# Studies on Behavior of Carbon and Fiberglass Epoxy Composite Laminates under Low Velocity Impact Loading using LS-DYNA®

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## Abstract

*The desired characteristics of materials in modern aircraft applications require high specific modulus and high specific strength for low specific weight. Composite structures, fabricated using carbon and glass fabrics in conjunction with epoxy resin manufactured via the heated vacuum assisted resin transfer molding (H-VARTM) process are now being considered as a low cost alternative to conventional materials without compromising the mechanical properties. It is important to study the response of composite structures under out-of-plane impact loading which may cause considerable damage to the different layers even at low impact energy levels. In the present study, response of composite laminates under low velocity impact loading was investigated using LS-DYNA. The composite laminates were manufactured by the H-VARTM process using basket weave E-Glass fabrics and plain weave AS4 carbon fabrics with the Epon 862 resin system and Epicure-W as a hardening agent. A composite laminate, with 10 layers of carbon and fiberglass fabrics, was modeled using 3D solid elements in a mosaic fashion to represent plain and basket weave patterns. Mechanical properties were calculated by classical micro-mechanical theory and assigned to the elements as orthotropic elastic material properties. The LS-DYNA results were compared with experimental drop test results using the Dynatup Low Velocity Impact Test Machine. The main considerations for comparison were maximum impact load and the energy absorption by the laminates. Progressive damage for fiberglass laminates was reported for six impact energy levels from 128 ft-lbf (incipient damage) to 768 ft-lbf (upper bound) with the increasing increments of 128 ft-lbf. For carbon laminates impact energy levels are half as that of fiberglass.*

## Introduction

Woven composites play an important role in modern aerospace industry because of its low specific weight with high specific modulus. Carbon composites are strong under in-plane loading while fiber glass composites show superior performance under out of plane loading, such as impact loading. Numerous experimental research efforts have been carried out to understand the behavior of composites under low velocity impact applications. Wang [1] in his research paper discusses about the low velocity impact properties of the 3D woven basalt/ aramid hybrid composites using experimentally collected data. Tan [2] studies the effect of impacting projectiles with different geometries on the high strength filler fabric. Cheeseman et. al. [3] studied the factors affecting the impact forces and the strains of ballistic impact on composite laminates. Bazhenov [4] presents the energy dissipation by bulletproof aramid fabric, while Iremonger [5] studies the mechanism of penetration for ballistic impact on composite armors.

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Apart from these experimental studies, several analytical, and numerical simulation approaches were presented. Mikkor [6] presents Finite Element model to study the impact behavior of preloaded composites panels. McCarthy [7] studies the bird strike on an aircraft wing leading edge made from fiber-metal laminates using novel SPH Finite Element approach. Donadon [8] in his research publication proposes a 3D micro-mechanical analytical model for study of woven hybrid laminates using CLT. Also Kermanidis et. al. [9] presents a Finite element approach for studying the bird impact on the horizontal tail of a transportation aircraft. Landa [10] presents an analytical model to study the impact behavior of soft armors. In modeling woven composites under impact, the experimental and the classical mechanics approach seems to be most expensive and highly complicated hence one has to depend on the numerical approaches which are fairly accurate, less expensive and less time consuming.

In the present study a Finite Element approach has been used to model the ten layered composite laminates using VPG 3.1.1 model builder and using LSDYNA as a solver. Two different configurations, 10 ply E-glass epoxy and 10 ply AS4 carbon epoxy laminates has been modeled and their impact behavior is compared with the experimental results.

## Modeling Details

### Building model in VPG

The woven-roven composite laminates were modeled in VPG, the finite element model builder using 8-noded solid elements. The solid elements are chosen to capture the stress levels across the thickness. Each cell of the composite structure is modeled as a cube mimicking the mosaic tile. The entire laminate structure is developed by copying the repetitive unit cell that is the smallest unit cell of the composite structure in 3D to get the complete plate.

The fiber impregnated in epoxy resin is modeled as orthotropic elastic material. The properties of unidirectional (E-glass/ AS4 carbon) fibers impregnated in epoxy resin is computed using the Chamis [11] micromechanics equations for the effective elastic modulus, shear modulus and the Poisson's ratios and assigned in warf (0°) and weft (90°) directions (shown in Table 1). The warf (0°) and the weft (90°) are modeled as two different parts in VPG. The solid cell size is assigned for both carbon and fiberglass laminates by calculating actual width and breadth of weaves. Total thickness of the fabricated laminates was measured and accordingly assigned to the elements. The layers were stacked over each other, which are in an (0-90°) alternate fashion to produce 10-layered composite laminates. Since the undulations are not modeled (mosaic model), care was taken so that one layer of actual weave is equivalent to two layers in the model. Laminates in the impact test machine holding fixture were clamped by tightening bolts by hand, which allows plate boundary to move in the direction perpendicular to z axis. To mimic this boundary condition in modeling, boundary nodes along y axis were fixed in y and z directions and boundary nodes along x axis were fixed in x and z directions. Also all the boundary nodes were fixed in all the rotations. Solid section was assigned to both warf and weft to simulate the solid structure of the laminate.

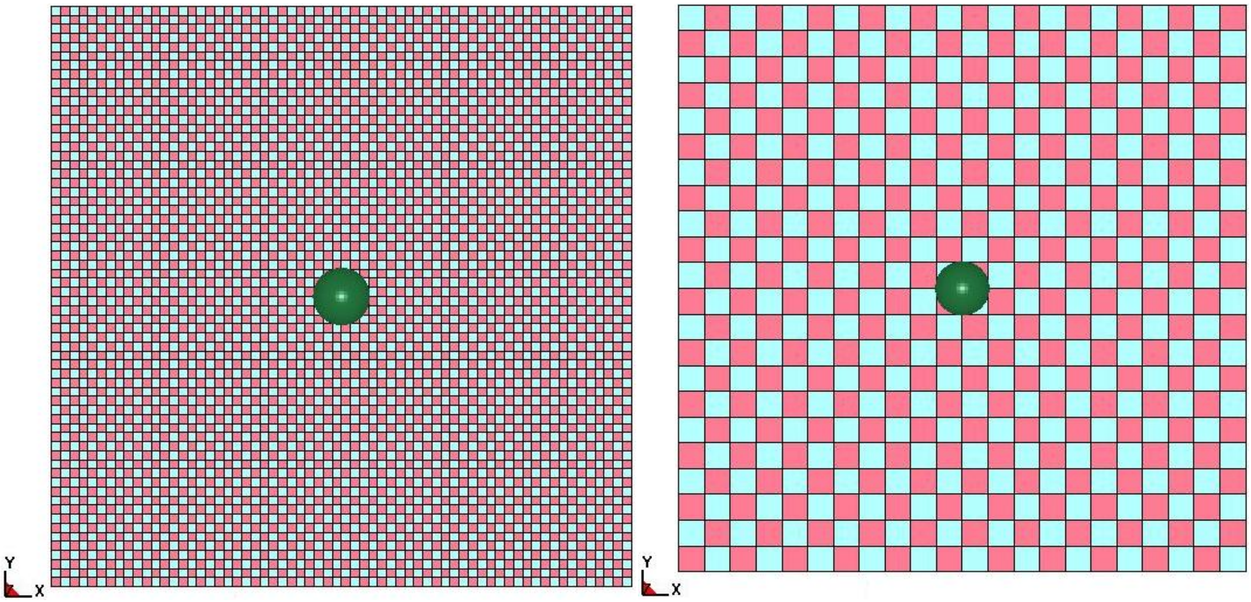
The ball was created separately using LS-PREPOST, to simulate the 0.5 inch solid steel impactor of the impact machine. Four nodded solid quad elements with 15 mesh density were assigned to ensure that the cell size of ball must be smaller than the cell size of either composite laminate. The steel ball was assigned with solid section similar to the composite laminate. It was constrained in 5 degrees of freedom (x and y translation and 3 rotation) allowing its z movement. The effective density equal to 0.4713 (lbf $^2$/in)/in$^3$, Young's modulus equal to 30 Msi and Poisson's ratio equal to 0.3 was assigned to the rigid material of the ball. The Finite Element model of composite laminates and the impactor is shown in Figure 1.

In the process of ball impacting the composite plate, the impact starts with the ball touching the composite plate (point to surface contact) and progresses as a surface-to-surface contact. In LSDYNA an automatic surface to surface contact has been assigned between warf and ball and weft and ball to accommodate the impact initiation and the impact progress.

The impact time duration, that is the termination time, computation time step and output time step were specified in the control cards of LSDYNA to control the computational run and to get the output at desired time interval. The output was in the form of d3 plots, which can be analyzed using the LS-PREPOST postprocessor.

Table 1: Properties of Carbon / Epoxy and E-glass / Epoxy laminates.

| Property | AS4 Carbon / Epoxy Laminate | | E-Glass / Epoxy Laminate | |
|---|---|---|---|---|
| | Warf (0°) | Weft (90°) | Warf (0°) | Weft (90°) |
| $E_a$ (psi) | 1.82 E+07 | 1.17 E+06 | 5.55 E+06 | 1.53 E+06 |
| $E_b$ (psi) | 1.17 E+06 | 1.82 E+07 | 1.53 E+06 | 5.55 E+06 |
| $E_c$ (psi) | 1.17 E+06 | 1.17 E+06 | 1.53 E+06 | 1.53 E+06 |
| $G_{ab}$ (psi) | 5.99 E+05 | 5.99 E+05 | 5.74 E+05 | 5.74 E+05 |
| $G_{bc}$ (psi) | 3.51 E+05 | 5.99 E+05 | 3.55 E+05 | 5.74 E+05 |
| $G_{ca}$ (psi) | 5.99 E+05 | 3.51 E+05 | 5.74 E+05 | 3.55 E+05 |
| $Pr_{ba}$ | 0.0176 | 0.2750 | 0.0787 | 0.2850 |
| $Pr_{ca}$ | 0.0176 | 0.4657 | 0.0787 | 0.4206 |
| $Pr_{cb}$ | 0.4657 | 0.0186 | 0.4206 | 0.0787 |
| Density (lbf $^{2}$/in)/in$^{3}$ | 1.50 E-04 | | 1.58 E-04 | |



(a) Carbon / Epoxy Laminate

(a) E-Glass / Epoxy Laminate

Figure 1: Finite element model of composite laminates and impactor

## Experimental Details

### Fabrication Using H-VARTM Process

Basket weave woven-roving FGI 1854 E-glass fabric manufactured by Fiber Glass Industries, Inc. and plain weave woven-roving AS4 carbon fabric manufactured by BGF Industries, Inc. with EPIKOTE Resin 862 (Bisphenol-F (BPF) epoxy resin) and EPIKURE Curing Agent W (Non-MDA, aromatic amine curing agent) was used to fabricate all the laminates.

The fabrication of the composite panels was done using the H-VARTM (Heated Vacuum Assisted Resin Transfer Molding) process [12]. Each panel consists of 10 plies of different fabrics depending upon the configuration of hybrid laminate. Four square test coupons of size 6 inch were cut from each panel, which were clamped in impact test machine. The clamped area was 0.5 inch from all the sides. The total impacted area was $5 \times 5$ inch$^2$.

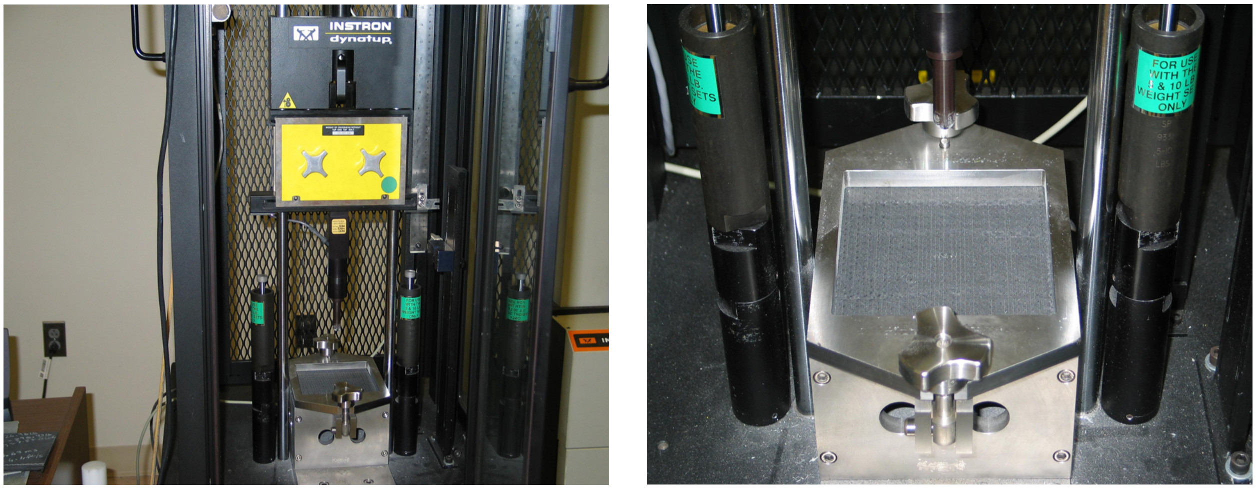
### Impact Test Procedure

All the impact tests were performed using the DYNATUP 8250 impact drop tower device as shown in Figure 2. The low velocity impact test facility consists of a drop tower equipped with an impactor and a variable crosshead weight arrangement, a high-speed data acquisition system, and a load transducer mounted in the impactor.

In this study the gravity mode was used for all low velocity impact tests. The crosshead / impactor weight was kept constant for all tests. The crosshead weight was maintained at 10.97 lbf and the weight of the impactor was 0.95 lbf leading to a total weight of 11.92 lbf. The low velocity impact facility is equipped with instrumentation to measure the velocity prior to impact. The high-speed data acquisition system has the capability of storing the entire impact event, and produce load-time, load-deflection, and energy-time curves. The objectives of the preliminary impact tests were (a) To establish the energy levels and drop height for the incipient damage threshold or lower bound and (b) To establish the energy levels and drop height for penetration or the upper bound.

To achieve the above objectives, a series of impact tests were performed and are discussed in the following paragraph. A random drop height was selected to perform the low velocity impact test on the woven composites. After impact, the specimens were examined for damage. The impact height was varied until the impact load-time history plots indicated no drop in impact loads due to possible impact damage. The energy level corresponding to this drop height was called as threshold energy level or lower bound. To establish the energy level for the beginning of penetration or the upper bound, the drop height was increased until there was no significant increase in the impact loads.

Once the lower and upper bound energy levels were established, the difference in drop heights between the lower bound and upper bound was calculated. Impact tests were performed on the test coupons between the lower bound and upper bound drop heights at 2 inch increments for Carbon/epoxy laminates and 4 inch increments for E-Glass/epoxy laminates. Thus this series of tests provided sufficient data to analyze the damage characteristics and to study the progression of damage in each of the two different material systems.



(a) Drop tower and impactor (b) Clamped plate

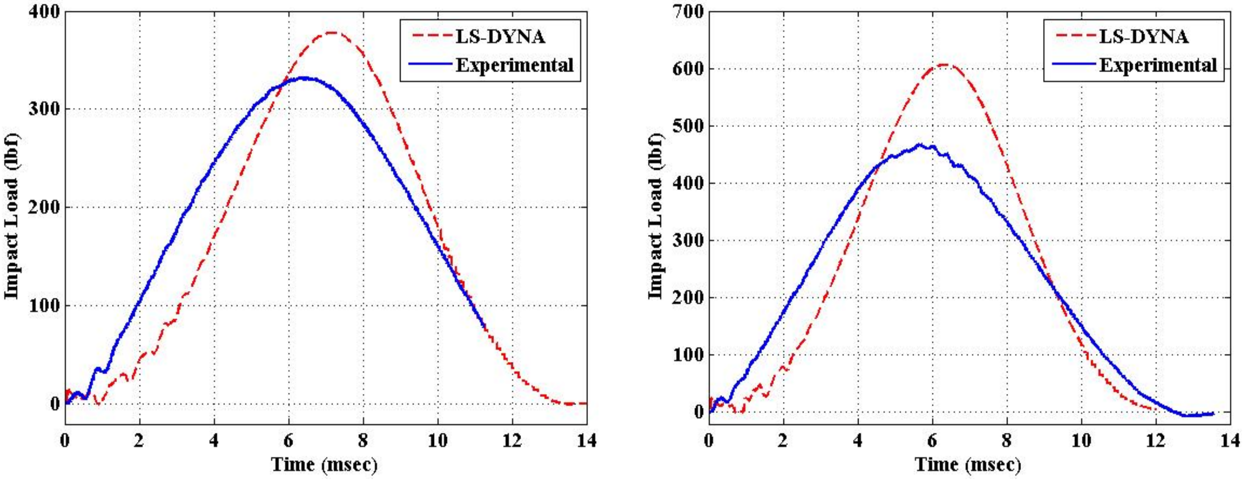
Figure 2: INSTRON DYNATUP 8250 Impact Test Setup

## Results and Discussion

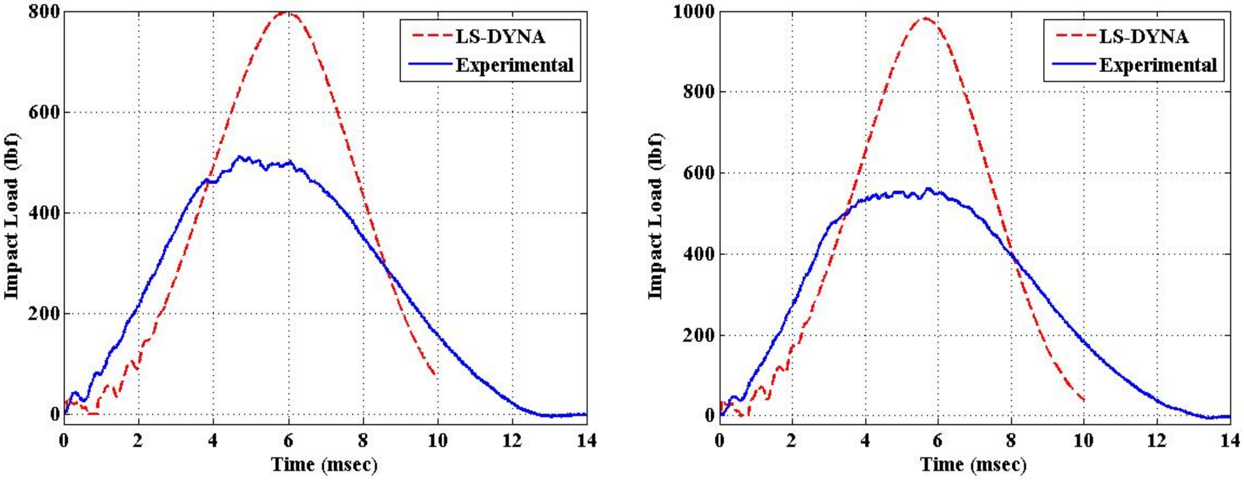
Figure 3 shows the experimental and the LSDYNA output of load Vs time comparison for Carbon/Epoxy laminates under various impact energy levels. The lower energy level was chosen from the incipient damage seen in the test and the highest energy level was penetration. The experimental and the LSDYNA comparison shows good accordance for their maximum load reached and the impact duration time for lower energy levels. As the impact energy increases inter-laminar damage occurs, which reduces the load carrying capacity of the laminate. In the LS-DYNA model orthotropic elastic material was used, which does not incorporate this damage phenomenon. Same behavior can be seen in strain energy comparisons shown in the Figure **. As the impact energy increases strain energy deviates from the experimental value. For better understanding of modeling behavior maximum load and maximum strain energy comparison plots for carbon/epoxy laminates are shown in the Figure 7.

While performing the experiments no significant damage was seen in E-Glass/epoxy laminates as compared to the carbon one. The lower bound in E-Glass was decided with incipient damage while the upper bound was seen when the load carrying capacity was not increasing. Figure 4 shows comparison of load vs time plots for E-Glass/epoxy laminates. It can be seen that load vs time plots are in agreement in the case of E-Glass/epoxy laminates, since the damage is minimal for the lower impact energy levels. However, it was observed that even in the case of E-Glass/epoxy laminates, as impact energy was increased, the deviation in the experimental and numerical results increased. Figure 8 shows Maximum load carrying capacity and the maximum strain energy comparison plots for E-glass/epoxy laminates, showing better correlation than carbon/epoxy laminates.

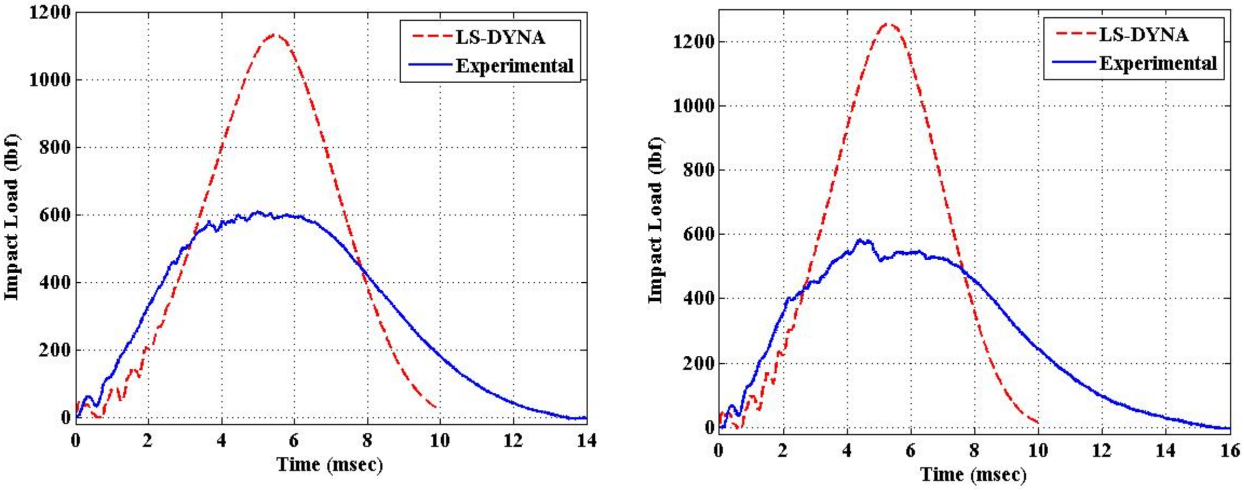
In reality, as the impact energy increases inter-laminar matrix cracking occurs, which reduces load carrying capacity. Progressive damage plots are shown for Carbon and E-Glass/epoxy laminates in Figures 9 and 10 respectively. If the matrix cracking is incorporated in the LS_DYNA model, it is expected to drop the impact load carrying capacity at higher impact energy levels simulating the progressive damage in the laminate from lower bound to upper bound. After incorporating matrix failure criteria it is expected to simulate the impact load as well as strain energy simulations more correctly as compared with the experimental data.



(a) 64 ft-lbf (b) 128 ft-lbf

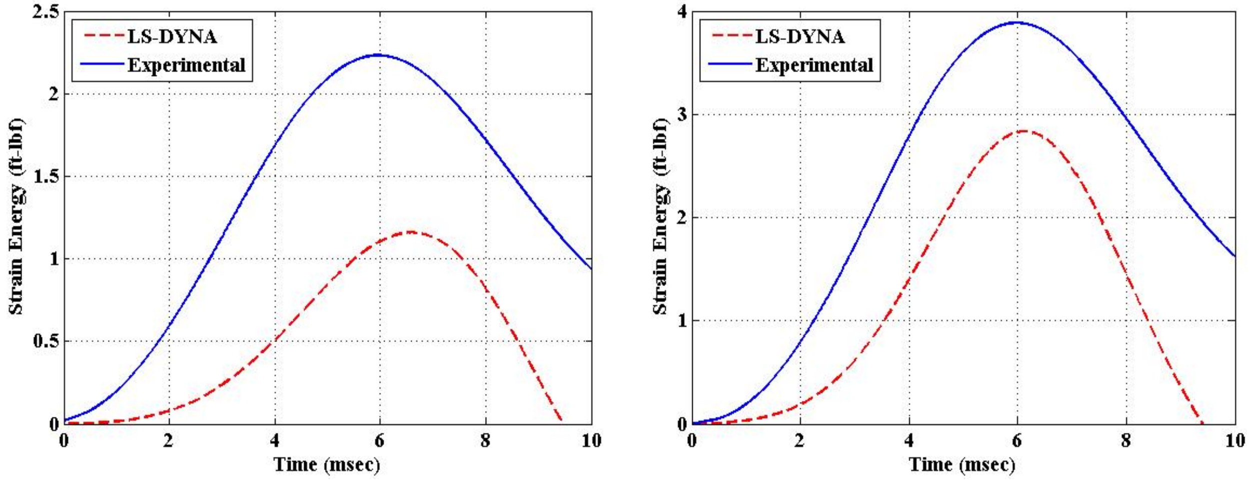


(c) 192 ft-lbf (d) 256 ft-lbf

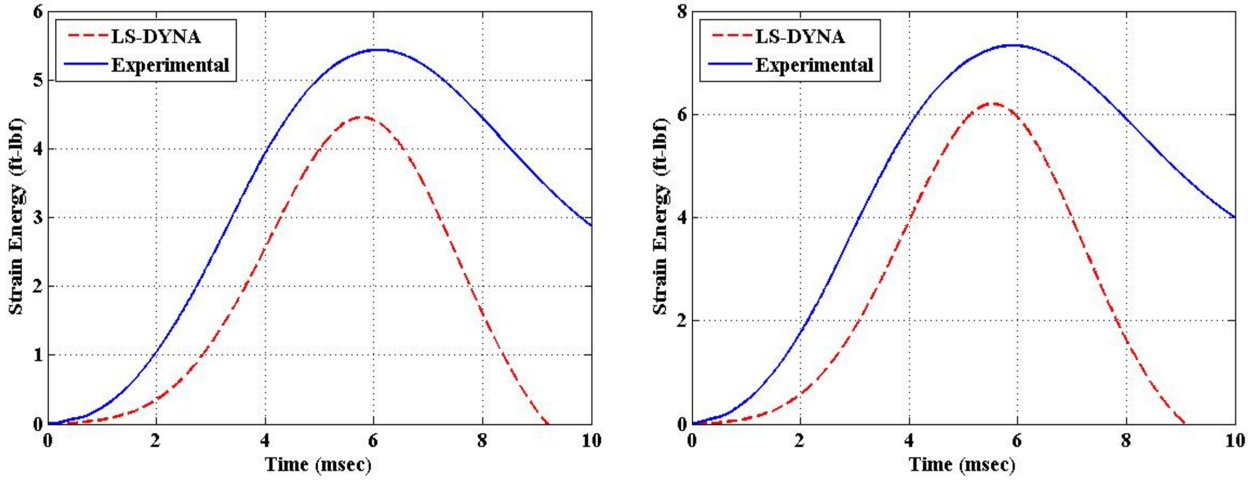


(e) 320 ft-lbf (f) 384 ft-lbf

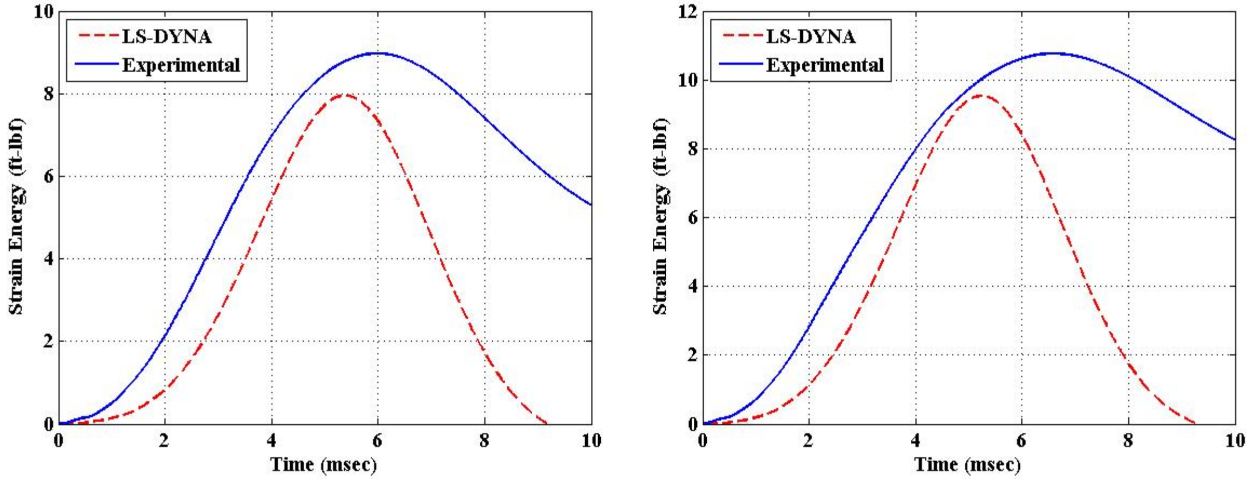
Figure 3: Impact load vs. time plots for Carbon/Epoxy laminates at various impact energy levels



(a) 64 ft-lbf (b) 128 ft-lbf

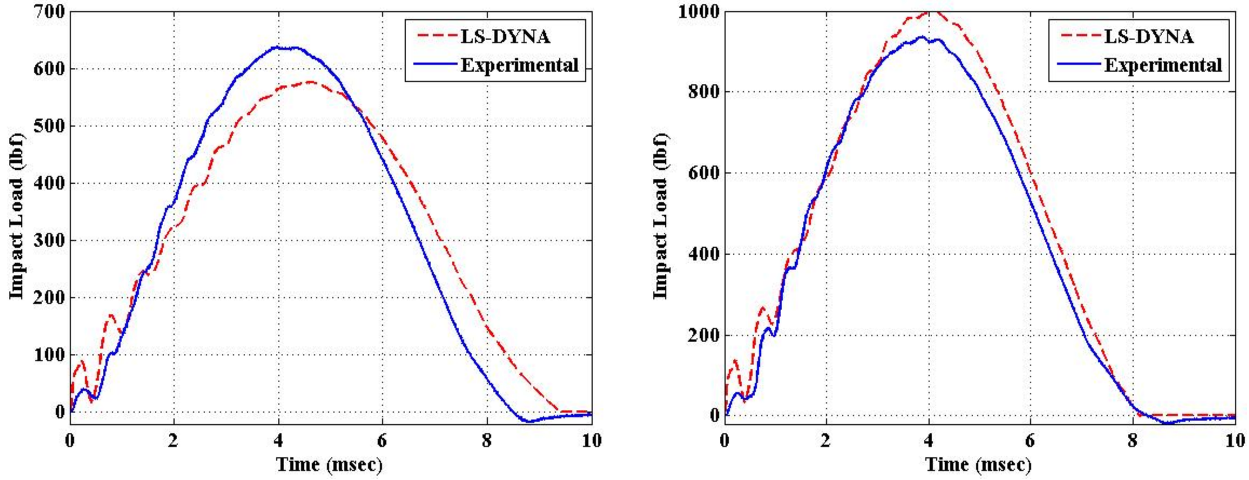


(c) 192 ft-lbf (d) 256 ft-lbf

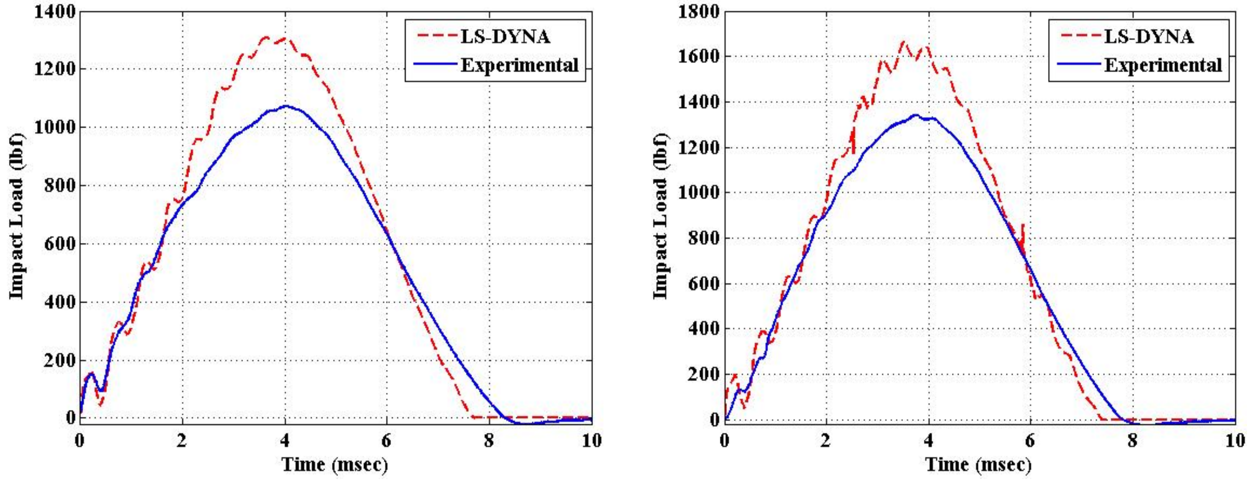


(e) 320 ft-lbf (f) 384 ft-lbf

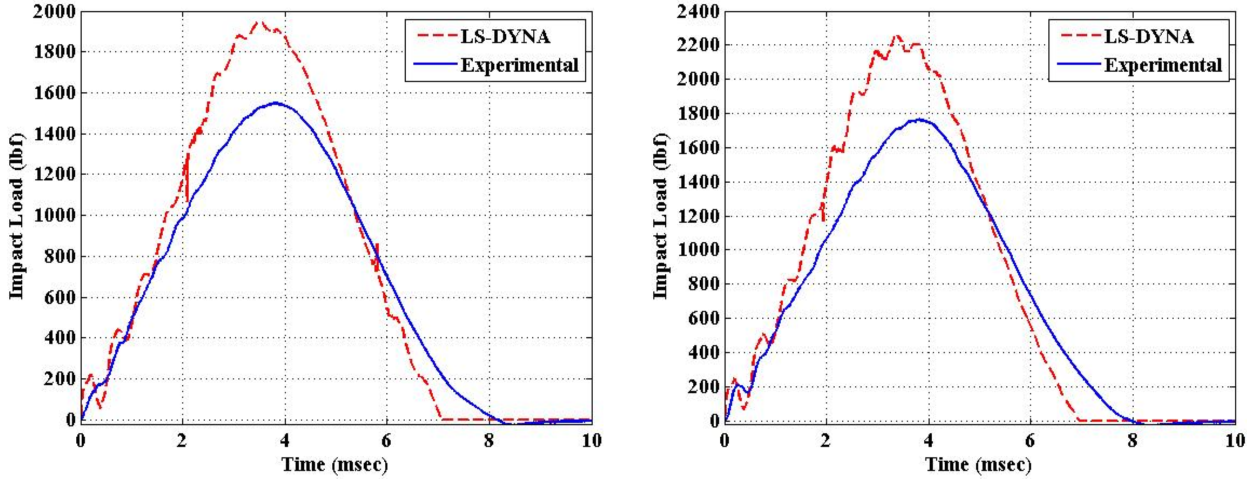
Figure 4: Strain Energy vs. time plots for Carbon/epoxy laminates at various impact energy levels.



(a) 128 ft-lbf (b) 256 ft-lbf

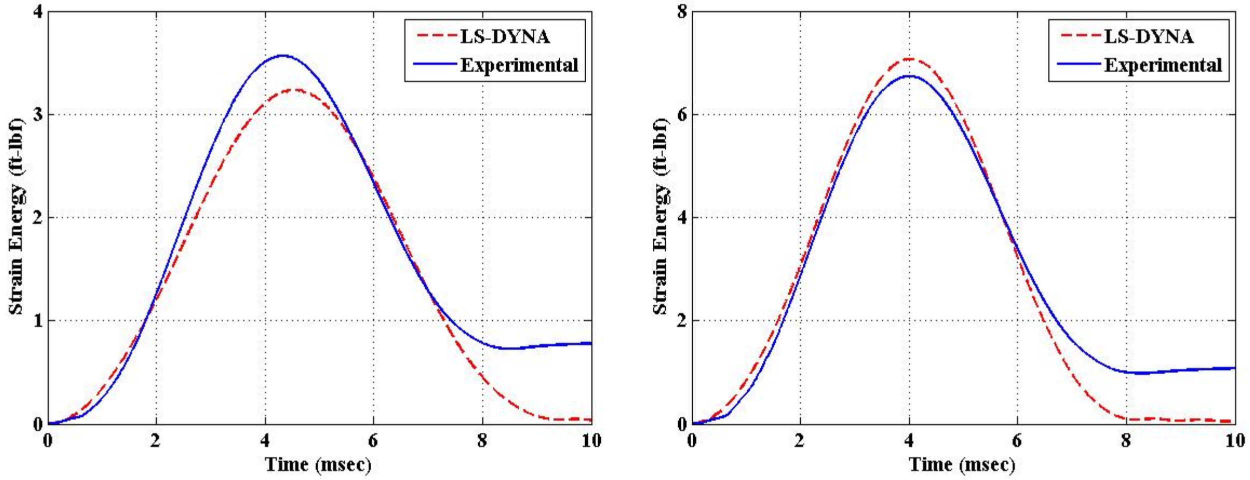


(c) 384 ft-lbf (d) 512 ft-lbf

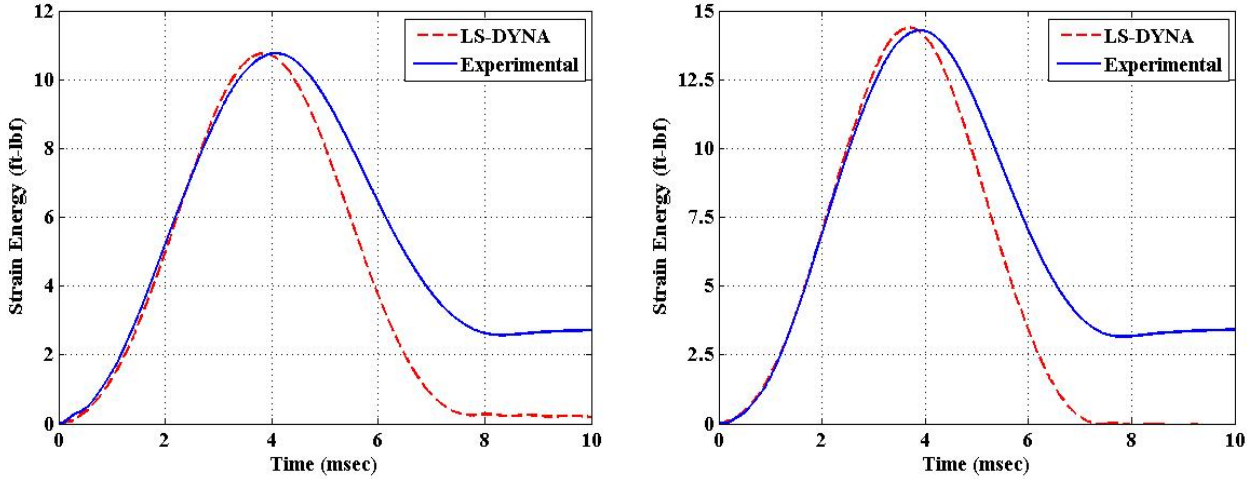


(e) 640 ft-lbf (f) 768 ft-lbf

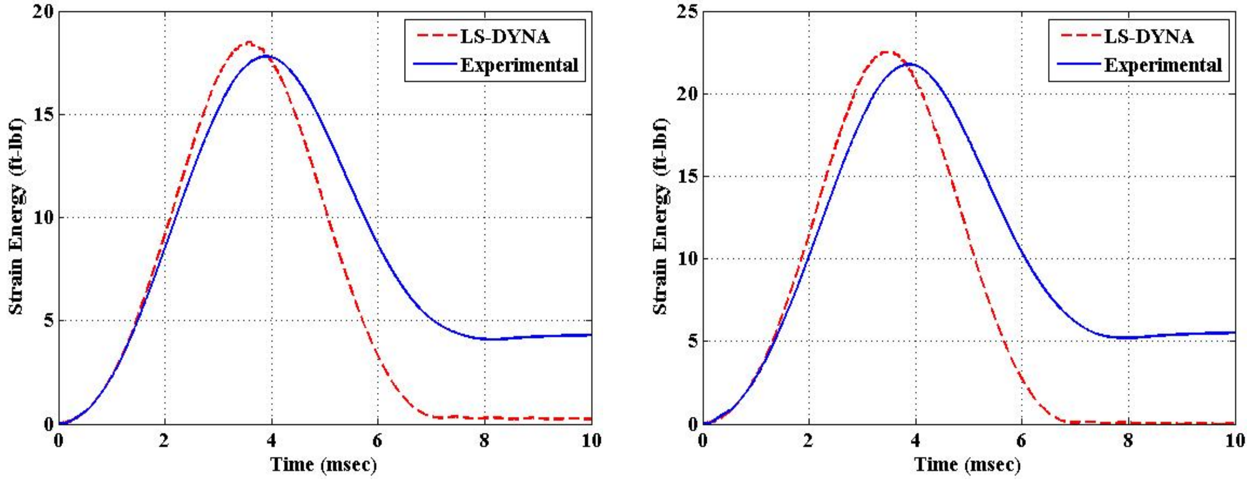
Figure 5: Impact load vs. time plots for E-Glass/epoxy laminates at various impact energy levels



(a) 128 ft-lbf (b) 256 ft-lbf

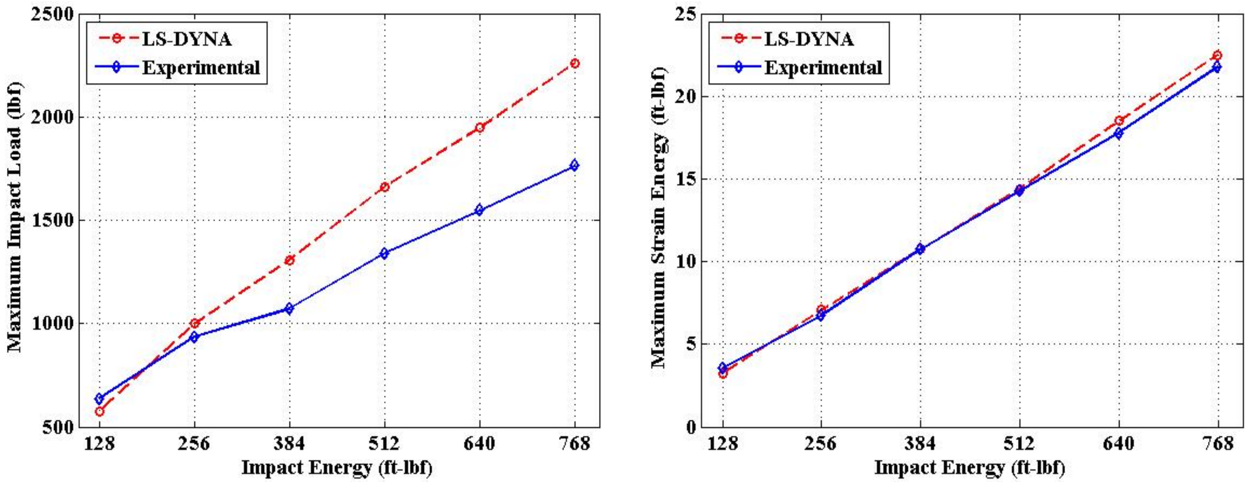


(c) 384 ft-lbf (d) 512 ft-lbf



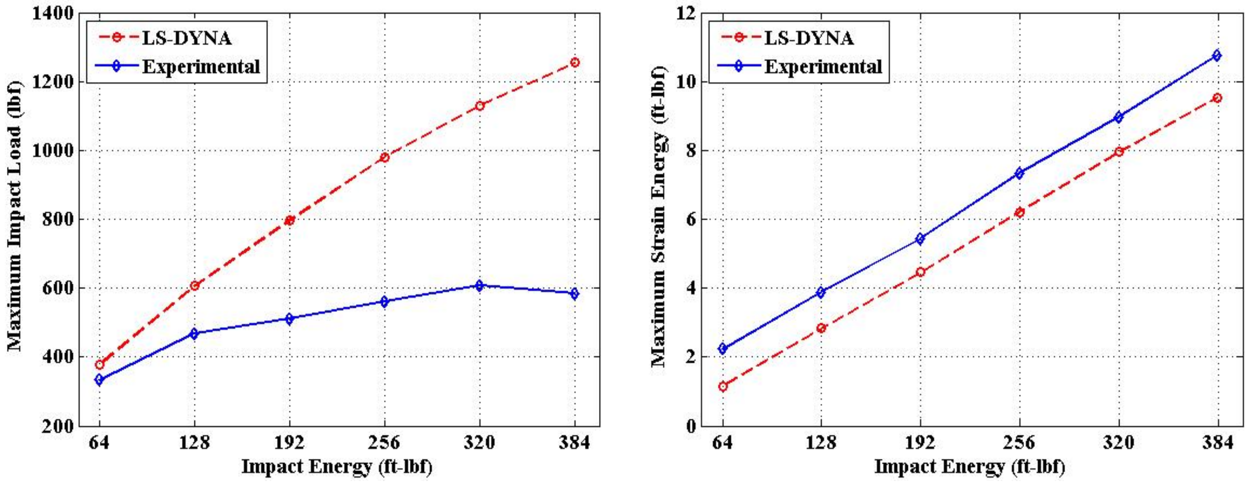
(e) 640 ft-lbf (f) 768 ft-lbf

Figure 6: Strain energy vs. time plots for E-Glass/epoxy laminates at various impact energy levels.



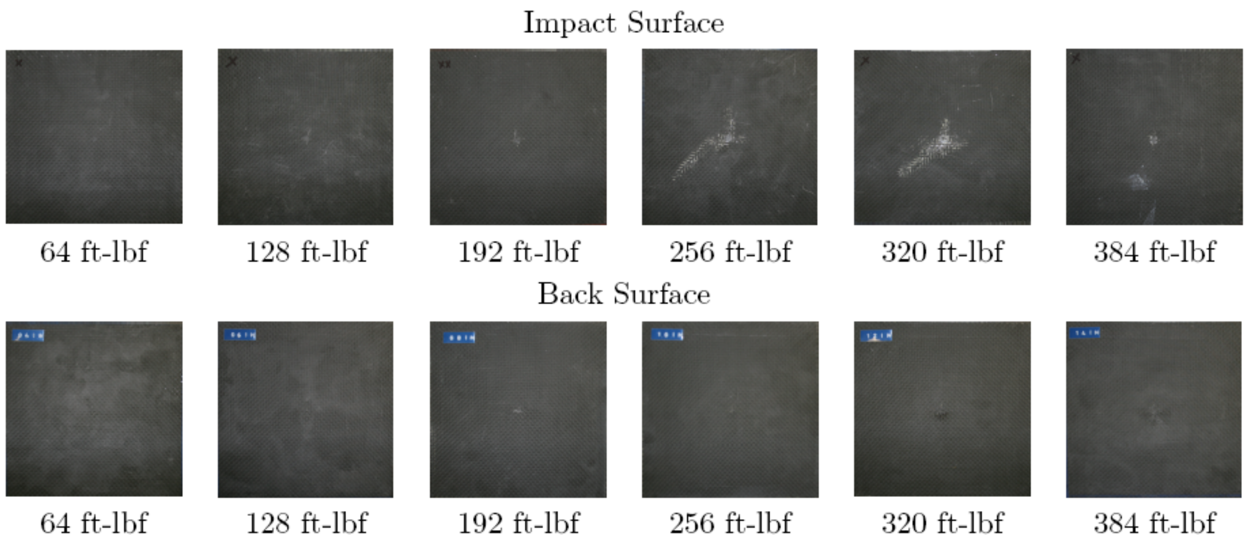
(a) Maximum Impact Load (b) Maximum Strain Energy

Figure 7: Comparative plots for E-Glass/epoxy laminates.



(a) Maximum Impact Load (b) Maximum Strain Energy

Figure 8: Comparative plots for Carbon/epoxy laminates.

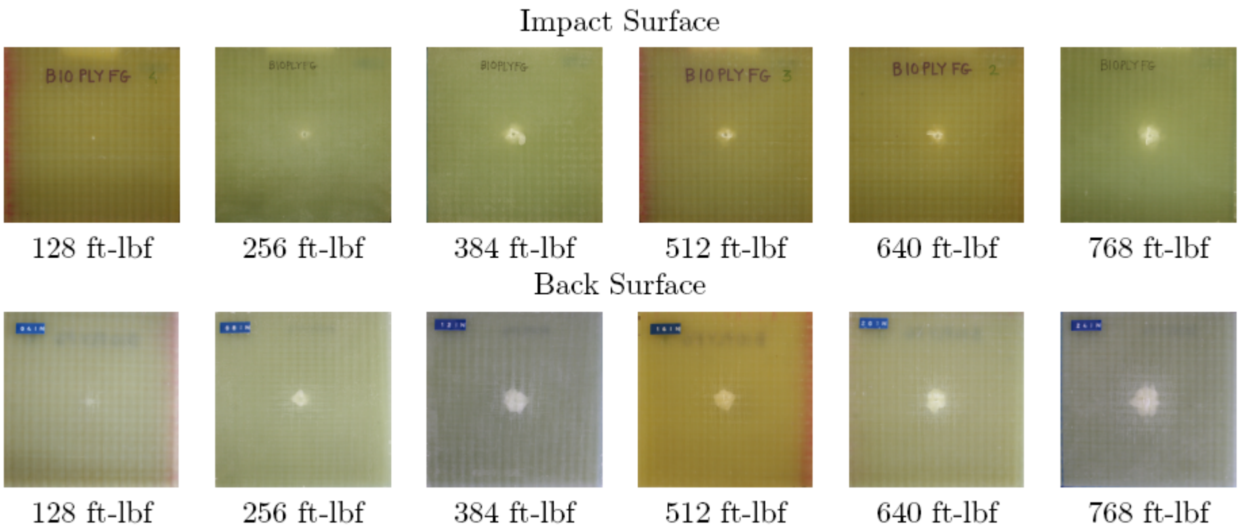

Impact Surface

64 ft-lbf 128 ft-lbf 192 ft-lbf 256 ft-lbf 320 ft-lbf 384 ft-lbf

Back Surface

64 ft-lbf 128 ft-lbf 192 ft-lbf 256 ft-lbf 320 ft-lbf 384 ft-lbf

Figure 9: Progressive damage of Carbon/Epoxy laminates


Impact Surface

128 ft-lbf 256 ft-lbf 384 ft-lbf 512 ft-lbf 640 ft-lbf 768 ft-lbf

Back Surface

128 ft-lbf 256 ft-lbf 384 ft-lbf 512 ft-lbf 640 ft-lbf 768 ft-lbf

Figure 10: Progressive damage of E-Glass/Epoxy laminates

## Summary

In the present study, response of composite laminates under low velocity impact loading was investigated using LS-DYNA. The composite laminates were manufactured by the H-VARTM process using basket weave E-Glass fabrics and plain weave AS4 carbon fabrics with the Epon 862 resin system and Epicure-W as a hardening agent. The LS-DYNA results were compared with experimental drop test results using the Dynatup Low Velocity Impact Test Machine. In the case of E-Glass/epoxy laminates, numerical results agreed well with the experimental results, however in the case of Carbon/Epoxy laminates, the results showed significant deviations at higher impact energy levels due to exclusion of damage model in the numerical simulations. In general LS_DYNA seems to be a powerful tool in simulation low velocity impact phenomenon for the most of composite materials manufactures using fiberglass materials and it can be effectively used if the damage models are incorporated in carbon composites. The present study can be easily extended for other weave patterns including twill, satin, and braided composites.

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