Proc. of the 32nd International Symposium on Shock Waves (ISSW32)
doi:10.3850/978-981-11-2730-4_0461-cd

Blast Wave Loading of Carbon Fiber Reinforced Polymer Plates in a Compartmentalized Setup and the Structural Health State of the Plates Post-Blast

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Abstract In this study, the focus was to investigate and develop a framework for the advancement of the structural performance of composites when dynamically loaded by a blast wave. The experimental goal mimics a large-scale structure that is separated, by a wall, into two distinct chambers. The purpose being to identify all recognizable patterns of dynamic, compressible, fluid flow in both chambers, when a blast wave occurred. To accomplish this, a spherical blast wave was produced by stringing a copper wire and subjecting the wire to a large voltage potential. A carbon fiber reinforced polymer plate separated the test chambers. From the global perspective, a z-fold schlieren imaging technique was utilized to track the spherical blast wave front and all subsequent waves generated. These visualization methods allowed for the qualitative studies of any wave created in the chambers and their effects on the carbon fiber reinforced polymer plate. From the local perspective, the quantification of the carbon fiber reinforced polymer plate's response was measured via strain gages, which is suggested in the structural health monitoring paradigm. Tentative results indicate the shock strength is not strong enough to visibly deflect the plate, although a strain response has been presumably measured. Despite this lack of visual evidence, a possibility exists that some of the internal structure has been damaged, hence the structural health monitoring techniques. Using the information discovered, additional experimental designs and processes were developed, and insight was garnered into better understanding the performance of composite plates.

1 Introduction

In this study, the focus was to investigate and develop a framework for the advancement of structural performance of composites when dynamically loaded by a blast wave while constructing an in-situ structural health monitoring technique for blast loaded composites. Blast waves are the explosive energy imparting itself upon the surrounding environment in very short timelines. A defining feature of blast waves are their exponential decay of properties behind the shock front [1]. The typical properties of a blast wave are heat, pressure, and in military applications, shrapnel. These components' interaction is dynamically imparted upon a structure, which typically overwhelms the structure, and cause varying levels of damage [2].

Our research is focused on the enhanced structural performance of composites, when the composites are subjected to dynamic loading imparted by a blast wave and any subsequent events. This has significant importance to the naval industry, as well as others. Militaries benefit from being lightweight, fast, and dangerous. Naval engineers have begun replacing traditional materials, like steel and aluminum, with composites in their ship design [3]. Adequate design must handle extreme events, such as blast waves, all while keeping personnel safe and the vessel operational.

The unique mechanics of composites lends itself to a broad design spectrum. For example, a composite laminate can be designed such that when a unidirectional loading is applied, a moment is produced within the laminate. This product has been exploited and used in the aerospace industry. For example, wings can be designed in such a way that they bend but do not twist, unlike metal wings that both exhibits bending and twisting [4]. Engine fan blades can be designed to twist when placed under extensional loading when spun [5]. Composite laminates provide the designer with the opportunity to tune their structure beyond what a traditional material, i.e. aluminum or steel, can provide.

In general, we impart a spherical blast wave upon the composite plate using an in-situ, tunable exploding wire apparatus capable of discharging approximately 29 kV in microseconds. Triggered by the current impulse, the data acquisition system records the time history of strain at different locations on the carbon fiber reinforced polymer plate. Additionally, we observe qualitatively, the fluid flow of the blast wave and any subsequent fluid dynamic events, such as reflections.

At this juncture in time, prior research has focused on open atmosphere blast loading of carbon fiber reinforced polymer plates [6], underwater numerical and finite element analysis for blast waves [7], and the effect that plate radius of curvature has on blast energy dissipation [8]. Our goal is to perform carbon fiber reinforced polymer plate analysis on a blast loaded plate while in an enclosed space and compare to a composite plate control sample.

Turkmen and Mecitoglu's research focused on blast loading of stiffened composite laminate plates [6]. They approached this problem from the perspective of an exponentially decaying products region behind the shock front. During the data analysis phase of the research they found that the blast waves pressure profile deviated slightly from an ideal exponential decay and they posited that this fluctuation is due to the dynamic nature of the blast pressure. Another assumption was made to simplify the analysis, that was to assume either uniform pressure distribution or non-uniform pressure distribution. Interestingly, they found that a discrepancy between the measured and predicted strains because of the adhesion between lamina layers and that the pressure varies the further the detonation center is from the experimental set up. The dynamic response frequency was found to be in good correlation to the experimental results.

Schiffer and Tagarelli explore the dynamic response of composite plate when subjected to underwater blasts [7]. Research into the dynamic response of ductile materials has been of interest since WWII and the dynamic behavior of beams, plates, and shells are well established. The challenge with composites is their anisotropy and their loading may produce some results that are unexpected, namely through coupling, that do not follow traditional response models. They look at the theoretical and experimental modeling of the scenario. The models considered the fluid-structure interaction with and without the cavitation effects as well as the flexural waves in the plate. Interestingly, they found that the thinner the plate, the less momentum response is noticed by the plate when loaded by an underwater blast wave. This makes sense if we consider an area of water as a membrane and notice that when it is very thick, the momentum will be greater when loading occurs. However, since we are dealing with a membrane, the cavitation effect reduces as the laminate become thinner. Because of the research, the team found that the plate response to underwater blast waves are dependent on five parameters. They are the aspect ratio, plate radius, mass, acoustic impedance, and peak pressure of the incident shock wave. The authors deduced that the response of an orthotropic plate is like an isotropic plate and that very small differences were found between cross-ply and quasi-isotropic plies.

Kumar, Stargel, and Shukla researched the response of curved carbon composite panels when loaded dynamically by a blast wave [8]. The experiments utilized a shock tube apparatus to control the blast loading. They used a three-dimensional digital image correlation to technique to obtain out of plane displacements. The two main observed failure mechanisms of the curved plates were delamination and fiber breakage. They found that the panel with the most curvature had the strongest blast dissipation. The authors posit that as the radius of curvature is decreased, the effect of shock loading on the panel will be decreased because less of the shock energy is transferred into the composite panel.

2 Experimental Goal

The experimental goal mimics a large-scale structure that is separated, by a wall, into two distinct chambers. The purpose being to identify all recognizable patterns of dynamic, compressible, fluid flow and the pressure profiles in both chambers, when a dynamic, energetic event i.e. a blast wave, occurred in one of the chambers.

3 Methodology

To accomplish our experimental goal, a spherical blast wave was produced by stringing a copper wire between two electrodes and subjecting the wire to a large and sudden voltage potential. The voltage potential is generated using an in-situ, tunable (10kV - 40kV), exploding wire apparatus with the exploding wire itself being located centrally inside the blast chamber. A carbon fiber reinforced polymer plate separated the test chambers. The carbon fiber reinforced polymer plate type is an all woven twill, 0°/90°. The plate is non-quasi isotropic, balanced, symmetric and has clamped corner boundary conditions. From the global perspective, a z-fold schlieren imaging technique was utilized [1]. Furthermore, a razor's edge acted as the schlieren edge to ensure proper vertical fluid flow visualization to track the spherical blast wave front and all subsequent waves generated. The visualization method allowed for the qualitative studies of any wave created in the chambers and their effects on the carbon fiber reinforced polymer plate.

3.1 Structural Health Monitoring

The development of a structural health monitoring system has been developed from the four-step paradigm presented by [9]. The carbon fiber reinforced polymer plate response, by the propagating blast waves, are measured using three axial Vishay Precision Group 125BZ strain gauges, oriented at 0º, 45º, and 90º per Fig. 1 are adhered to the face of the panel not exposed to the initial blast wave.

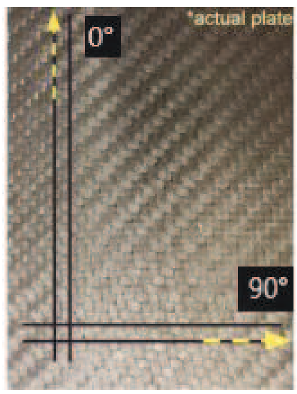

Fig. 1 Carbon fiber reinforced polymer plate with indicated directions

The choice of using strain gages, over accelerometers was due to the mass loading caused by the accelerometers. Furthermore, the carbon fiber reinforced polymer plate will have an increased compliance when subjected to the blast loading. Therefore, the use of strain gages to measure the change in plate compliance is justified. Each strain gauge is connected to a Vishay Precision Group Micro-Measurements 2310B Signal Conditioning Amplifier, and the four signal amplifiers are then connected to a Teledyne Lecroy WaveSurfer 3034z, 350 MHz oscilloscope, such that each response signal is recorded in a separate channel.

3.2 Image Processing

The methodology implemented to track and record the blast waves requires a multi-step, programmatic approach. The process involves the automatic importing of the high-speed photograph, which we consider raw data. Then we take a non-blast wave image and perform distortion correction and background noise removal. Removal of any background noise essentially leaves a binarized image which allows for the skeletonization the photograph. The photograph is then discretized, the desired pixel are detected. The desired pixels are the blast wave and each pixel's location is recorded. The discretized sub-images (local) are reconstructed into a global image.

These steps outlined in Fig. 2 have allowed for the tracking of many blast waves, simultaneously. This is powerful, the ability to identify and track these regular and irregular shock waves allows for the deduction of the shock wave motion. Additionally, the toolkit can track the development and propagation of the Mach stem, in time.

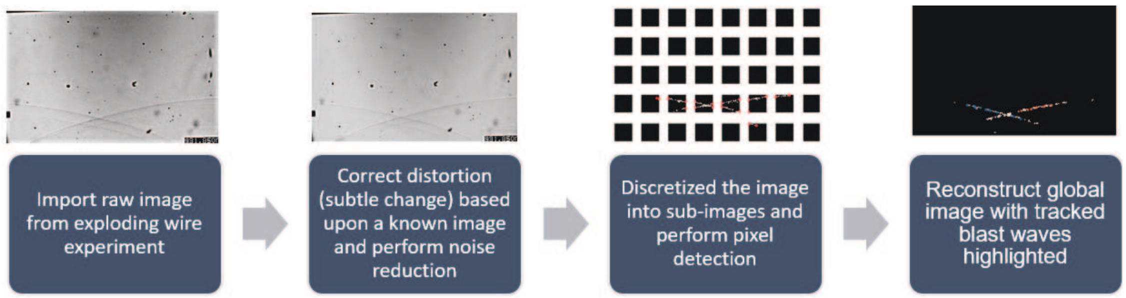

Fig. 2 Importation of the raw images are performed. Distortion correction, from a known grid image, is performed. The removal of background noise is performed. The image is then discretized into sub-images and the blast wave detection algorithm is performed. The sub-images are stitched together to reconstruct the global image.

3.3 Experimentation

The experimental design mimics a structure what has been effectively separated into two equal volume chambers by a carbon fiber reinforced polymer. The internal volume of the test structure is 0.0125 m^3 (760 cubic inches). The two chambers serve different purposes. The first chamber, denoted as the "blast chamber," is where the blast event and some pressure readings will occur. The second chamber, denoted as the "unobstructed chamber," is free of any obstacles and has pressure sensors mounted flush with the chamber's wall. The purpose of the unobstructed chamber is to identify any overpressure patterns that develop because of the dynamic loading and deflection of the carbon fiber reinforced polymer plate into the unobstructed volume.

3.3.1 Physical Experimentation

Four high-voltage capacitors deliver a 29 kV to the copper wire, which explodes due to ohmic heating and the runaway reaction into an expanding plasma cloud, which results in the propagation of a shock wave that strikes the carbon fiber reinforced polymer plate. The plate is located within the blast box and effectively separates the blast chamber from the unobstructed chamber. The shock wave is visually recorded by z-fold schlieren high-speed imaging for numerical modeling and analysis. The shock wave apparatus supports the panel with the simply supported boundary conditions and has pressure gauges that can read the pressure difference on both sides of the carbon fiber reinforced polymer plate.

The experimentation consisted of two structural states of the carbon fiber reinforced polymer plate. The first being an as manufactured state, which is termed "pristine". The second structural state being the pristine plate now with a 6.35 mm (.25") hole drilled centrally and completely through the plate.

3.3.2 Blast Box

The blast chamber was constructed with stock 80/20 aluminum t-slotted extrusion and related connecting components, allowing for ease of fabrication and adaptability of the setup. Acrylic panels of 6.35 mm (0.25") thickness fit the t-slots of the 80/20 to provide siding for the chamber to contain the shock wave along with its associate pressure, gas emissions etc. Holes laser cut into the acrylic siding accommodate pressure sensors on both sides of the carbon fiber reinforced polymer plate and the exploding wire electrode component. A Polylactic Acid electrode post fabricated, via additive manufacturing, was implemented to optimize the shock origin in the blast chamber to achieve minimal shock reflection off the post. The post houses two brass rods, functioning as electrodes, with shallow slots at their tops to provide a stringing path for the exploding wire. A tightening polylactic acid collar fits the post to hold it upright at the bottom of the blast chamber, allowing for positional adjustment of the electrode post to achieve a central location of the exploding wire in the chamber. Central detonation of the wire maximized the distance of the initial shock front from the chamber walls, thus minimizing the amount of shock reflection that would compromise data acquisition.

The carbon reinforced polymer plate was constrained in a simply supported manner, incorporating a garolite rod to perform as a roller on one edge of the plate and rubber pads to constrain the opposite edge in a pin-like manner. The two other edges of the plate were left free. Additionally, 80/20 t-slotted extrusion accommodates sliding angle clamps which effectively can constrain the plate in a clamped manner at four corners as desired, see Fig. 3.

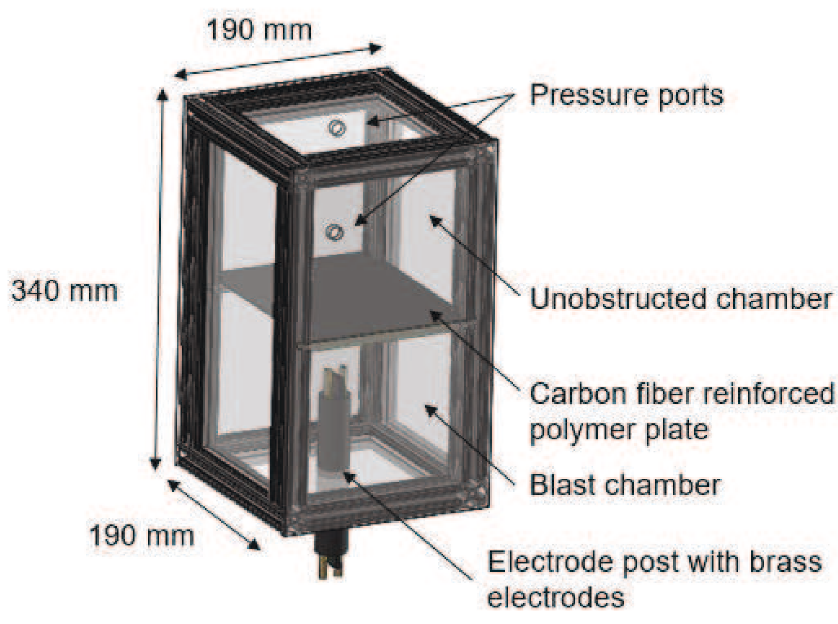

Fig. 3 Blast box with electrode post inserted, carbon fiber reinforced polymer plate, and pressure sensor wall mounts. The boundary conditions are simply supported parallel to the transverse axis and free-free parallel to the longitudinal axis

3.3.3 Blast Chamber

In the blast chamber (lower half of blast box, Fig.3), a copper wire is strung between to electrodes allowing for the exploding wire to be detonated centrally. The resulting blast wave travels throughout the chamber imposing dynamic loads upon the carbon fiber reinforced polymer plate. The plate deforms and creates time-dependent pressure field within the unobstructed chamber. Additionally, a dynamic strain field is generated.

3.3.4 Visualization

To visualize the blast wave and any subsequent fluid dynamics events related to the blast wave, we used a z-fold schlieren optic technique with a Shimazdu HPV X-2 high-speed camera. Z-fold schlieren optics is a common method for visualizing the fluid dynamics at any time step during an experiment. The method is more adept to the qualitative assessment of the fluid flow rather than the quantitative information of the density gradient [1]. This schlieren method works by using a series of mirrors that creates and directs a parallel beam of light through the test region. Post-test region, another series of mirrors are used to direct the light through lens and past a schlieren edge. The schlieren edge is key for "cutting" light, so the density gradient can be observed. All this effort was to direct the encoded light information into a high-speed camera. To detonate the wire, an in-situ, tunable exploding wire apparatus has been built [1], see Fig. 4. The high voltage circuit consists of four capacitors, electromagnetic switches, a triggering circuit, and three ports to connect electrodes to deliver the electrical energy required to detonate the wire.

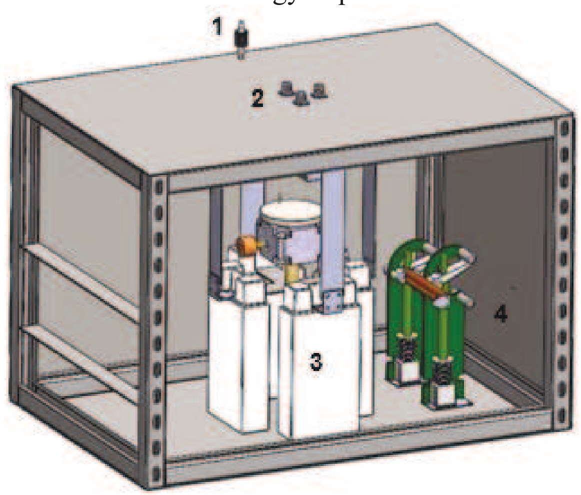

Fig. 4 Exploding wire apparatus. 1) A Rogowski coil used to trigger the hardware simultaneously. 2) Electrode ports that connect to the blast box electrodes. 3) Four Capacitors with a max 10 kV per capacitor (40kV max). 4) Electromagnetic switches that arm and disarm, as well as, allow the charging and discharging of the stored voltage

4 Results

Recent developments of the investigation into the enhanced structural performance of carbon fiber reinforced polymer plate, when subjected to our in-situ exploding wire setup, has identified that the energetics of the blast wave yield no qualitative deflections, when observed via high-speed photography. This was expected due the enhanced stiffness properties of carbon fiber reinforced polymer plates when levied against more ductile materials, such as aluminum. However, investigation of a quantifiable structural response of the carbon fiber reinforced polymer plate, when subjected to a blast wave generated by a 29 kV setting, produced voltage data that included mixed signals. The mixed signals included an electro-magnetic frequency signal as well as a strain response. Figs. 5 and 6 shows a common voltage response amongst experiments in the same strain gage orientation direction.

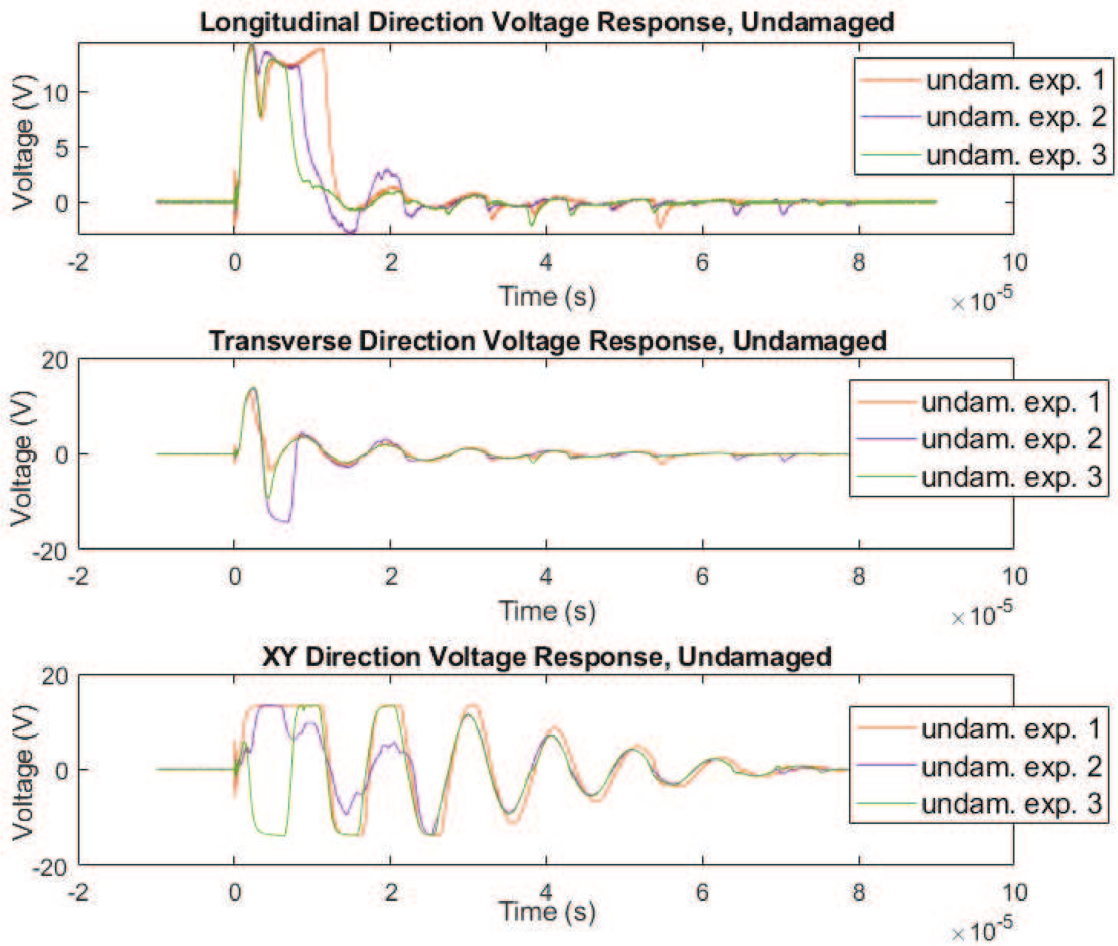

Fig. 5 The pristine plate's voltage signal responses. Three experimental results are presented for each strain gage direction.

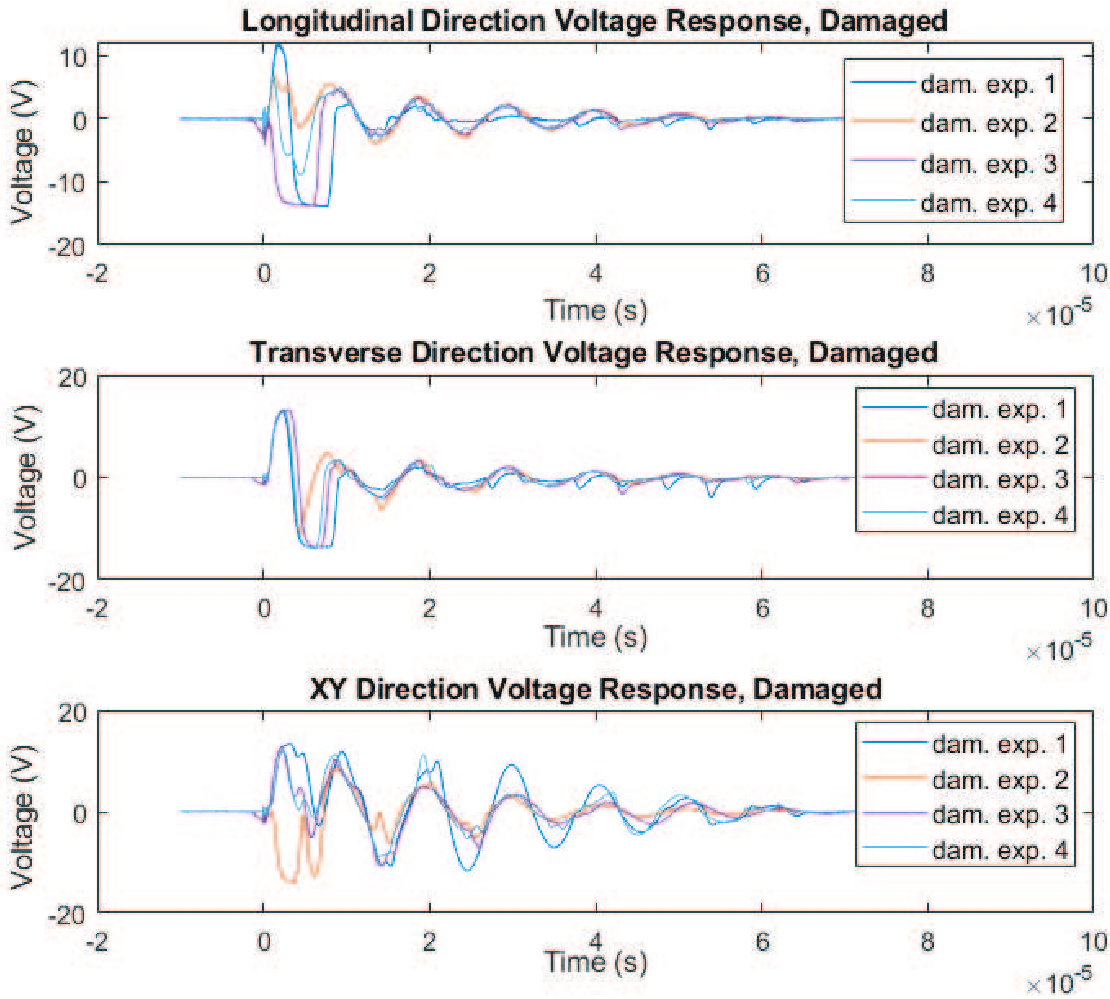

Fig. 6 The damaged plate's voltage signal responses. The damaged plate consisted of a 6.35 mm diameter hole drilled centrally and through the plate.

Notice in Figs. 5 and 6 that the mixed signal response is indicates that the transitory response of the signal has the mixed signal modes in the first 10-20 microseconds, then the electromagnetic field decays and only an indicated strain-stress response remains.

5 Discussion

The strain response of the plate, in both the undamaged and damaged state, was unexpected considering that the high-speed photography indicated zero deflection. The current assessment indicates two potential scenarios. The first is that the carbon fiber reinforced polymer plate deflection was sub-pixel size, hence it was not captured by the high-speed camera and hence the strain on the plate may not have been large enough to produce a visible deflection. The second is that the strain response measured the out-of-plane shear and the stress waves generated by the blast wave loading, like an impact-echo nondestructive evaluation test, and the deflection would not be visible in our viewing plane. We can investigate this by measuring the response along different viewing planes or further studying the electro-magnetic frequency signals independently from the strain response.

6 Conclusion

Based on the lack of visually observable deflection, these tentative results indicated that the blast wave was not strong enough to cause notable deflection. Despite these visual findings, the possibility remains that internal structural damage occurred in these experiments. Data gathered on the plate's strain response provided insight into this potential damage that has occurred. Various methods suggested by [7] have been considered for the structural integrity analysis, and the strain response SHM method is implemented. Using the information gathered, additional experimental designs and processes have also been developed, and new insight was garnered into the design and performance of composite structures.

Because blast waves produced using the exploding wire apparatus have a short experiment turn-around time of approximately 100 – 250 seconds, depending on voltage setting, it is possible to rapidly capture data. With this in mind, a large dataset can be produced by means of running up to 30 experiments in an hour to effectively study the behavior of interest.

Future work will involve developing this large dataset. This is imperative to the identification of structural damage from the loading that the shock wave imposes on the plate. Such a dataset will include the study of plates of varying fiber direction and count, and different plate configurations and boundary conditions, which will be exposed to the blast wave impulse many times.

Acknowledgements

The authors would like to thank the United States Air Force Research Laboratory through the generous funding, award number: FA6541-1-17-1-0004 and the National Science Foundation - Fluid Mechanics (CBET), award number: CBET-1803592. Additionally, we would like to acknowledge the University of California – San Diego's High Energy Physics Group for their continued support.

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