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In this work, high-pressure impact loading was implemented on a thermoplastic-metal hybrid panel via free piston shock tube. Finite element models, and pressure-time and deflection-time histories, were used to correlate the deformation characteristics to an applied blast loading. Deformation characteristics are obtained in real time during the blast test using fringe projection methods. To correlate and better describe experimental observations, finite element models were developed in LS Dyna for the

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High strain rate events pose high levels of complexity when analyzing a materials deformation characteristics. In high strain rate events like blast and impact, understanding the damage progression within the tested material is crucial when optimizing material design to give a desired performance. Under extreme loading cases inertial effects play a large role on how a material system performs. When a structure is blast loaded and begins deformation, inertial effects cause the structure to continue to deform past its stressed equilibrium point even after the main front of the shock wave has passed until it stabilizes its inertial effects with the material’s strength. At the point of momentary rest, the inertial effects are zero, and the structure begins to rebound causing the structure to elastically “snap back”. This behavior may repeat and oscillate to release the energy that was transferred into it until remaining at rest at its plastically deformed state.

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BACKGROUND AND INTRODUCTION

For primary structural applications fiber reinforced composites are often passed over in favor of more traditional metal alloys, because the inherent multi-phase nature of the fiber-matrix construction results in more complex damage mechanisms during extreme loading events such as vehicle crashes, ballistic impacts, and blast [1], [2], [3],[4]. To improve performance in these types of applications, attempts have been made to leverage the benefits of both composite materials and metal alloys, while minimizing the weaknesses of each constituent. By integrating both composite and metal materials in a single hybrid system, the collective mechanical properties in a joint material system can be improved [5]. Fiber metal laminates (FML's) are examples of a hybrid composite system designed to exploit the advantages of both metal alloys and fiber reinforced composites. When tested under blast events, FML panels exhibited superior energy absorbing capabilities at lower mass per areal density compared to traditional metal cladding [6]. However, under extreme loading events like those under blast, experimental observation techniques and damage assessment is difficult to quantify and is often overlooked. Understanding the dynamic deflection of a blast panel is crucial in engineering design, as the potentially large dynamic deflections during blast can cause contact damage to surrounding structures or injury to vehicle occupants if not properly accounted for [7]. To properly engineer FML's for blast applications, it is critical to have robust finite element methods validated with experimental blast data allowing for a full comprehension on the damage mechanisms and dynamic characteristics of the material system

In this study, asymmetric thermoplastic composite/metal hybrid panels are experimentally characterized using laboratory scale simulated high pressure blast loadings. Compared to a symmetric hybrid panel, eliminating the metal backing simplifies the system to the interactions of a single interface between the two dissimilar material systems for improved understanding of the response of each constituent. To fully understand the dynamic characterization, high speed imagery is used to optically calculate dynamic deflections of the thermoplastic composite via fringe projection methods. Non-destructive evaluation (NDE) techniques, such as C-scan, are used to quantify delamination through the thickness of the composite. A finite element model of the shock tube apparatus and composite-metal hybrid panel is developed using the loading conditions in the shock tube and the experimentally characterized material properties of the thermoplastic composite. The novel experimental setup allows for improved understanding into the dynamic response of the hybrid metal-composite material system in real time and the NDE methods, combined with finite element results, elucidate better understanding into the internal damage mechanisms.

METHODS

In this study, the hybrid composite material system consisted of a 2.3mm thick 7075-T6 aluminum "facesheet". The thermoplastic composite utilized in this study was 3.18mm thick 0/90 Toray Cetex® TC940, which is a continuous e-glass fiber (GF) reinforced polyethylene terephthalate (PET) prepreg tape. TC940 offers good impact resistance, stiffness, and durability to complement the properties of the aluminum alloy. The constituent materials were bonded with a 1mm layer of Plexus MA310, a two-part methacrylate adhesive intended for structural bonding of thermoplastic, metal, and composite applications. Hot press consolidation was considered but ultimately not utilized due to the thermal stresses induced at the interfaces of the aluminum and composite under manufacturing at elevated temperatures.

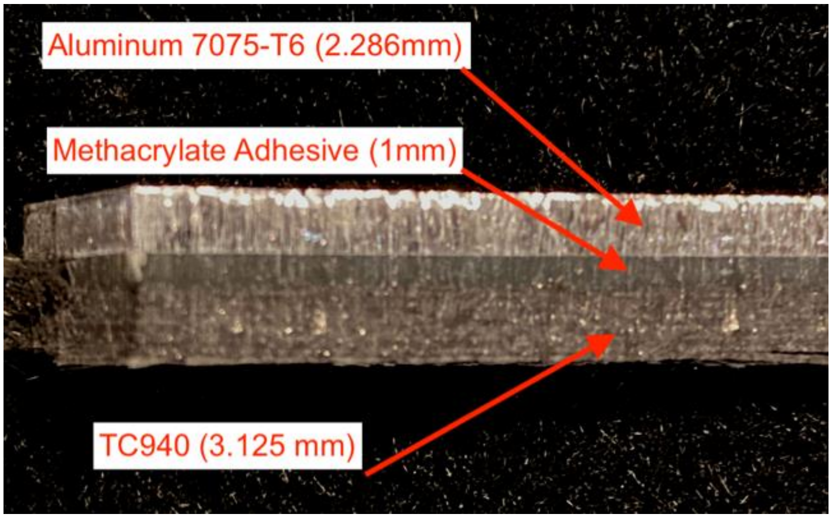

Figure 1. Cross Section of Material Configuration

A free piston shock tube (Figure 2) outfitted with an exit nozzle was implemented to conduct a pseudo-blast load event on the hybrid material system to simulate a near field blast event as seen in Patton [8].

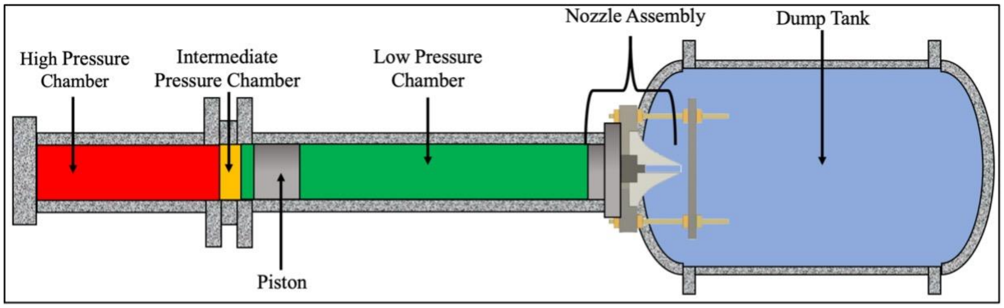

Figure 2. Schematic of Free Piston Shock Tube

The hybrid panels were tested under simulated blast conditions and their deflections, both dynamic and permanent, were recorded via fringe projection techniques. Fringe projection is an optical method that uses grating lines to map the deformation by two images a reference image consisting of a flat or undeformed object, and an image of a deformed object. The grating lines or, fringe pattern, is projected onto the back of a specimen and the deflection is measured optically, without the need for physical markings on the specimen (Figure 3).

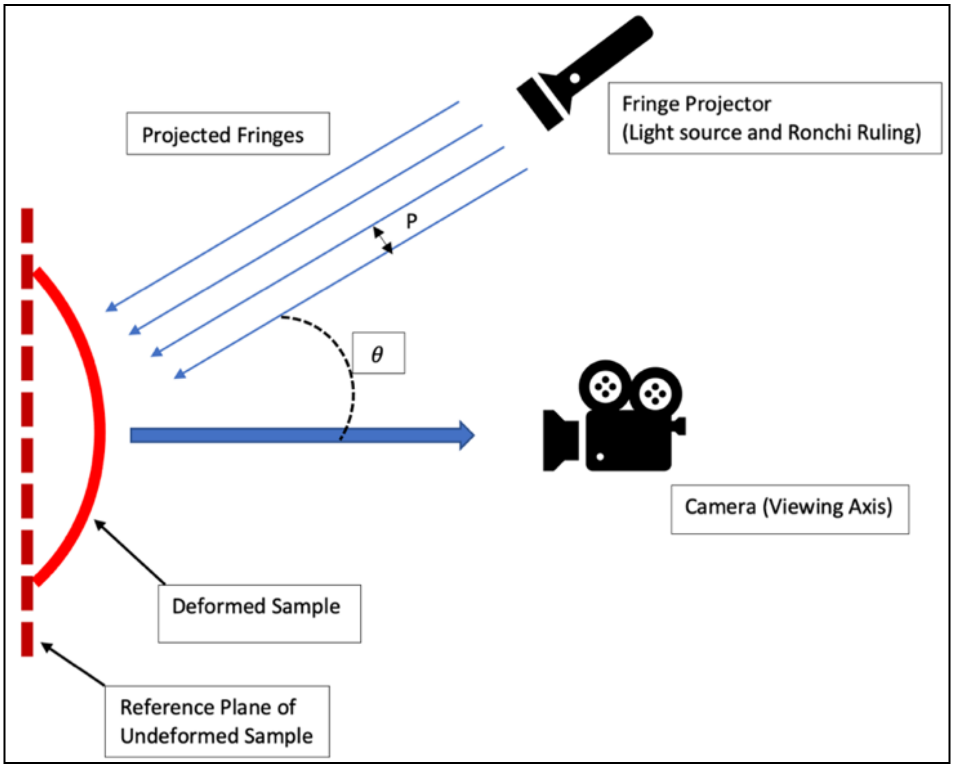

Figure 3. Simplified Schematic of Fringe Projection Technique

As the material deforms, the lines that are projected on the back of the object track the deformation contour of the back of the plate and are then their images are analyzed for the panels respective deflection profile using the object and initial reference images (Figure 4). To project these fringes, a 1000-watt halogen light was used and focused with a 150mm PCX lens and a 101.6mm half ball lens. The focused light was then passed through a Ronchi grating of 20 lines/mm. The grated image was then projected onto the specimen through a 12.5-75 mm zoom TV lens.

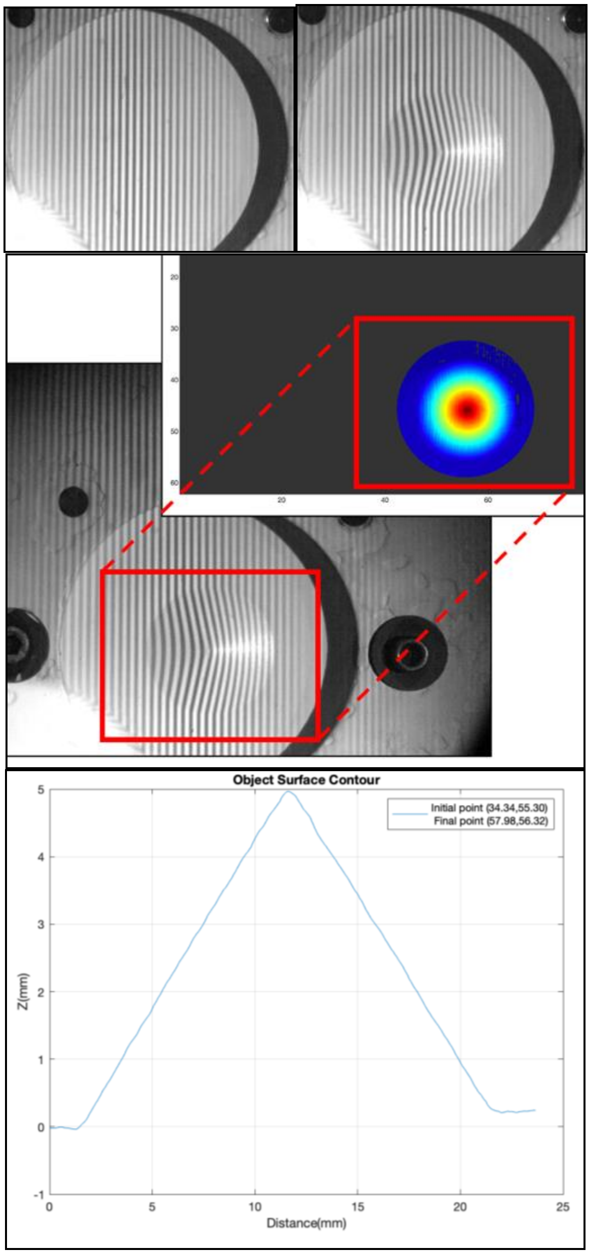

Figure 4. Fringe Projection Image Processing Steps Top: Object and Reference Image. Middle: Fringe Projection Analysis Result. Bottom: Surface Contour Plot of Object Image

RESULTS AND DISCUSSION

Before testing the hybrid composite panels, initial calibration tests were conducted using a rigid steel plate outfitted with a PCB M109C11 pressure sensor at the center of the plate so that the local pressure-time histories could be recorded near the nozzle. It was important to run these calibration tests using a rigid plate, because real-time pressure readings could not be obtained during the hybrid panel tests as introducing a hole and integrating a pressure sensor would induce damage into the hybrid panel. During the calibration tests, the average maximum pressure measured at the center of the plate was observed to be 42MPa. This initial pressure data was used to calibrate the air pressure loading in the shock tube FE model to obtain a representative pseudo-blast loading on the material.

The shock tube blast simulation experiments were conducted under the exact same initial conditions as the pressure profile characterization in the calibration tests. High speed imagery and fringe projection were used to calculate the dynamic and permanent deflections of the composite-metal hybrid panels. High speed imagery of the projected fringes was captured throughout the duration of the blast loading and used for dynamic deflection calculations. For validity, after the test was conducted and all vibration attenuated from the system, a final fringe projection photo was taken in the permanently deformed state and the final deflection was validated with a physical measurement from a dial gauge probe.

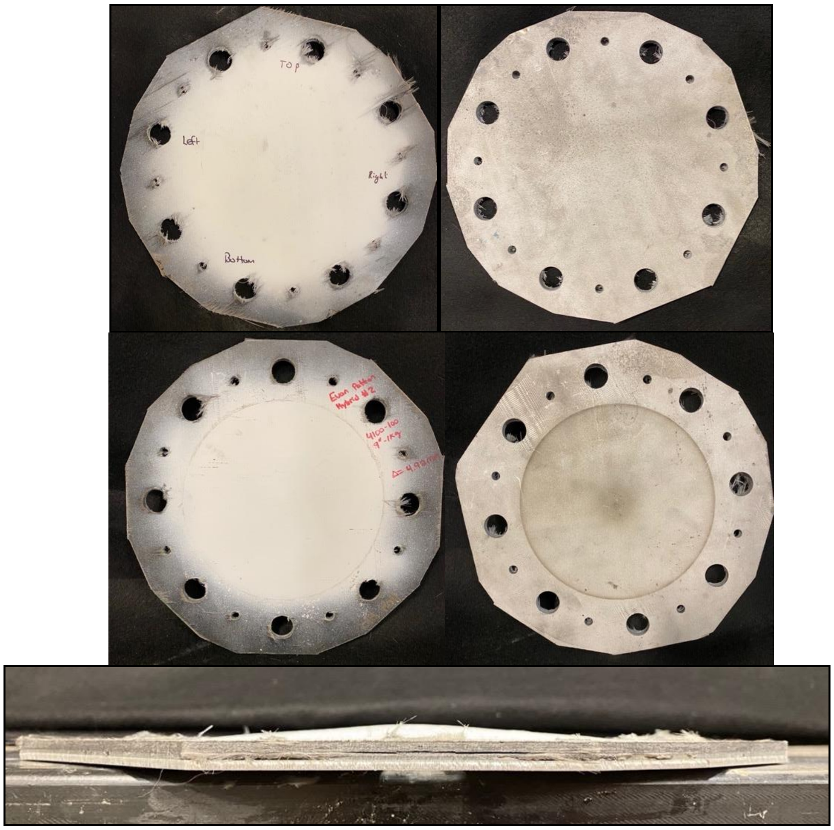

Figure 5. Pre and Post Pseudo-Blast Tested Hybrid Panels

The composite-metal hybrid panels experienced consistent permanent and dynamic deflections as reported in Table I. The panels observed plastic deformation in the front facing aluminum and extensive delamination in the composite. Ultrasonic testing was conducted on the delaminated panels to obtain a damage characterization seen in figure 6. When assessing the delamination extent, both C-Scans and destructive analysis revealed heavy delamination throughout the entire composite.

TABLE I. MAXIMUM RECORDED PERMANENT AND DYNAMIC DEFLECTIONS

Test Object ID	Permanent Deflection	Dynamic Deflection
HP1	4.97mm	11.09mm
HP2	4.92mm	11.23mm
HP3*	6.47mm*	12.06mm* (Cracking Observed)
HP4	5.00mm	11.10mm
HP5	4.59mm	10.36mm
Average	4.87mm	10.95mm
Standard Dev.	0.1896	0.3952

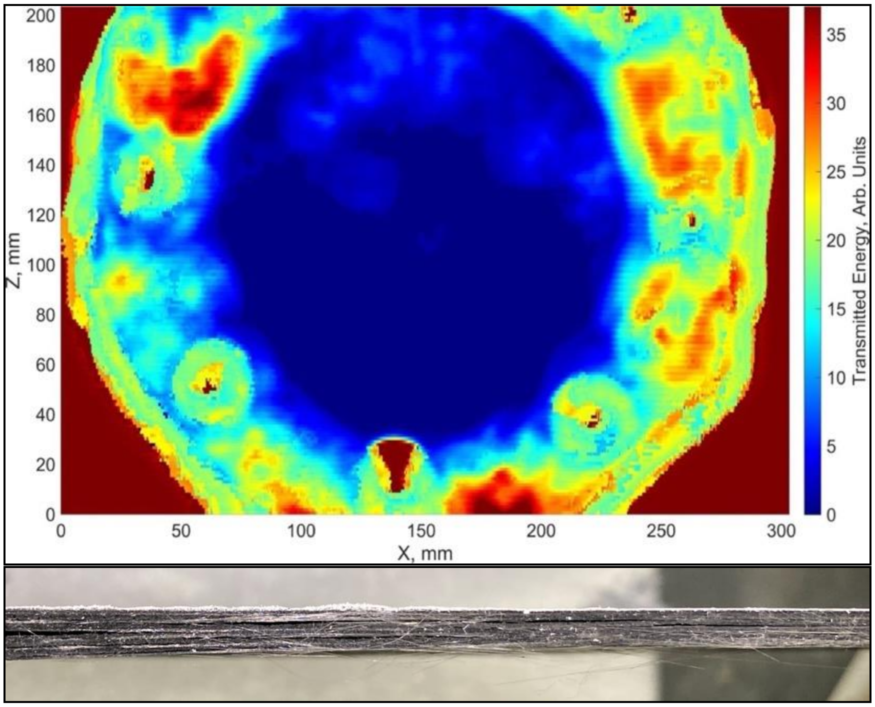

Figure 6. Above: Composite C-Scan Below: Cross Sectional Cut of Composite Section

To correlate experimental findings with a numerical model, an LS Dyna MAT_054 model was constructed to simulate the blast loading on the composite hybrid panel. Utilizing the findings from MAT_054, observations could be drawn from the material test that otherwise would be difficult to quantify or label like damage mechanisms, deformation behaviors, and ply by ply delamination. To build the material properties for the composite material card, an extensive characterization process was conducted in Patton [9] and used to build the material properties in Table II.

TABLE II. MAT_054 COMPOSITE MATERIAL MODEL FOR TC940

RO(g/mm^3)	0.00189
EA (MPa)	3.53e4
EB/EC (MPa)	6530
GAB/GCA (MPa)	2320
GBC (MPa)	2122
XC (MPa)	378
XT (MPa)	960
YC (MPa)	68.2
YT (MPa)	15.4
SC (MPa)	27

The aluminum material properties were built from a Johnson cook model for 7075-T6 [10] and the adhesive was modeled using manufacturing data specs [11]. Tie break constants were formed using experimental test data to capture delamination seen in the experiments conducted by Patton [8].

Overall, the computational model agreed with delamination and deflection data in the experiments. Extensive delamination is seen through the thickness of the composite with a large near completely delaminated layer as seen in the post damage side view shown in Figure 5.

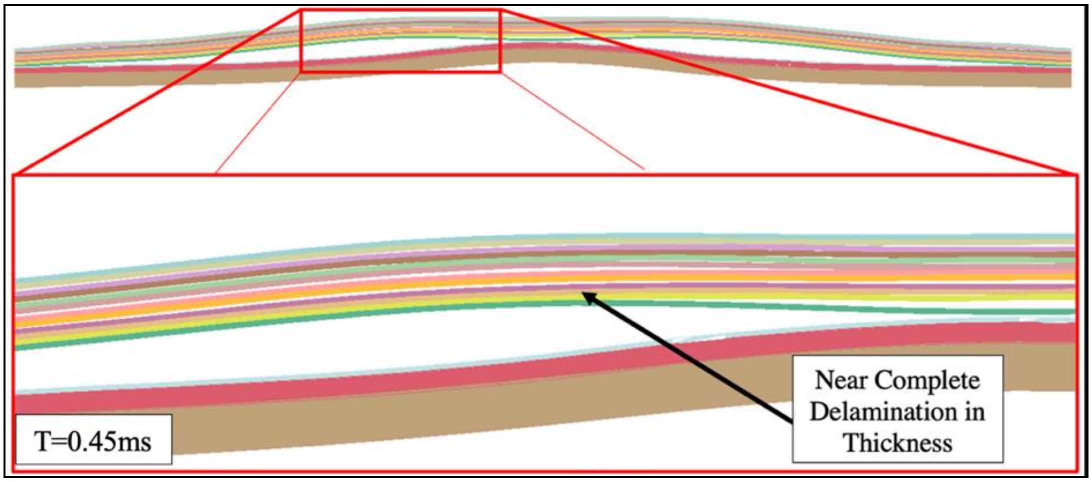

Figure 7. Simulated Delamination

The model exhibited a peak deflection on the back side of the composite of 9.93mm compared to the experimental average of 10.95mm, a 9.3% difference. The permanent deflection observed by the model was 5.00mm, compared to the experimental average of 4.71mm, a 5.8% deviation.

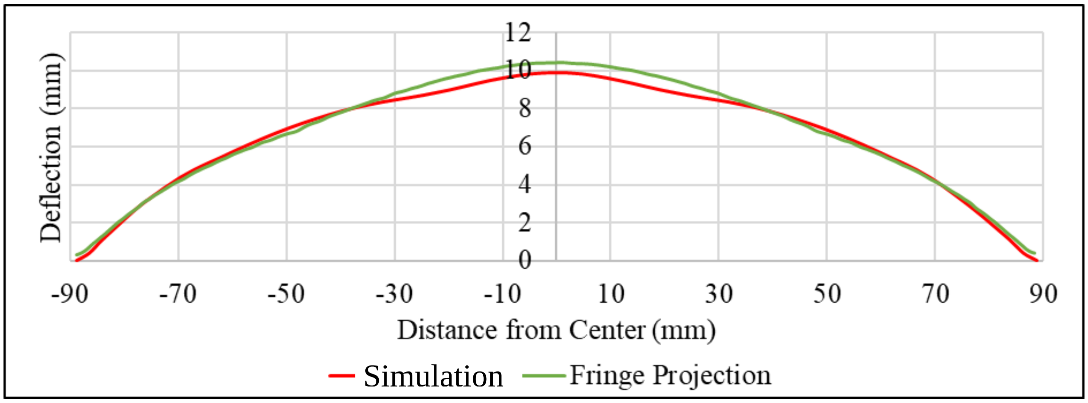

Figure 8. Deflection Contour at Peak Dynamic Deflection

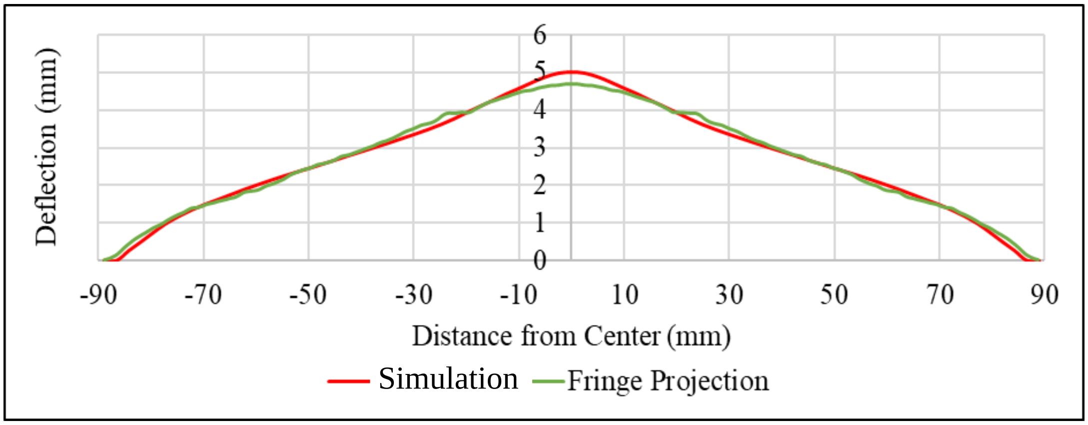

Figure 9. Deflection Contour Permanent Deflection

With consistencies among the model and experimental results deflection and generalized damage characteristics, it could be assumed that interpolations of observations could be drawn. When C-scanning the composite, delamination could easily be seen, but a ply-by-ply analysis of each composite layer could not be obtained due to the destructive nature of the composite material to attenuate any sonar waves used in the NDE technique. Due to the strong correlations between the model and the experiments, assumptions for ply-by-ply delamination were drawn. Figure 10 shows the delamination extent in each layer. The area percentage of delamination represents the entire area within the unclamped circular blast section.

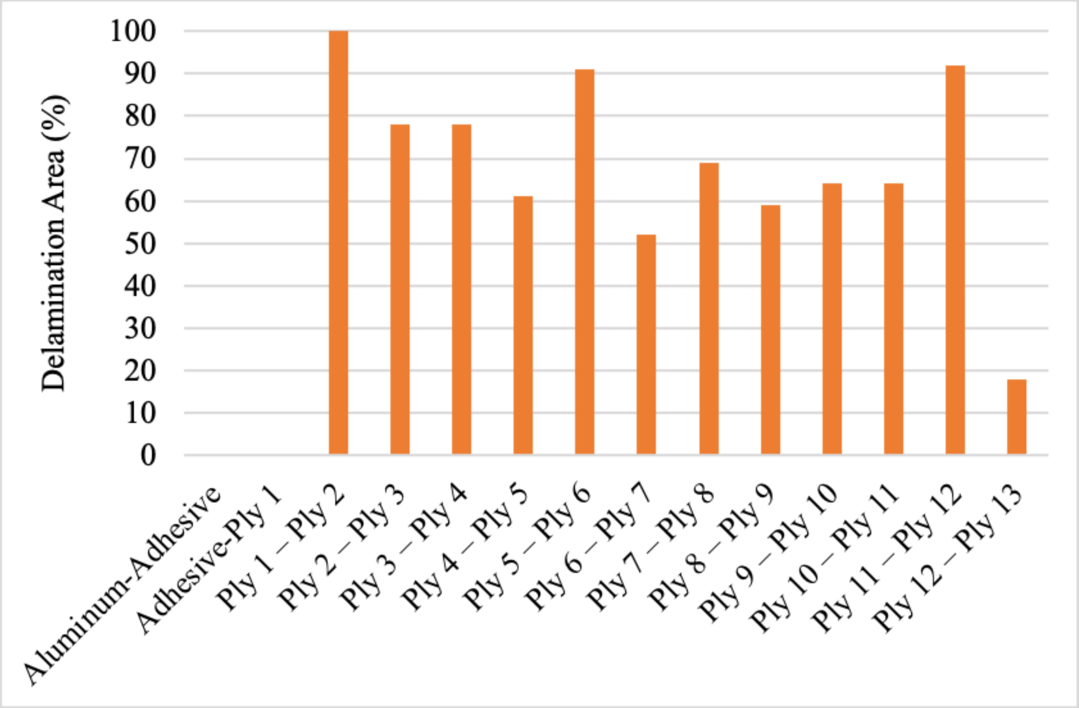

Figure 10 Delaminated Area in Composite

The time history of the experiment and the model follow very similar trends, the sample rate for the fringe projection was limited to the frame rate of the camera. For the experimental set up in the blast experiments, a data sample rate of 0.25ms was obtained for the fringe projection. In the case for the simulation, the sample rate was able to be set much lower and illustrate phenomena that may not have been able to be observed with fringe projection. The simulation was used to analyze these time periods. Additionally, around 4.5ms the material holder, fringe projection system and high-speed camera began to experience vibration due to the shock tube loading. This led to questions regarding fringe projection recordings after this time period so the history after 4.5ms was omitted from the analysis and characterization after this time period depended on the simulation.

Figure 11 depicts a time history and their correlations to deflection and delamination in both the experiments and simulation. First deflection in both the experiments and model was nearly instant after pressure loading impacted the test object. However, the moment of peak load, to peak deflection was roughly 0.5ms apart. This is not surprising as the rise time for the pressure was nearly instantaneous. More interestingly however, in the simulation the first sign of delamination was between the first and second composite ply and manifested nearly instantly. The highly localized pressure from the blast load created an area of high shear and normal stresses that exceeded the tie break constraints of the composite model that was based on experimentally obtained failure criteria. Delamination propagated throughout the composite thickness and propagated to the extents seen in Figure 10. There was no sign of further delamination after roughly 0.75ms. With the extensive delamination accumulated in the material earlier in the blast loading, it should be worth noting that the majority of the rebounded deflection characteristics seen after t=2.3ms could be attributed from layers separating creating “fluff” as the blast loading progresses.

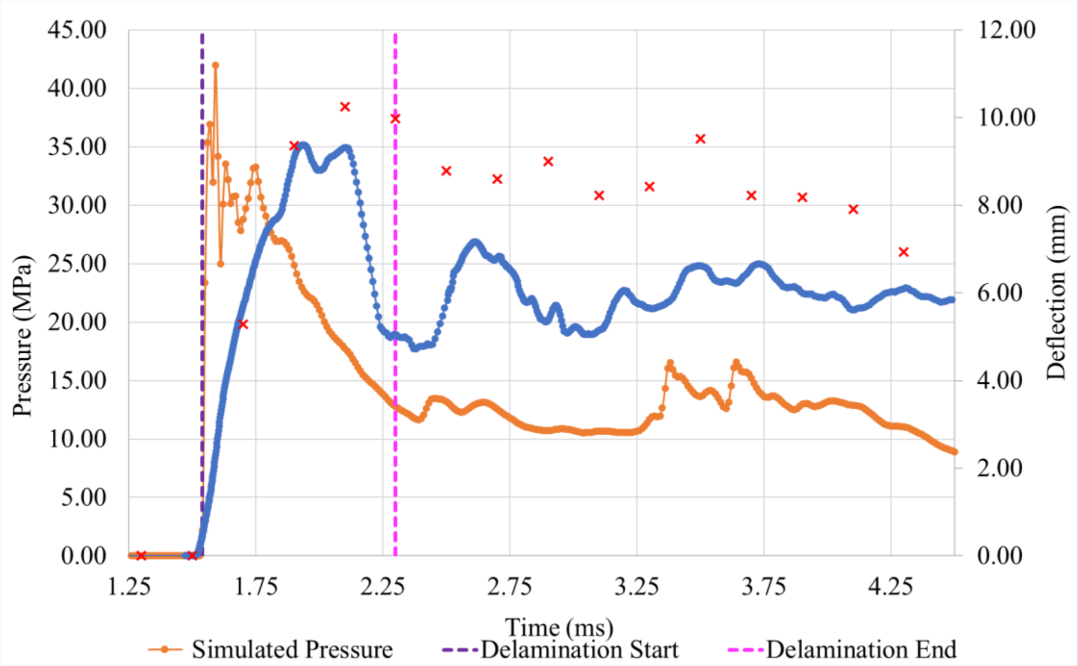

Figure 11. Time Histories of Simulation and Experiment

The respective absorbed energies of each constituent material are listed in figure 12. The aluminum absorbed the most amount of energy through plastic deformation as seen in figure 13. It is important to note however that the absorbed energies of the adhesive and composite are solely due to the strain energy within the material due to the deformation experienced in the plastically deformed aluminum. The composite not having a defined yield point and not plastically deforming, and the adhesive being modeled as an elastic material and not plastically deforming result in no plastic accumulations of energy. Furthermore, the energy absorbed in the material panel by delamination has not been tracked. Further work needs to be conducted to measure the crack energy release rate of the composite delamination to correlate delamination area with the energy needed to manifest the delamination.

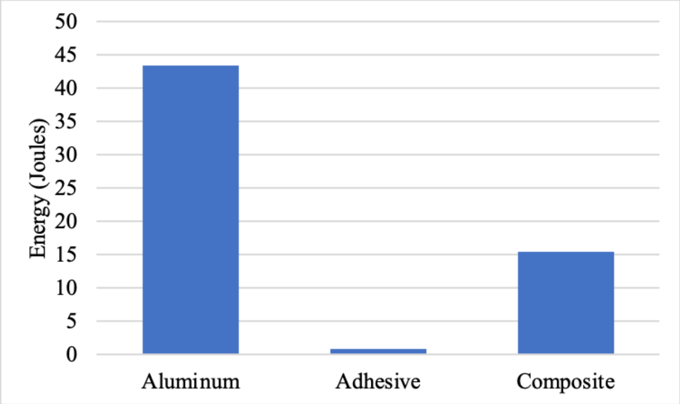

Figure 12. Absorbed Energy Plot of Each Material

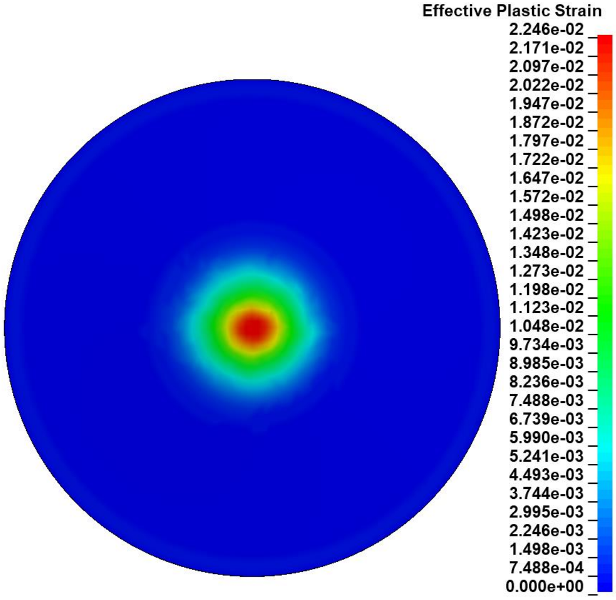

Figure 13. Plastic Strain Accumulated in Aluminum Layer

CONCLUSIONS

The model serves as a vital tool when assessing characteristics unable to be captured during the high speed testing. The experimental process was captured very well in the simulated model with strong correlations among the deflection characteristics (less than 10% deviation from the recorded values), and delamination areas. With this correlation, assumptions could be drawn to better describe the failure mechanisms within the hybrid material panel enabling future design work to further optimize the material system for desired characteristics. As experimentally observed and numerically validated, the dynamic deflection was observed to be a result of elastic deformation of the composite, elastic and plastic deformation of the aluminum and also by the delamination and the resulting separation between composite layers. The delamination was governed by high localization of shear and normal stress and the low strength of the mechanical characteristics of the ply interfaces within the composite. The metal facesheet is able to absorb a large amount of energy via plastic deformation and governs the residual deflection assuming the panel does not fail (i.e., metal and composite rupture). Further work would be needed to describe the role of delamination in regard to the energy absorbing capabilities of the panel.

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