Laser-Induced Damage to Mechanically Loaded Laminated

Satyender Kumar[1], N R Das[2]

1) Mewar University, Rajasthan, India
2) LASTEC, DRDO, Delhi, India
*satyender_bharna@yahoo.com, 09868233275

Key Words: LMI, Composite Materials, ablation

Abstract

This paper describes the lethality of laser-directed energy weapons in causing structural failure to mechanically loaded laminated composites in UAV. Failure of laminated composites is controversial, even under ambient temperature. However, a successful attempt has been conducted here to predict the mechanical and thermal behavior of the heated panel. This is further complicated by the anisotropic behavior of the composite material and the thermal effect. The problem is thermally and structurally non-linear. This work can be considered as an above preliminary experimental analysis. It provides insight (verified by experimentation) approximate solutions good enough for information regarding the damage effect of composite due to laser irradiation. This paper presents the investigations of laser damage assessment on composite materials under loaded conditions by applying bending stress on test samples and evaluating the thermo mechanical parameters of irradiated samples through various characterization techniques. The bending stress on test samples was created by a loading device consisting of a load cell and target fixture for holding the samples. The damage effects were investigated on glass fiber reinforced polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) composites in the form of thin rectangular sheets. A carbon dioxide laser operating at its fundamental wavelength of 10.6 micrometers was employed in the studies that produced a power density of 1 kW/cm^2 on test samples. The damage morphology of the samples was studied by LYNX Dynoscope. Ablated mass was measured for both the materials.

Introduction

Therefore, it is necessary to understand the response of laminated composite thin shell structure to sudden and intense loading. The objective of the approach is to predict the response of mechanically loaded and intensely localized spot heated composite structures irradiated by laser. The reason for using numerical methods is due to already practically verified non-linearity of the thermal and mechanical responses. This work concerns the current directed energy program investigating lethality of lasers and its support. A laser load of sufficient magnitude can cause structural failure for ballistic missiles, fixed-wing planes, UAV/RPVand helicopters. Laser loading can damage main structural components or vulnerable internal components, which can result in the failure of the missile or aircraft mission. Therefore, it is necessary to understand the response of laminated composite thin shell structure to sudden and intense loading. It should be emphasized that the subject of the failure of laminated composites is controversial, even under ambient temperatures. Since the processes under consideration have a very important impact in directed energy weapon environment, they should be dealt with effectively. This can be done as a result of understanding the processes and their nature and the ability to predict them quantitatively. If this expertise and knowledge is available, the designer of a directed energy laser weapon can ensure the desired performance and can choose an optimum design from many alternate possibilities. Also the power of prediction enables the operation of existing laser weapons more efficiently. On the other hand, the helicopter structural designer can determine critical laminated composite panels of the structure needing strengthening or redundancy to survive laser strikes at a relatively low cost. The prediction of behavior in a given physical situation requires the values of the relevant variables governing the process of interest.' In this thesis work on directed energy laser weapons against helicopters, the complete prediction gives us the values of static and thermal loads, stresses, and strains; it also provides heat transfer parameters such as temperature distributions throughout the domain of interest.

The theoretical calculations offer many advantages over a corresponding experimental investigation. Such advantages are apparent in low cost, speed, complete information, and ability to simulate realistic and ideal conditions. Still, there are drawbacks and limitations, the most important of which is that the validity of the mathematical model limits the usefulness of the computation. This work involves a problem of complex composites geometry and sensitive materials properties, as well as non-linearities. The extremely intense high temperatures, incipient structures with post-buckled loadings and spot heating, make it hard to solve numerically. Up to now, to the best of the author's knowledge, no one has analyzed the problem of laser damage in loaded laminated composite panels.

The foundation of framework analysis was laid in the period 1850-1875 by Maxwell and Mohr, amongst others. These concepts provide the methodology of matrix structural analysis that underlies finite element theory. A lack of quick solution methods for multiple algebraic equations prevented any true further advance for eighty years. These limitations were relieved somewhat in 1932 when Hardy Cross introduced the method of Moment Distribution. This made it feasible to solve more complex problems by orders of magnitude.

The finite element method, as a numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems, has extended and been applied to the broad field of continuum mechanics. The finite element method has received much attention in engineering schools and industry due to its diversity and flexibility as an analytical tool.

Damage assessment basics:

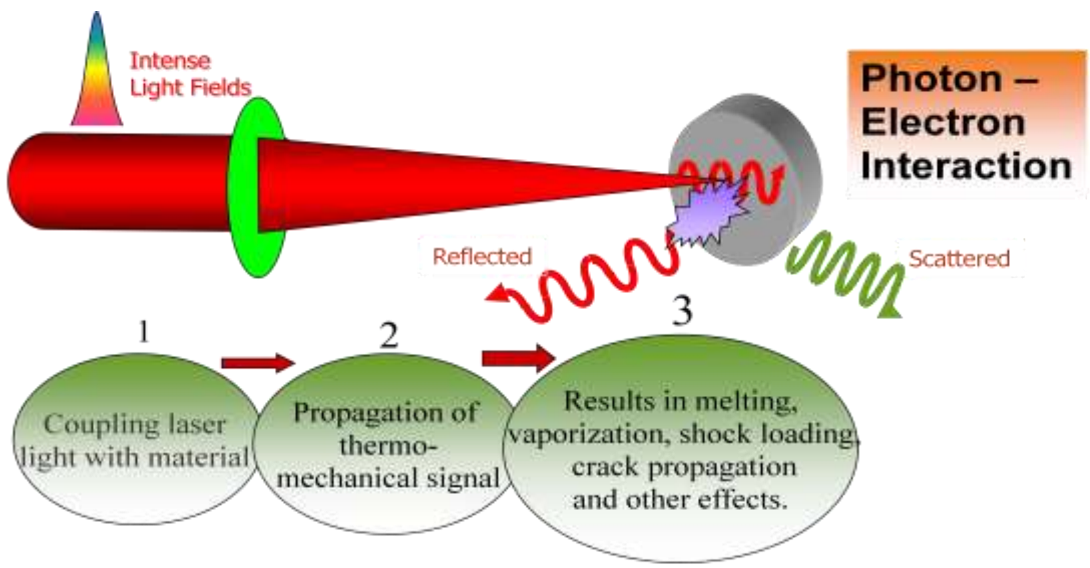


Fig.1

Thermo-elastic Stresses

It occurs under the action of fast transitory temperature fields in the material. The potential △φ of the thermoelastic stresses is defined by

$$\Delta\varphi = \alpha_T \left(\frac{1+\nu}{1-\nu}\right)\Delta T$$

Boundary Condition :

$$\varphi(r, z, 0) = 0,$$
$$\delta\varphi(r, z, 0)/\delta t = 0$$

Where,

α_T : the coefficient of linear expansion

ν : Poisson's coefficient

ΔT : The temp change

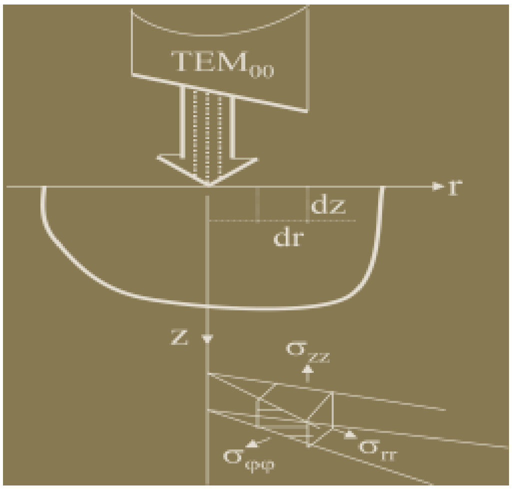


Fig.2

Various defects like material yield, defect formation, cracking etc occurs if stress exceeds a certain limit

Qualitative Description for Composite

Convective cooling and radiative emission are negligible.

- Absorptivity @10.6μm on specimen composite is near unity.
- Radius of the area over which the resin is at temperature T_M is much larger than specimen thick.

Heat transfer from back is negligible

$$K\frac{\partial^2 T}{\partial^2 z} - \rho C_P \frac{\partial T}{\partial t_e} = 0 \qquad (0 < z < \delta, t_e > 0)$$
$$T(+0, T_e) = T_M \qquad (t_e > 0)$$
$$K\left(\frac{\partial T}{\partial z}\right)_{z=\delta} = 0 \qquad (t_e > 0)$$
$$T(z, +0) = T_0 \qquad (0 < z < \delta,)$$

Where,

t_e(sec) = time after onset of heating (i.e, exposure time), δ(cm) = slab thickness, z(cm)=Distance inside slab (measured from hot surface), T_0(^{0}C)=Initial slab temperature(assumed to be 25^{0}C), T_M(^{0}C)=Temperature of hot surface, T(^{0}C)=Temperature at time t_e, depth z, ρ(gm/cm^2) = slab density, C_P(J/gm^{0}C)=Specific heat,
K(watts/cm^{0}C)= Thermal Conductivity.

The solution of the boundary value problem:

$$T - T_0 = (T_M - T_0)\left\{1 - \frac{2}{\pi}\sum_{n=1}^{\infty}\left(n-\frac{1}{2}\right)^{-2} exp\left|-\left(n-\frac{1}{2}\right)^2 kt_e\right| sin\left(n-\frac{1}{2}\right)x\right\}$$

For $(0 \le z \le \delta, t_e > 0)$ where,

$$x \equiv {\pi z}/{\delta}$$
$$k = {\pi^2 K}/{\rho C_P \delta^2}$$

Theoretical :

Substituting, t_e =2sec, P=100W, r= 0.5cm, x=π, k=0.580sec^{-1}

T-T_0 =115^{0}C

$$T_M - T_0 = 332^0C \text{ , where, } T_0 = 25^0C$$
$$T_M = 357^0C$$

Experimental :

$$T_M = 330^0C \text{ for Resin 5208}$$

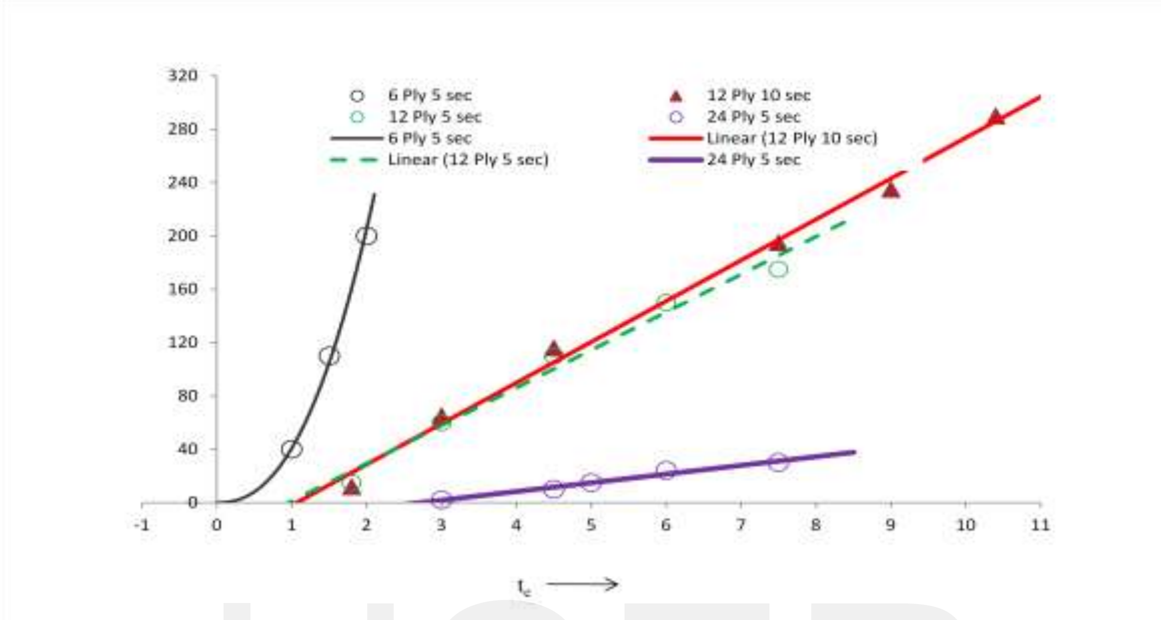


Fig.3 Temperature profile with respect to time

It was assumed that mass loss during low intensity range is mainly due to resin sublimation and this sublimation occurs at a const rate per unit area. The rate at which resin mass is sublimated:

$$dm/dt_e = -\gamma A' (t_e),$$

The energy balance eqn :

$$\eta_1 P = L_1 \gamma A'(t_e) - A'(t_e) k \left(\frac{\partial T}{\partial z}\right)_{z=0}$$

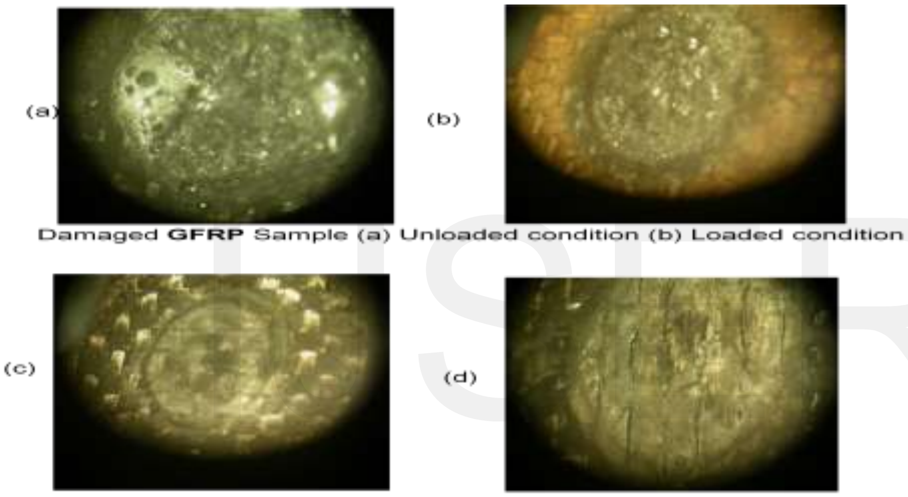
where, κ:thermal conductivity, L_1:heat of decomposition & sublimation,
η_1:effective absorptivity, P: power, $\gamma(gm/cm^2 sec)$:const, A' :expanding area behind fiber.

Results : **Table-I**

Sample/ Damage Effects	CFRP					GFRP				
	Undamaged	WL	L	% of Reduction		Undamaged	WL	L	% of Reduction	
				WL	L				WL	L
Ablated Mass Loss(g)	8.465	8.345	8.110	1.4	4	101.830	101.090	100.170	0.7	1.6
Char effect	-	High	High	-	-	-	Low	Low	-	-

Table-II:

Sl No	Sample	Thk (mm)	Dim(LxW) (mm)	Peak Temp(^{0}C)		Online Loading Effects			Structural Tensile Strength				
				Front	Back	External BS(Before Damage in MPa)	Residual BS(After Damage in MPa)	% of Reduction of External BS (or Strength	Before Damage (MPa)	After Damage (MPa)		% of Reduction of Sample Strength	
										WL	L	WL	L
1	CFRP	6	90x45	1220	80	16.7	4.7	72	4.52	3.52	2.89	22	36
2	GFRP	6	120x45	1230	75	104.4	41.6	60	157	135	108	14	31



Damaged **GFRP** Sample (a) Unloaded condition (b) Loaded condition

Damaged **CFRP** Sample (c) Unloaded condition (d) Loaded condition

Fig. 4: Damage of GFRP and CFRP

Conclusion:

Bending stress of approximately 100 MPa was created on GFRP samples of dimensions 120 mm × 45 mm and thickness 6 mm. A reduction of 60% of bending strength was obtained when irradiated with laser at said power density. For CFRP samples, a reduction of 72% of bending strength was obtained at a bending stress of approximately 20 MPa. The tensile strength of these materials was also measured before and after laser irradiation by universal testing machine(UTM). For CFRP samples, reduction of tensile strength was found to be 22% and 36% respectively for unloaded and loaded samples. For GFRP samples the corresponding values were found to be 14% and 31% respectively. The ablated mass was founded to be more for both the materials when the test samples were irradiated to laser beam under loaded conditions. So in conclusion, that when irradiation was under mechanical loaded conditions, they generally damage more than the unloaded conditions. So A laser load of sufficient magnitude can cause structural failure for ballistic missiles, fixed-wing planes, and helicopters. Laser loading can damage main structural components or vulnerable internal components, which can result in the failure of the missile or aircraft mission. The mass loss during the intensity radiations is mainly due to resin sublimation.

Acknowledgement

The authors express deep gratitude to everyday for support to carry out the experimental work. Technical support from all members of optics group is kindly acknowledged. The authors wish to acknowledge the support from everybody who was involved directly or indirectly with this work.

References:

1. K. G. Kibler and H. G. Carter, "Laser Damage in Graphite- Epoxy Composites," General Dynamics Research Report ERR-FW-1564 (15 October 1974)
2. T. Ender, H. T. Clark, and T. C. Grimm, "Response of Advanced Fiber Composite Materials to Laser Heating (U)," McDonnell Douglas Corporation Report MDCA 3540 (1975) (Confidential)
3. K. G. Kibler, "Laser-Induced Strength Reduction in Graphite-Epoxy Compression Sandwich Beams," General Dynamics Research Report ERR-FW-1795 (1976)
4. K. G. Kibler, H. G. Carter, and J. R. Eisenmann, "Residual Strength of Laser-Damaged Composites," Journal of Composite Materials 9, 28 (1975)
5. M. E. Waddoups, J. R. Eisenmann, and B. E. Kaminski, "Macroscopic Fracture Mechanics of Advanced Composite Materials," Journal of Composite Materials 5, 446 (1971)
6. R. J. Thorn and G, H. Winslow, "Vaporization Coefficient of Graphite and Composition of the Equilibrium Vapor" J. Chem Phys 26 186 (1957)
7. J. M. Whitney and R. Y. Kim, "High Temperature Tensile Strength of Graphite/Epoxy Laminates Containing Circular Holes," Journal of Composite Materials 10, 319 (1976)
8. E. L. McKague, Jr., "Development of a Graphite Fiber Tow Test Method," General Dynamics Research Report ERR-FW-1588 (December 1974)
9. N.R.Das, A.K. Srivastava, R. Kumar, Satyender Kumar, and A.K. Maini, "Study of Thermo Elastic Stress Mechanism due to High Power Laser Induced Effects on Materials" Proceeding of 3rd International Conference on Current Developments on Atomic, Optical & Nano Physics with Applications(CDAMOP-2011) held at Delhi University, pp.196, Dec 14th -16th 2011, New Delhi, India.
10. Satyender Kumar, K.P. Singh, N. R. Das, "Study of Beam Parameters for High Power Lasers" Proceeding of National Conference of Material Science (NCMS 2014) held at Mewar University, pp. 65, Oct. 17-18, 2014, Chittaorgarh (Raj.), India.
11. Satyender Kumar, K.P. Singh, N.R. Das, A.K. Srivastava, "Study of Laser Beam Parameters" Proceeding of Conference on Advance Techniques & Devices in Mathematics & Physical Sciences CATDMP 2015 (An International Meet) held at SRM University, NCR Campus, pp. 114, Jan. 23-25, 2015, Ghaziabad(U.P.), India.
12. N. R. Das, Satyender Kumar, M.B Mathur, A.K. Srivastava, "Laser Damage Studies on Composites under Loaded Conditions" Proceeding of 4th International Conference on Current Developments on Atomic, Optical & Nano Physics with Applications (CDAMOP-2015) held at Delhi Uni., pp. 218, Mar 10th -14th 2015, New Delhi, India.