (1994).

During impact the outer surface of the helmet on coming in contact with the rigid surface comes to a stop. The head inside the helmet, however, continues to travel with its initial velocity and hits the foam padding which through its compression reduces the acceleration of head. The essential components of a helmet are a shell, a protective padding and a retention system. There are other components such as peak, visor, goggles etc. that are not important for analysis. The shell is commonly made of short fiber reinforced plastic or poly-carbonate. The shell behaves elastically and its properties can either be determined by simple rule of mixtures if volume proportion of the fibers is known or like we have done, tests have to be done to determine the properties. The shell is provided to prevent the penetration of the helmet by a sharp object. However, the usefulness of this property is sunject to debate.

The foam padding is the other major constituent of helmet and it works on the principle that the impulse is equal to change in linear momentum. The impact force experienced by the head will is reduced if the duration of impact is increased. The foam padding increases the duration of impact due to its low stiffness properties. In most helmets expanded polystyrene is used as protective padding. The stress-strain law of protective padding is quite difficult. The crushable foam is a non-linear rate dependent compressible material and requires special constitutive laws. Two of these constitutive laws are available in PAMCRASH™ (Material types 2 and 20). However determining the constants in these laws requires extensive experimentation. Yettram et al. report that strain rate sensitivity of the stress-strain law is negligible for the range of test velocities considered here. As a first attempt, the liner is treated as elasto-plastic material undergoing linear strain hardening. We use material type 1 available in PAMCRASH™. The disadvantage of using this model is that it does not represent the stress-strain behaviour of foam accurately. Foam exhibits volumetric bulk and shear plasticity, whereas material type 1 can model only shear plasticity. The advantage of using material type 1 lies in obtaining the constants required for the constitutive law through simple uniaxial test. Between the foam and head there is very thin layer of comfort foam which is very soft. The deformation of this has been neglected and a gap of 3 mm is kept between the head form and the foam liner.

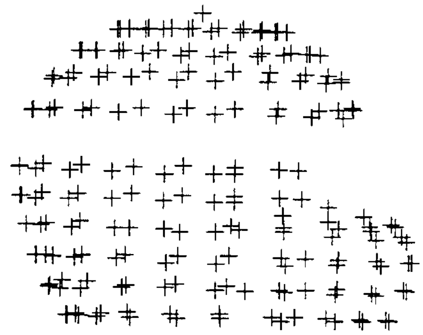

Fig. 1- CMM Data Points of Helmet

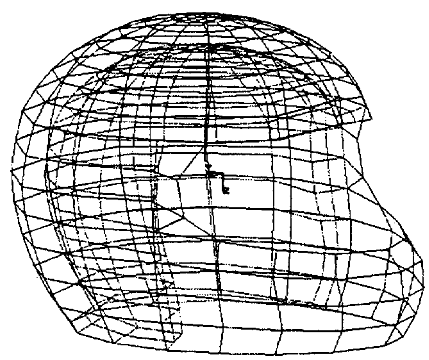

Fig. 2 -Solid Model of Helmet

The dimensions and the coordinates of various components of the helmet were measured using a CMM. These were used to generate a solid model in CAD package IDEAS™. From the CMM data curves were created. Surfaces were then created and the solid model created was meshed. The outer shell was meshed as shell mesh having four noded elements. The foam layer was modeled using solid elements. Number of shell elements was 220 and number of solid elements 360. The head-form is assumed rigid being much harder as compared to the foam. The head can be modeled using shell elements and giving it suitable visco-elastic properties available in literature. However we have not felt that to be necessary for our model as we are interested in overall head accelerations. The non-penetration condition at the head-form foam interface is implemented through contact elements. The contact elements also have to be introduced between the foam and the outer shell as also between the shell and the rigid impacting surface. The contact elements also allow the bodies to slide with respect to each other. In Pam Crash the contact constraint is implemented through penalty method, where geometrical inter-penetrations between the contacting surfaces is penalized by counteracting forces that are in essence proportional to the penetration depth. The coefficient of friction between the head form and the foam, and between the foam and shell were determined by simple experiments. The values were found to be 0.3 and 0.6 respectively.

The impact period in helmets is of 5-6 ms in duration. An accurate solution to such problems requires very small time steps and a very fine mesh is required in the impact region as compared to regions further away. An explicit scheme is used, as for small time steps it is computationally less expensive as compared to implicit schemes. PAMCRASH™ used here employs explicit time marching scheme. The output from finite elements modeling are displacements, velocity and acceleration at various locations in the helmet.

RESULTS OF SIMULATIONS

Plots of head form accelerations vs time has been shown superposed for the drop test and simulation in Figure 4. Acceleration values start rising from the time the head form and foam come in contact and a sharp peak is observed at about 3 ms where the acceleration reaches a local maximum of 160 g approximately. Before the foam comes in contact with the head form, the shell bounces back and the foam rebounds along with it. Once the foam comes in contact with the head form the nodes in contact on the foam and the head form have the same velocity untill the time they separate (about t = 10 ms.). It is seen that at point of maximum acceleration the head form has reached a zero velocity and also its maximum displacement at t = 8 ms (Figures 3a and 3b). The head form rebounds after that. The foam with initial thickness of 25 mm is compressed to almost 10 mm. This explains why helmets of poor quality with insufficient foam thickness offer little protection to the user. The velocity of the shell reaches a maximum of 3.2 m/s at 2 ms. At this time, as suggested by Brands et al., both the shell and head form are compressing the foam padding – the shell is moving upward whereas the head is moving down. At t = 8 ms the head form rebounds while still maintaining contact with the foam which also starts recovering. They finally separate at t = 10 ms the time at which the velocity of the foam suddenly drops close to the shell velocity. The head form velocity at the end of impact is about 4.3 m/s.

Even though the overall trends of the experimental and numerical results are the same, there are some exact material properties for the foam liner were not available and we used standard material properties found in literature for the helmet foam. Differences between results and experimental values can are attributed to this.

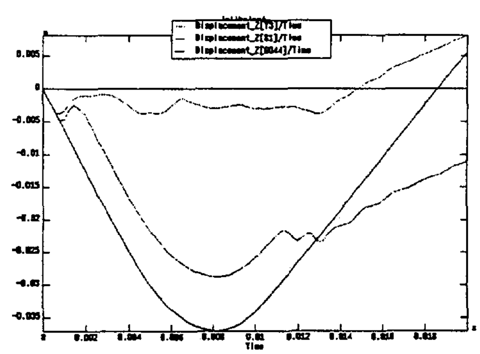

Fig. 3(a) - Displacement curves for the helmet drop test simulation (Node 73 is on the shell, Node 81 is on the foam and Node 644 is on the head-form)

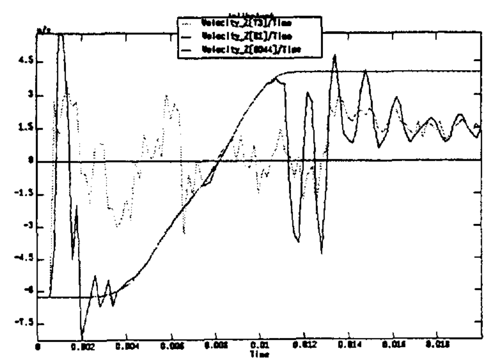

Fig. 3(b) - Velocity curves for the helmet drop test simulation (Node 73 is on the shell, Node 81 is on the foam and Node 644 is on the head-form)

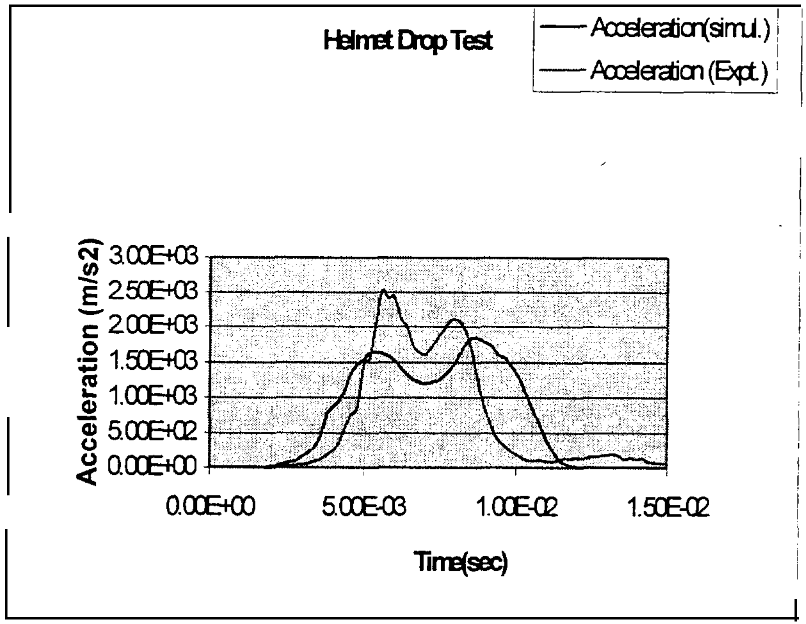

Fig. 4 - Experimental validation of the acceleration curves obtained from simulation.

MODELING OF IMPACT ON WINDSHIELD

The Windshield of a car consists of three layers with the inner layer consisting of polyvinyl butyl (PVB) which is a resistant, adherent plastic film bonded together between the two layers of glass under heat and pressure. Once sealed together, the glass "sandwich" behaves as a single unit and looks like a normal glass. Annealed, strengthened or tempered glass can be used to produce the laminated glass. The glass may crack upon the impact, but the glass fragments tend to adhere to the plastic interlayer rather than falling free and potentially causing injury. Hence when broken by impact, laminated glass tends to remain integral in its frame, minimising the risk of injury from sharp edges and flying and falling glass and strongly resists penetration by the impacting object or person. Our aim was to model the head deceleration on impact with the windshield.

IMAPCTOR MODEL :The impactor is modeled as a hollow hemisphere of 165mm diameter of 10 mm thickness. Then the hemispherical shell was divided in to parts to create a mapped shell mesh. Material set for the impactor was PAMCRASH™ 'null material', which does not compute internal forces thus reducing computation time. We were not interested in deformation and stress experinced by the impactor, but in the overall velocity and acceleration. Number nodes for the impactor was 1549 and which led to 15 18 shell elements.

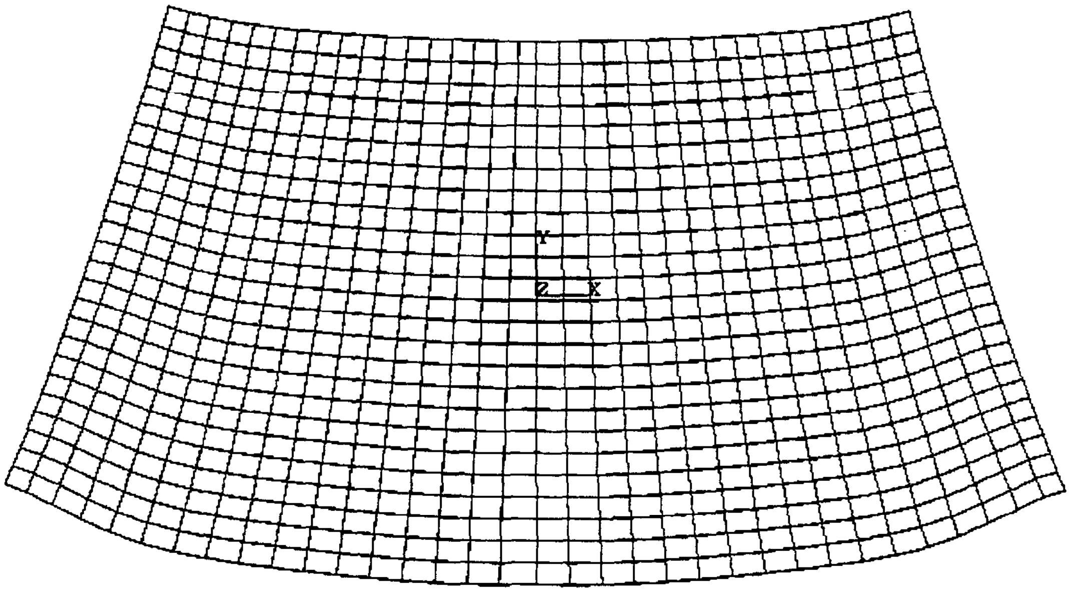

Fig. 5 - Mesh on windshield of a car

WINDSHIELD MODEL :For the windshield, CMM data for the symmetrical half of the windshield was read into IDEAS through a program file. The surface was created through these points by using 3D-spline and loft operations. Two additional surfaces were created by offsetting the midsurface by 1.5 mm each, thus creating the top glass, middle PVP and bottom glass layers. All these layers were created separately to have ease in defining the material properties in PAMCRASH™ and meshed separately by mapped mesh option. These were reflected to get complete windshield surface with shell mesh on it. The three separate layers were then assembled in IDEAS as shown in Figure 5. The three layers finally had 910 nodes and 892 shell elements. This assembly of windshield was exported to PAMCRASH™ for further impact analysis.

ANALYSIS OF WINDSHIELD IN PAMCRASH™ : Modelling the windshield presents some special problems. Even though the CMM data can be used to create the mesh, the constitutive properties are difficult to ascertain. The material properties of glass and PVB were taken from material science handbook (Harward) The sensitivity of the parameters were evaluated and tuned to match the impact profile. The initial properties chosen are:

Glass Density = 2400 Kg/m^3, Young's Modulus = 7.44 e+10 N/m^2, Yield stress = 3.44 e+06 N/m*, Poisson's ratio = 0.2, Thickness of glass = 0.002 m (for single layer)

PVB (polyvinyl Butyl) Density = 950 Kg/m^3 ,Young's Modulus = 5.0 e+07 N/m^2, Poisson's ratio = 0.22, Thickness = 0.001m

Boundary Conditions : The windshield is fitted into the frame. This translates mathematically into end condition somewhere in between the two ideal cases of simple support and fixed-fixed (cantilever), as the clamping is not fully rigid. However our finding is that the fixed-fixed assumption is fairly good. Impact simulations with simply supported end conditions produced the response shown in Figure 6.

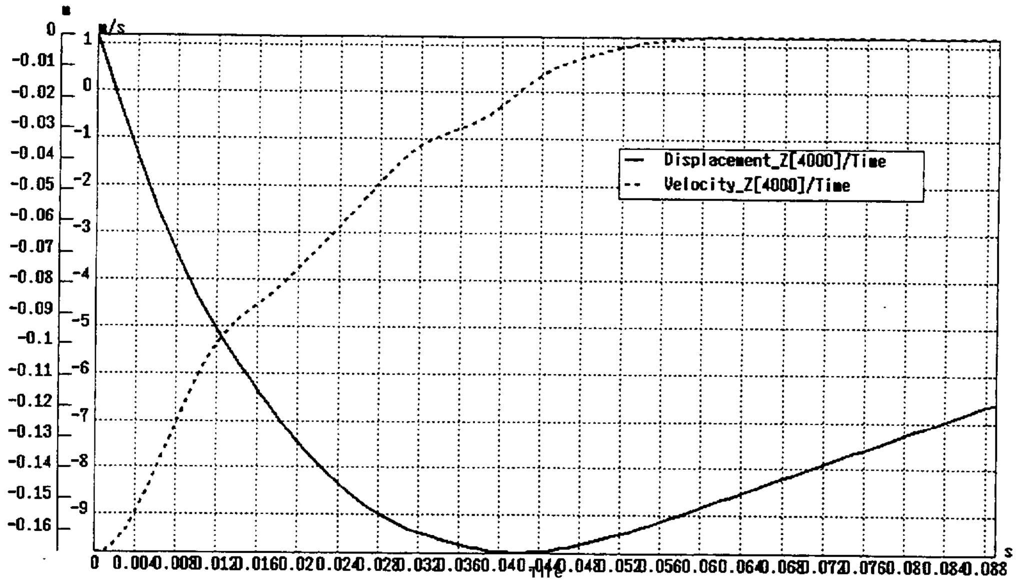

Fig. 6 Impact simulated with simply supported boundary conditions

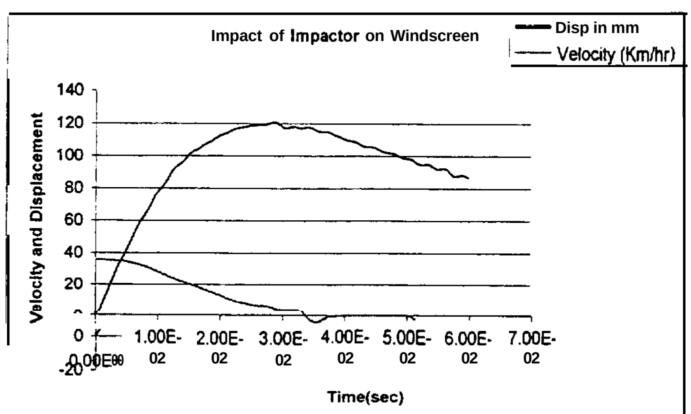

Fig. 7 : Experimental data of windshield - impactor impact

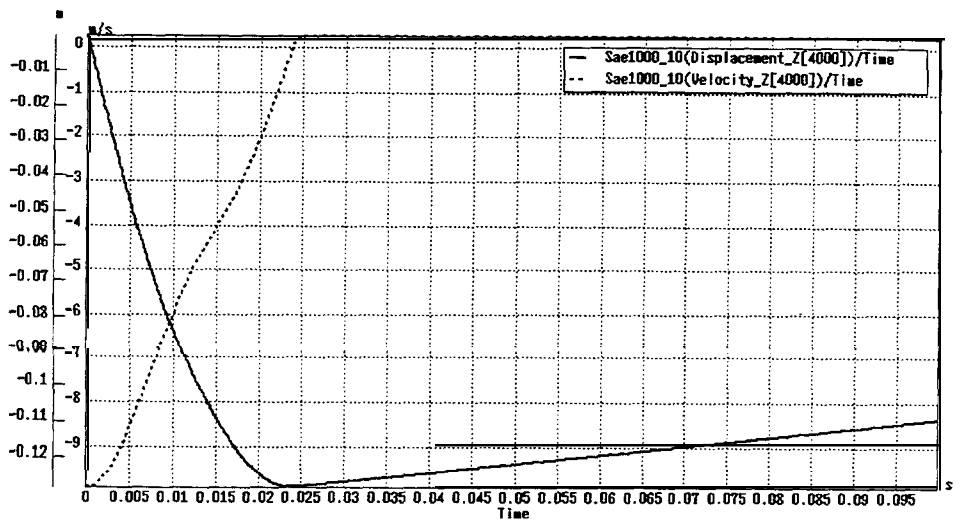

Fig 8 : Impact simulated with fixed end conditions

This simulation gave a peak displacement of 0.167 m after 0.056 s from the start of impact as shown in Figure 6. This differs from the experimental data shown in Figure 7. The simulation for fixed-fixed end condition shown in Figure 8 is closer to the experimental data.

To conclude that fixed-fixed is the appropriate model, we had to eliminate the effect of variation in material property of the glass or PVB. Parametric variation in the material properties were introduced with simply supported end conditions. In the study it was found that by varying the parameters by 20% from their nominal values, the peak displacement of impactor tip was varying between 0.160 to 0.170m. which differs from the experimental measure. We concluded that fixed-fixed is the appropriate model to use and carried out an extensive parametric study to determine sensitivity of parameters to fine tune the model.

PARAMETIC STUDY OF WINDSHIELD

Material properties of components were not available as the original tests were carried out on old vehicles. We used handbook (Harward) values for glass and PVP properties. In the following section, we describe a series of simulations with perturbed component properties that we carried out to determine sensitivity of various parameters. We perturbed the following parameters: Thickness of glass layer (t_g), thickness of PVB layer (t_p) Coefficient of friction between upper glass and impactor (μ_{ig}), Coefficient of friction between glass and PVB layer (μ_{gp}), Poisson's ratio of glass (v,), Poisson's ratio of PVB (v,), Yield stress of glass (σ_g), yield stress of PVB (σ_p), Young's modulus of PVB (E_p), Young's modulus of glass (E_g)

A typical summary table of parametric variation study is shown in Table 1. The table lists perturbed values of parameters and their effects on peak displacement of impactor ($x_{max,}$), time to reach the maximum displacement (t_{max}) from the start of impact, time to change of sign of velocity curve (t_{vel}) and accelerations of impactor tip point in z directions, the impact direction.

EFFECT OF VARIATION OF THIKNESS OF GLASS (t,): In the parametric study, glass thickness was varied by 20% and 40% above and below of the initial assumed value of 0.002 m. From the study it was found that with increase of glass thickness by 20%, there was decrease in peak value of displacement by 8.07%, decrease in the peak time of displacement by 4.1% and decrease in the velocity peak point (where velocity curve changes the sign) by 3.98%. For increase in thickness by 40%, there was decrease in peak value of displacement by 14.3%, decrease in the time of peak displacement by 8.3% and decrease in velocity peak time by 7.8%. It was noted that for glass thickness of 0.0022m, peak displacement of 0.124 m.

TABLE 1- Effect of variation of thickness of Glass

t_g (m)	x_{max} (m)	t_v (sec)	t_{vel} (sec)	a_z (m/s^2)
0.0010	-0.1631	0.0271	0.02800	629.2000
0.0015	-0.1427	0.0250	0.02590	1016.7000
0.0020	-0.1286	0.0240	0.02510	1024.2300
0.0025	-0.1182	0.0230	0.02410	1160.3500
0.0030	-0.1102	0.02'20	0.02310	1589.6000
0.002 1	-0..1262	0.0239	0.02500	1321.8000
0.0022	-0.1240	0.023 1	0.02410	1294.0000
0.0023	-0.1220	0.0023	0.0241	1334.720

EFFECT OF VARIATION OF PVB THICKNESS (t_p) PVB thickness was varied by 20% above and below of the initial assumed value of thickness 0.001m. It was found that due to increase in the thickness by 20%, there was decrease in the peak displacement by 1.1%, the time at which peak displacement occurred was unchanged and decrease in the velocity peak time by 0.4%. When the thickness was changed by 40%, peak displacement decreased by 2%, time of peak displacement and time of velocity peak were same. It was noted that for PVB thickness of 0.002m the peak displacement was 0.125545m.

EFFECT OF VARIATION OF COEFFICENT OF FRICTION BETWEEN GLASS AND PVB LAYER (μ_{gp}). For increase in coefficient of friction by 20%, peak displacement time and velocity peak time remained same whereas the peak displacement increased by 0.4%. for increase by 40%, the velocity and peak displacement time remained the same as 0.024s and 0.0252s respectively. For change by 40% value, peak displacement time and velocity time remained same but increase of peak displacement by 0.42%. Hence coefficient of friction between PVB and glass had no effect on the displacement and velocity curves of impactor.

EFFECT OF VARIATION OF COEFICENT OF FRICTION BETWEEN GLASS AND HEMISPHERICAL IMPACTOR (μ_{ig}). For increase in the value by 20%, displacement time and velocity peak times remained unchanged where as increase in peak displacement of impactor by 0.0031%. For 40% increase in the value of friction, peak displacement time and peak velocity time were found to be the same but there was a decrease in displacement peak by 0.01%. Hence there is no effect of coefficient of friction between glass and impactor on the displacement peak time and magnitude. The peak time of acceleration was found 1 00g in each case.

EFFECT OF VARIATION OF POISSONS RATIO OF GLASS (ν_g). For change in initial value by 20% and 40%, displacement peak time and velocity peak time remain unchanged. Displacement peak value increased by 0.8% and 0.016% respectively.

EFFECT OF VARIATION OF POISSONS RATIO OF PVB(ν_p). There was no change in the peak displacement time and peak velocity time for the change in poison's ratio by 20% and 40% of assumed value. The peak displacement increased by 0.08% and 0.016% for increase in poison's ratio by 20% and 40% respectively.

EFFECT OF VARIATION IN YIELD STRESS OF GLASS (σ_g) For increase of 20% and 40% of initial values, displacement peak value decreased by 5.1% and 9.1% respectively. The time of peak displacement decreased by 4.3% and 12.5% respectively whereas peak velocity time reduced by 4.3%. Sub iterations were made and it was found that for yield stress of 3.8e+06 N/m^2, the displacement magnitude is 0.124955m.

EFFECT OF CHANGE IN YIELD STRESS OF PVB (σ_p). For increase of 20% in value of yield stress, there is only 0.04% increase in peak displacement. The peak acceleration in every case is more than 100g. The peak displacement time and peak velocity time remains unchanged from their original values. Hence there is no effect of yield stress of PVB on simulation results.

EFFECT OF CHANGE IN YOUNG'S MODULUS OF GLASS (E,). Parametric changes in the Youngs modulus of glass showed that for an increase of 20% from the initial value there is a change of 0.3%, 0% and 0.4% in peak displacement, peak displacement time and velocity peak time respectively. Hence Young's modulus of glass has no effect on the results.

EFFECT OF CHANGE IN YOUNG'S MODULUS OF PVB (E_p). Variations in the Young's modulus of PVB had no effect on the simulation values such as peak displacement magnitude, peak displacement time as well as peak velocity time. There is only 0.24% increase in the peak displacement magnitude for the increase of 20% of initial value.

CONCLUSIONS OF PARAMETRIC STUDY. Neither the Young's modulus of glass nor the Young's modulus of PVB influenced the results of velocity or displacement magnitude and time. Similarly there was no effect of variation of friction between glass and PVB as well as friction between glass and impactor. Following parameters influenced the simulation results:

1. Thickness of glass (t_g)
2. Yield stress of glass(σ_g)
3. Thickness of PVB(t_p)
4. Poissons ratio of PVB (ν_p)

By conducting further simulations by varying only the four parameters above, the following properties were decided as the final properties.

Glass Properties

t_g =0.0022m
E_g = 7.44e+10 N/m'
σ_g = 3.8e+06 N/m^2
ν_g = 0.2
μ_g = 0.8

PVB Properties

t_p = 0.002m
E_p = 5.0e+07 N/m^2
σ_p = 2.07e+05 N/m^2
ν_p = 0.21
μ_p = 0.3

Figure 9 shows the displacement and velocity time history of the simulation with the above parameters. This gives a good correlation with the experimentally measured values.

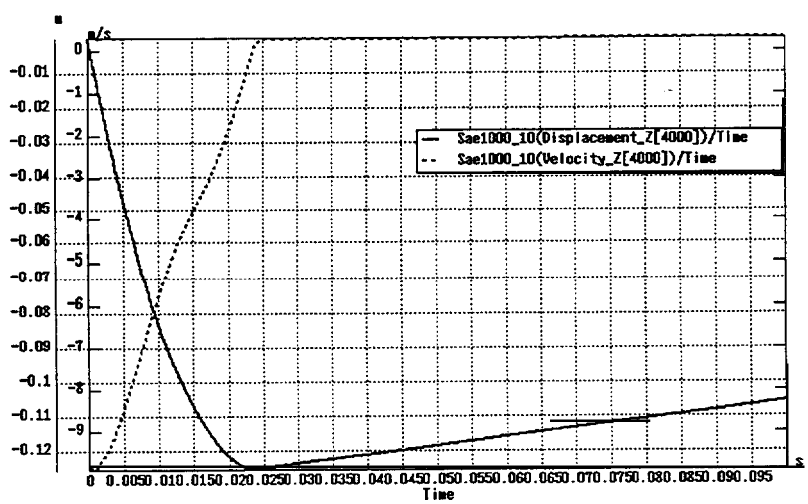

Fig. 9 - Simulation results of the wind screen impactor impact with tuned parameters.

HELMET IMPACT ON WINDSHIELD

We had data for impact on the same windshield for a headform encased in a helmet and a verified dynamic model for the helmet. We next assembled the helmet on top of the impactor in PAMCRASH™ and ran simulations.

The boundary condition used for windshield was fixed boundary type. Surface-surface contact was defined between helmet and upper glass, outer shell and foam layer, where as self impacting contact with edge treatment was defined between glass and PVB. The coefficient of friction between helmet outer shell and foam was given as 0.4. A contact thickness of 1 mm was defined between the helmet and upper glass layer where as contact thickness of 1.5 mm was defined between glass and PVB. In this case the helmet was allowed to impact the windshield with the velocity of 37.3 km/h (i.e. 10.36 m/s). Figure 11 shows the assembly of helmet with impactor and windshield.

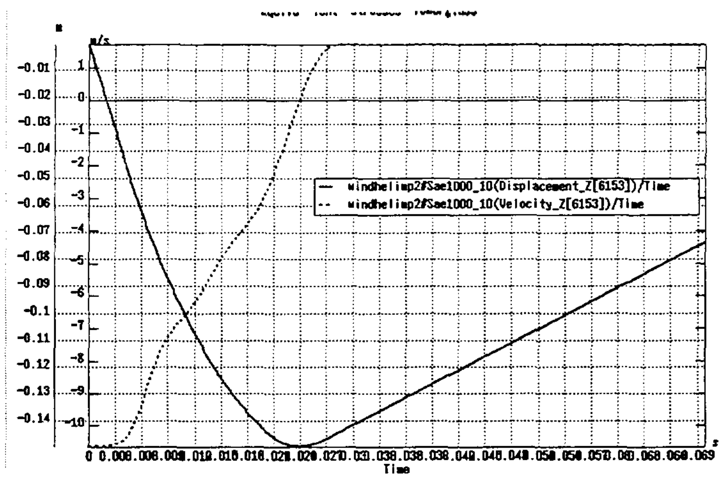

Fig. 10 Simulated Velocity and displacement for the impact of the helmet(including head-form)and the windshield

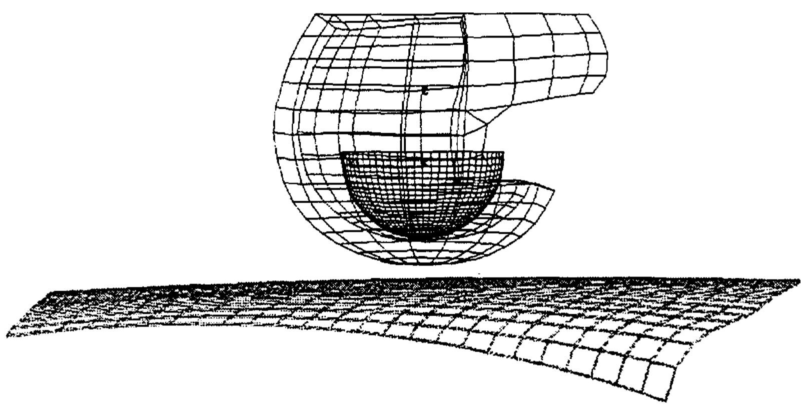

Fig. 11 - Assembly of helmet and impactor with windshield

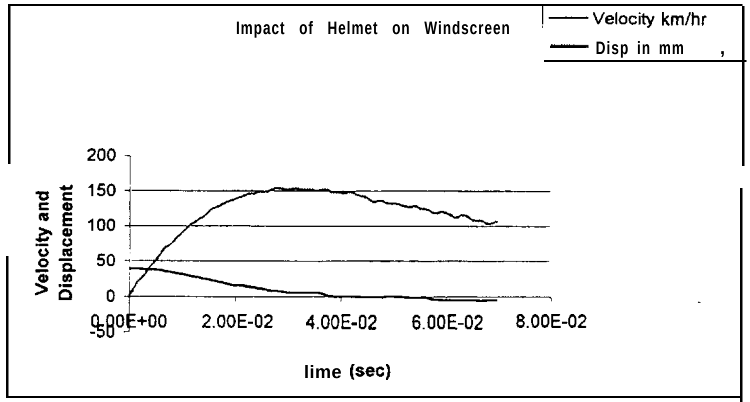

Fig. 12 - Velocity and displacement curve for windshield- helmet- impactor crash

The simulation peak magnitude displacement of 0.147 m is very close to the experimental result of 0.150m. The time of peak of displacement 0.024s is close to experimental results of 0.027s. Also the time of velocity peak changing the sign in 0.028s which is close to experimental results of 0.03s. The experimental results are shown in Figure 13. The displacement and velocity curves of the experimental results are shown in Figure 12.

CONCLUSIONS

An FE model using PAMCRASH™ for laminated windshield that predicts acceleration time histories for head impacts has been established. Motion-time history of the head obtained in modelling is qualitatively similar to the experimental data. Small variations in modulus of the glass and PVP, thickness of PVP, friction coefficient between impactor and glass do not modify the impact characteristics significantly. Thickness of glass, yield stress of glass, Poisson's ratio of PVP and affect impact characteristics. The end fixity conditions for the windshield are closer to fixed-fixed than simply supported.

REFERENCES

1. Gilchrist. A and Mills. N. J. "Modelling of the impact response of motorcycle helmets", 1994.
2. Harald Zellmer, Federal Highway Research Institute, "Investigation of the Performance of Motor Cycle Helmets Under Impact Conditions". STAPP car crash conference., 1993, pp. 59-68.
3. Brands, D. W.A., Thunnissen, J.G.M. and Wismans, J.S.H.M., 1996, "Modelling Head Injury Countermeasures: a 3D helmet model", AGARD Specialists' meeting on Impact Head Injury:Responses, Mechanisms, Tolerance, Treatment and Countermeasures.
4. Schreiber, P.H. , Pilkey, W.D., Crandall, J.R., and Cheng, Z. Q., "Limiting Performance of Bicycle Helmets Under Impact Loads", 1998.
5. Gilchrist. A and Mills. N. J. "Impact deformation of ABS and GRP motorcycle helmet shells." Plastics, Rubber and Composites Processing and Applications 2 1 ,1994, 141-l 50 .
6. Gilchrist. A and Mills. N. J., 1996, "Protection of The Side of the Head." Accid. Anal. And Prev., Vol.28 No. 4, 1996, pp.525-535.
7. Miyairi Hiroo and Nagai Masahiro , "Shock absorption performance of full-face rider helmets" Adv. Composite Mater., Vo1.5, No. 1, 1995, pp. 63-71.
8. Mohan, D., B. K. Mishra, K.P. Kothiyal and A.K. Banerji, "Helmet and head injury study of crash involved motorcyclists in Delhi", Proceedings of the IRCOBI conference on biomechanics of impacts, 1984, pp. 64-73.
9. Haward RN, Strength of plastics and Glass, Cleaver Hume Press Ltd, New York.