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Analytical Investigations on the Damage of Composite Body Armor

Lakshmi L [1], Nandakumar C G [2]
[1](PG Student, Department of Ship Technology, Cochin University of Science and Technology, India)
[2](Associate Professor, Department of Ship Technology, Cochin University of Science and Technology, India)

Abstract : *Lightweight ballistic body armor made of laminated composites exhibits superior ballistic performance compared to metallic materials and could replace high density metallic materials of body armor giving sufficient energy saving and mobility for the wearer. But, damage of composites body armor when subjected to ballistic impact causes sufficient strength reduction mainly due to matrix cracking, delamination and fiber breakage and thus resulting in overall failure of the ballistic panel. Hence, damage assessment is essential for the development of improved materials and design methods in the field. Finite element analysis of composite body armor with and without human surrogate target has been considered for the purpose.*
Keywords: *ballistic impact, body armor, composites, damage, failure*

I. Introduction

Terminal Ballistics among various disciplines of ballistics deals with various process taking place during projectile-target impact. Lightweight high performance ballistic material has been introduced into the field of terminal ballistics by combining one or more than one high performance ballistic material inorder to defeat more than one type of ballistic threat or for employing it for any other special requirement. And it was globally employed for all armor industries. Lightweight body armors emerged due to two major contributing factors which included energy saving and increased mobility replacing ductile monolithic body armors made of steel. During medieval period, steel was a popular choice as armor material. Besides, being of good strength and ductile properties steel is cheap and readily available. But its unfavourable fact of having high density made it unsuitable for lightweight protection and hindered mobility when such armor is worn by a wearer. Thus investigations continued and made the researchers to investigate for novel materials to get lighter armor protection which could give the same level of protection as offered by steel. And among them, laminated composite materials emerged as a potential candidate of lightweight armor material due to their distinct properties of high strength and low density. Last three decades witnessed a steady increase in the use of lightweight polymeric composites for structural applications. Strength and durability possessed by it make them ideal candidate for military and defence applications. Ballistic fibres used include aramids and high modulus polyethylene. Thermoplastic and thermoset resins are used for lightweight ballistic material. Laminated composites emerged as an optimal solution in the design of lightweight armor due to low weight, high specific strength and tailorability. Impact damage assessment of laminated composites subjected to ballistic impact is essential for developing improved materials and for reliable design methods accounting for impact. Numerical modeling of ballistic impact for understanding damage mechanisms is feasible and cost effective compared to experimental techniques. Finite element analysis of curved laminated composite target plate with and without human surrogate target has been considered in the present study. Curved target plate and human surrogate target modeled as elastic support has been considered for proper fit.

II. Impact Damage

The introduction of composites into the field of Terminal Ballistics instead of metal as material of body armor is of great significance. Ballistic impact into laminated composites has certain influencing parameters. Material properties dealing with overall stiffness and contact stiffness have important effect on impact response of structure. The constituent materials which includes fibers, matrix and fiber matrix interface have a major role and controls the initiation and growth of impact damage. Impact damage of laminated composites is influenced by thickness, size and boundary condition of the laminated composite panel. Density, elastic properties, shape, initial velocity and incidence angle of the projectile also influences the impact damage. The effect of layup, stitching and environmental condition also matters for the damage due to impact [1]. Laminated composite structures subjected to impact fails mainly in two modes viz; intra-ply failure mode, where the damage happens at the fibers, the polymer matrix and the interface between the fibers and the matrix and inter-ply failure mode, where the composite fails by delamination of the plies. During ballistic impact of laminated composites the target response is a combination of global and local response [2]. Transition between locally dominated response and globally dominated response depends on impact velocity of the projectile. For low velocity impact, velocity is less than 100 m/s and global energy absorbing mechanism is dominant. Transfer of impact energy to the target takes longer time and spreads through larger area of the target. Damage due to low velocity impact starts with occurance of matrix crack. A tensile flexural stress creates the crack in the bottom ply of the thin laminate and is perpendicular to the plane of the laminate and is called tensile crack. Contact stresses creates crack near the top of the thick laminates and are known as shear cracks. Matrix cracks developed induces delamination at interfaces between adjacent plies either from bottom to top or from top to bottom in the laminates. Delaminations or debonding between adjacent laminates reduce the strength of the laminate.

Considering local response, as strike velocity increases, initiation of matrix cracking followed by delamination occurs and results in transverse shear and bending cracks. And as a result fiber fracture petal formation, occurring of hole expansion or wedge through and final mechanism of hole friction takes place. Length of projectile in contact with panel, inplane compressive stress acting on the projectile and coefficient of friction between projectile and laminated composites influences frictional load. The penetration energy can be estimated by adding the energies required to produce each type of failure involved in the penetration process which includes fiber failure, matrix cracking, delamination, and friction between the impactor and composite. High-velocity impact and hyper velocity impact involves projectiles moving at extremely high velocities and the stress induced by the impact is many times the material strength [3].

The main failure modes observed in metal during ballistic impact includes ductile failure, adiabatic shear plugging and discing[4]. Impact resistance of metallic target deals with the amount of work done in plastic deformation. The damage due to impact in metallic armor starts from the surface and can be detected by the visual inspection of target surface. But impact damage of composites including delaminations, matrix cracking and fiber breakage causes strength reduction and are not detectable by visual inspection of the surface of the target. Main difference of the failure of laminated composite from the metallic armor is its tendency to delaminate. The disturbed area of impact energy for composites is larger when compared to the disturbed area of monolithic armor.

Ballistic impact modeling for understanding damage mechanisms of laminated composites provide the possibility of reducing physical experimentation which reduces design time, cost of material and testing cost.

III. Failure Criteria

Failure criteria associated with isotropic material viz; stress dominated, strain dominated and interactive serve as a baseline reference to the development of appropriate criterion for failure of laminated composites. Tsai-Hill, Tsai-Wu and Hoffman are interactive failure criteria and these are not associated with failure modes. Stress dominated, strain dominated and Hashin's interactive failure criteria are associated with failure modes [5]. Hashin's failure criteria can be used to identify various modes of failure viz; tensile fiber failure and compressive fiber failure, tensile matrix failure and compressive matrix failure. It can be used for identifying the failure of laminated composite panels under ballistic impact in a progressive analysis. For that, knowledge of stress components of composite laminate in three material directions are essential when subjected to ballistic impact. A detailed and accurate linear elastic analysis can define the stress field to desired quality and give a strong and well formulated basis for incorporating failure criteria.

IV. Investigations on Composite Body Armor

4.1 Description of Geometry and Structure

The flat laminated composite of Kevlar/epoxy with dimension 0.254m×0.305 m and the curved Kevlar/epoxy laminated composite with dimension 0.305 m along the straight edges and 0.254 m along the curved with radius of curvature 3.63m is chosen. It consists of 4 plies with stacking sequence of $[0, 90]_s$. The laminated plate is of 10 mm thickness and considered as four edges simply supported. Material properties of Kevlar/epoxy laminated composite are given in TABLE.1.

TABLE1 Material properties of Kevlar/epoxy Laminated Composite

Material property with unit	Value
Density(Kg/m^3)	1650
Young's Modulus(E1)GPa	17.989
Young's Modulus(E2)(GPa)	17.989
Young's Modulus(E3)(MPa)	1.948
Poisson's ratio(ν12)	0.08
Poisson's ratio(ν23)	0.698
Poisson's ratio(ν31)	0.0756
Shear Modulus(G12)(MPa)	1.857

4.2 Classical Solution

Response of flat Kevlar/epoxy laminated composite subjected to transverse loading is considered by using the Classical Laminated Plate Theory [6]. Maximum deflection of rectangular laminated plates subjected to uniform transverse pressure loading of q_0 is given by: $W_{max}=0.0157qa^4$ $[D1+ 2D3\ (a/b)^2 + D2\ (a/b)^4]^{-1}$(1) Where D1, D2 and D3 are plate rigidity obtained by laminated plate theory.

4.3Finite Element Analysis

4.3.1Description of the finite element model

A composite target plate has been analysed using MSC Nastran [7]. CQUAD4 element of the Nastran library has been used for modeling the panels. The element is a quadrilateral flat plate connecting four grid points. The element is capable of representing in plane bending and transverse shear behaviour. Finite element model consists of 16 elements and 25 nodes and shown in Figure 1.

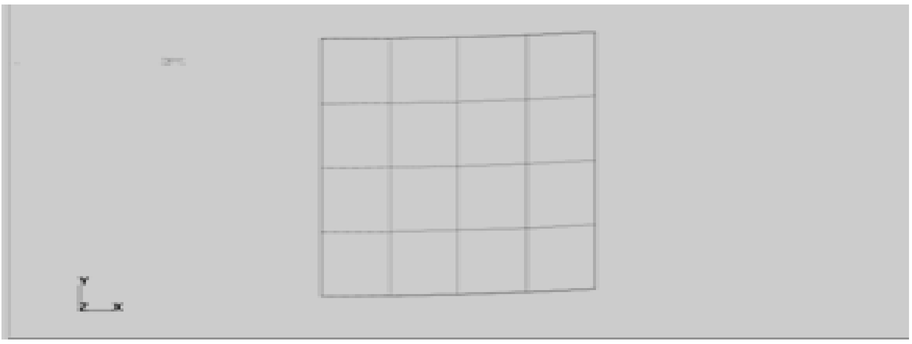


Fig.1 Finite element model of curved target plate

Analysis has been carried out using transverse pressure loading of 100 kPa considering low velocity impact for quasi static perforation of plates by punch penetration similar to projectile impact [8].

4.3.2 Analysis

Displacements of composite flat target plates are calculated using Finite Element Method and classical solution and are obtained as 0.00284m and 0.00273m respectively. Finite element solutions of deflection and stress output of curved laminated composite are shown in Fig.2, Fig.3, Fig.4 and Fig.5 respectively. TABLE 2 shows the stress output in each layer of the curved laminated composite panel having 4 plies.

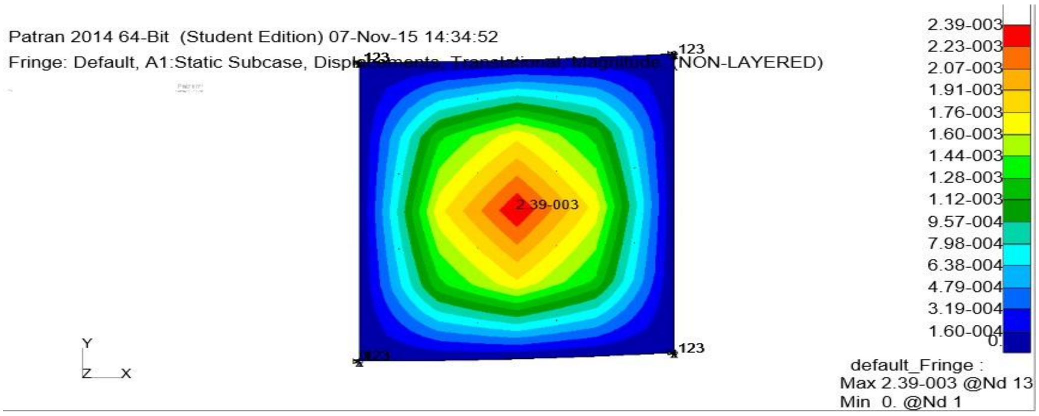
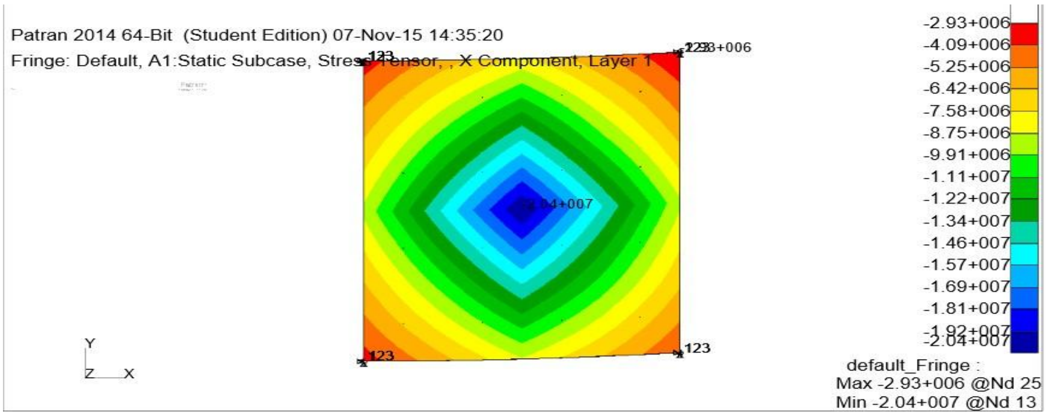


Fig.2 Deformation of curved laminated composite



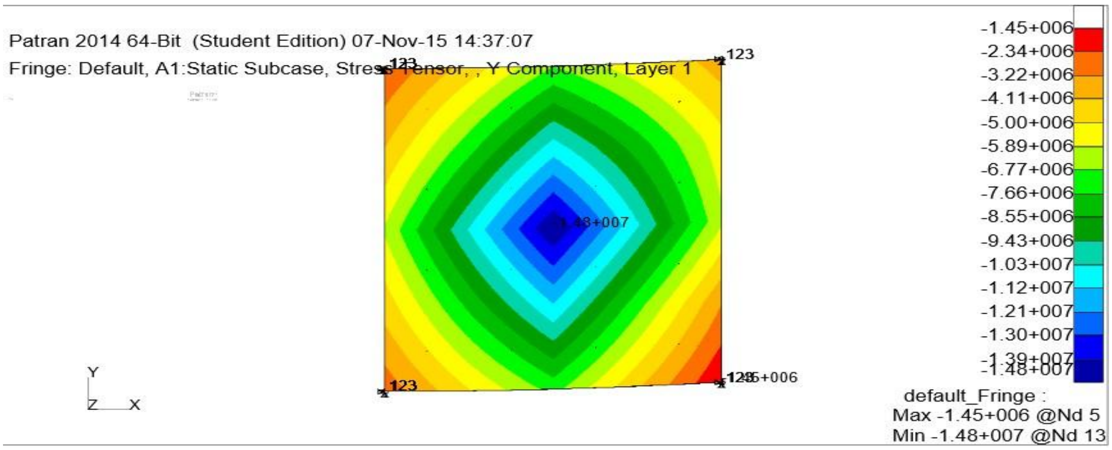


Fig.4 Transverse stress output for layer 1 of curved laminated composite

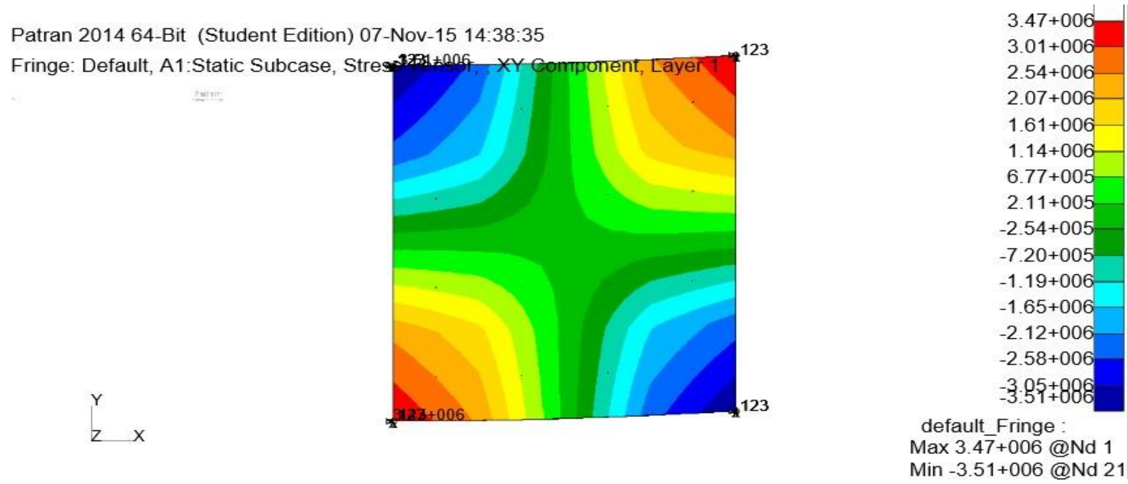


Fig.5 Shear stress for layer 1 of curved laminated composite

TABLE 2 Finite element solution of stresses in each layer of curved Kevlar/epoxy Laminated Composite

Orientation	Layer no.	Stress in longitudinal direction (MPa)		Stress in transverse direction (MPa)		Maximum shear stress (MPa)
		Maximum	Minimum	Maximum	Minimum	
0	1	-20.4	-2.93	-14.8	-1.45	-3.51
90	2	-4.92	-0.484	-6.80	0.975	1.17
90	3	4.92	0.484	6.80	0.975	-1.17
0	4	20.4	2.93	14.8	1.45	3.51

V. Analytical Investigations on Composite Body Armor and Human Surrogate Target

Valid surrogate target equivalent to human torso is essential for considering proper fit of armor. The interaction among projectile, body armor and human surrogate target which is essential for evaluating the protective effectiveness of armor against blunt injuries is the real situation to be considered and that situation arises when the armor is worn by a wearer which most of the studies have failed in taking into account. The comparison of armor responses on gelatin or clay surrogate targets with those on a human torso with properly selected material parameters of the model that allow same deformations as obtained from experimental results and the corresponding parameters of clay are considered [9]. When the armor is worn by a wearer most likely a gap arises between back face of armor and surface of human torso instead of a perfect contact. Inorder to study the effects of target geometry, surrogate targets need to be developed. Equivalent elastic support is considered for surrogate target considering proper fit and equivalent stiffness for elastic support is obtained from material parameters of clay above. The modulus of subgrade reaction is given by Vesic equation,

$k_s' = 0.65(E_s b^4/E_f I_f)^{1/12} \times E_s/1-\mu^2$ (2) here Es, b, Ef, If and μ are Modulus of clay, Width of panel, Modulus of panel, Moment of inertia based on cross section of panel and Poisson's ratio of clay respectively and material parameter for equivalent elastic support is obtained using this. Elastic modulus and Poisson's ratio of clay have been considered as 149 MPa and 0.4994 respectively. Equivalent stiffness obtained for elastic support is 158 MN/m. Thus, Curved geometry for target plate has been considered along with equivalent human surrogate target modeled as elastic support for proper fit.

5.1Finite Element Analysis

5.1.1Description of geometry and structure

Curved geometry has been considered for laminated composite. Elastic support with equivalent stiffness has been considered for all nodes for generating equivalent human surrogate target.

5.1.2Description of the finite element model

Elastic support has been modeled as spring element CELAS2 of MSC Nastran. They behaves like simple extension or compression or rotational spring carrying either force or elements. Spring elements are also called zero dimensional or scalar elements connecting 2 degrees of freedom with one at each grid point.

Finite element model consists of 16 elements and 25 nodes Finite element model of target plate modeled with human surrogate target as elastic support is shown in Fig. 6.

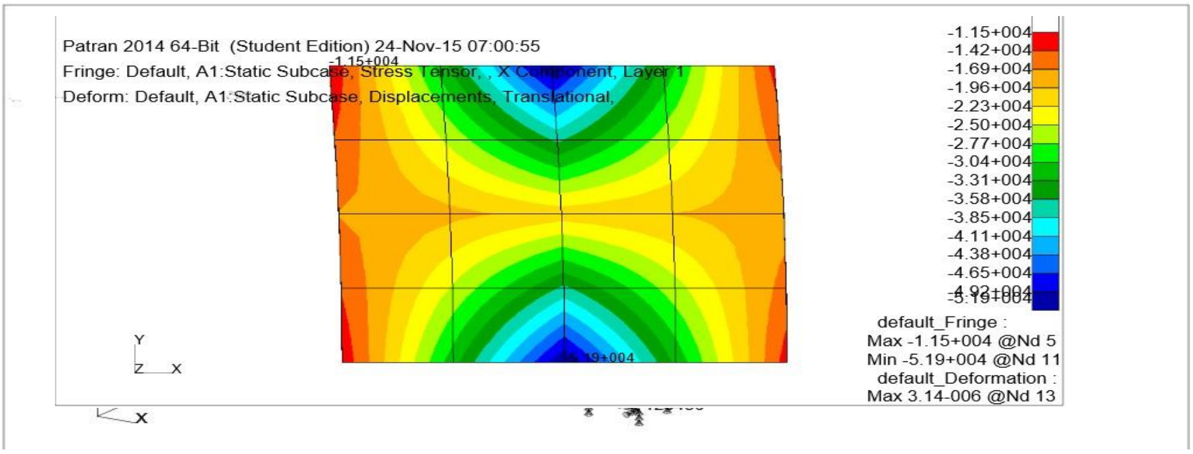


Fig.6 Finite element model of target plate modeled with human surrogate target as elastic support

5.1.3Analysis

The finite element model has been analysed for a transverse pressure loading of 100 kPa. Finite element results of stress and deflection for laminated composite curved plate with human surrogate target are shown in Fig.7, Fig.8, Fig.9 and Fig.10 respectively. Stress output of each layer of curved laminated composite is shown in TABLE 3.

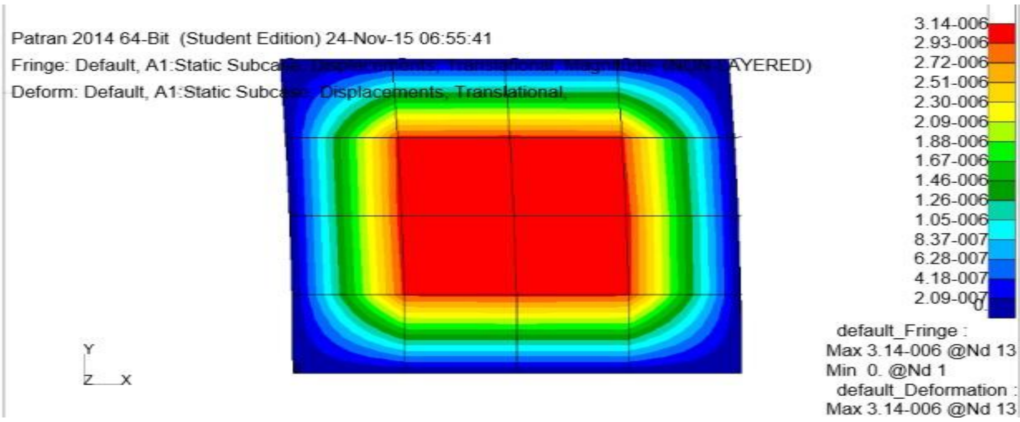


Fig.7 Deformation of curved laminated composite with human surrogate target

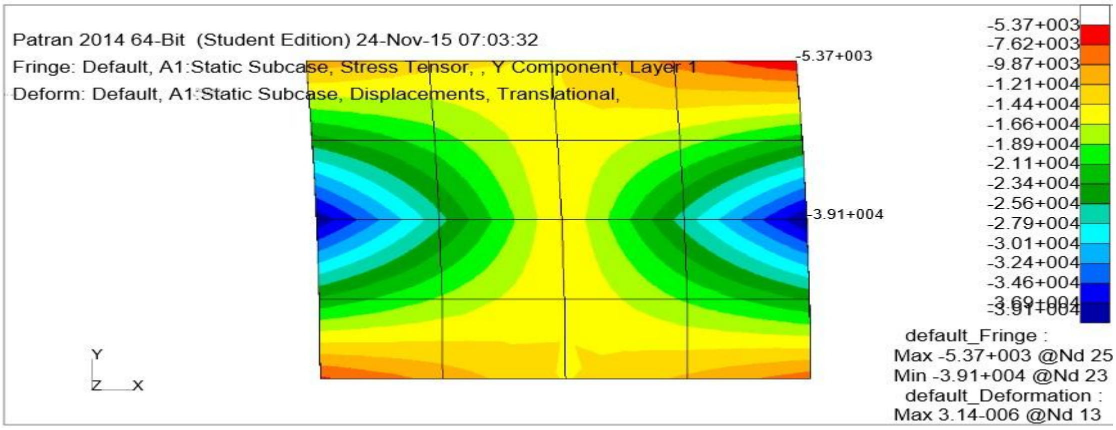


Fig.8 Longitudinal stress for layer 1 of curved laminated composite with human surrogate target

Fig.9 Transverse stress for layer 1 of curved laminated composite with human surrogate target

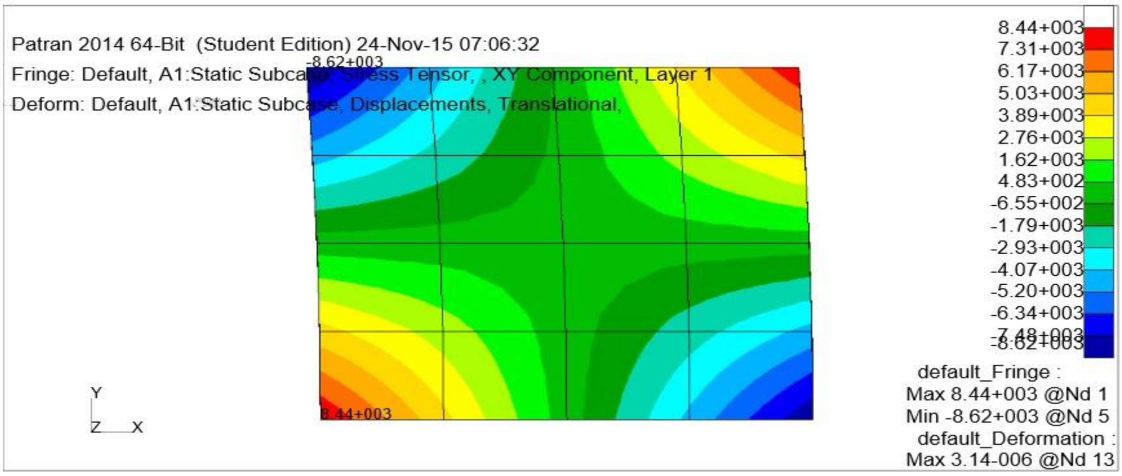


Fig.10 Shear stress for layer 1 of curved laminated composite with human surrogate target

TABLE 3 Finite element solution of stresses in each layer of curved Kevlar/epoxy laminated composite considering human surrogate target

Orientation	Layer no.	Stress in longitudinal direction (MPa)		Stress in transverse direction (MPa)		Maximum shear stress (MPa)
		Maximum	Minimum	Maximum	Minimum	
0	1	-0.0519	-0.0115	-0.0391	-0.00537	-0.00862
90	2	-0.0130	-0.00179	-0.0173	-0.00384	0.00287
90	3	0.0130	0.00179	0.0173	0.00384	-0.00287
0	4	0.0519	0.0115	0.0391	0.00537	0.00862

VI. Results and Discussions

The finite element analysis of curved composite body armor with and without human surrogate target has been considered and results are presented in TABLE 4.

TABLE 4 Curved Composite Body Armor With and Without Human Surrogate Target

	Curved Composite Laminate	
	without surrogate target	with surrogate target
maximum deflection (m)	2.39×10^{-3}	3.14×10^{-6}
maximum longitudinal stress(Pa)	20.4×10^{6}	51.9×10^{3}
maximum transverse stress(Pa)	14.8×10^{6}	5.37×10^{3}
maximum shear stress(Pa)	3.51×10^{6}	8.62×10^{3}
maximum support reaction(N)	823 N (for longer side)	496 N (at the centre of the panel)

Since Armor has been idealized as plate on elastic support, the reaction of elastic support implies the response of human torso during ballistic impact and is a measure of protective effectiveness of armor against blunt injuries.

VII. Conclusions

Analysis of flat laminated composite target plate has been considered and validated with solution from classical laminated plate theory. Curved laminated composite target plate with and without human surrogate target has been considered. The interaction between curved laminated composite body armor and human torso during ballistic impact has been realised with the incorporation of human surrogate target modeled as elastic support with proper fit. Deflection, longitudinal stress, transverse stress, shear stress and support reactions have been evaluated. The reaction of elastic support which is a measure of the protective effectiveness of the body armor against blunt injuries during impact has been evaluated and presented. Linear elastic analysis has been carried out and the stress field has been determined to the desired quality which gives a strong and well formulated basis for incorporating failure criteria for damage assessment.

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