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Quantitative validation of carbon-fiber laminate low velocity impact simulations

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ABSTRACT

Simulations of low velocity impact with a flat cylindrical indenter upon a carbon fiber fabric reinforced polymer laminate are rigorously validated. Comparison of the impact energy absorption between the model and experiment is used as the validation metric. Additionally, non-destructive evaluation, including ultrasonic scans and three-dimensional computed tomography, provide qualitative validation of the models. The simulations include delamination, matrix cracks and fiber breaks. An orthotropic damage and failure constitutive model, capable of predicting progressive damage and failure, is developed in conjunction and described. An ensemble of simulations incorporating model parameter uncertainties is used to predict a response distribution which is then compared to experimental output using appropriate statistical methods. Finally, the model form errors are exposed and corrected for use in an additional blind validation analysis. The result is a quantifiable confidence in material characterization and model physics when simulating low velocity impact in structures of interest.

1. Introduction

Fabric reinforced polymer laminates are used in a wide variety of structural applications. Numerical analysis of composite structures is critical for design and damage tolerance assessment. Laminates consisting of fabric reinforced lamina further complicate analysis methods because each ply cannot be idealized as a unidirectional layer, but is in reality a complex yarn structure with crimp and undulations. Therefore, a homogenized approach to lamina modeling is needed [1,2] for woven fabric architectures. Additionally, laminates exhibit directional dependent strength, stiffness and toughness. Abnormal loads, such as transverse impact, can inflict considerable damage in components that significantly reduce the design envelope. For this reason, low velocity impact (LVI) is a commonly studied condition when assessing damage tolerance of composite laminates with relevancies spanning from defense applications to recreational products [3–21]. The likelihood of occurrence coupled with the potential for subsurface, barely visible impact damage (BVID) that can significantly degrade a component make this ‘old’ problem still a rather pervasive issue to consider in engineering designs. There are a number of influential variables in the impact event that merit consideration when discussing the nature of the response and the anticipated damage mechanisms. Some of more relevant physical parameters that have been explored by researchers include projectile material, shape, mass and velocity [10–14], the target laminate boundary conditions [15,16], stack sequence and fabric architecture [17], as well as the thickness [18].

One distinct limitation in most numerical studies to date is the lack of vetting through sampling the entire parameter space [9,19–21]. With the advancement of high performance computing, large ensembles of simulations can be run with the goal of better quantifying the uncertainties inherent in model predictions. Furthermore, validation can only be achieved within some statistical space when the bounds of model uncertainty are fully explored. Validation, an essential element in the qualification of numerical models, is used to build quantifiable confidence in simulation results. The definition of validation is: “The process of determining the degree to which a computer model is an accurate representation of the real world from the perspective of the intended model applications” [22]. Each input of the model adds a degree of freedom making the isolation of the highly contributing inputs difficult. To remedy this, a sensitivity analysis is conducted prior to the implementation of a validation analysis.

While many post impact damage analysis techniques to evaluate damage tolerance rely on the compression after impact (CAI) experiment [9], this study will utilize a quasi-quantitative analysis of the impact delamination and damage [23] zone to assess the nature and extent of damage. Detailed insight of the

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impact-damaged zone is achieved through ultrasonic mapping [24]. Additionally, post-impact specimens are scanned and imaged using 3D computed tomography (CT) for even greater insight into the nature and extent of damage mechanisms.

This work documents a validation effort for the LVI modeling of carbon fiber reinforced composite. In the case of LVI with post-test non-destructive evaluation (NDE), quantitative as well as qualitative assessment is necessary. Where the residual strength is untested in both experiments and model, the qualitative metrics such as crack length and depth, delaminated area and quasi-quantitative metrics such as load time shape are an important way to assess relevant engineering statistics. However, a qualification metric must be quantifiable and contain sensitivities to many of the input parameters. Calibration, or the isolation and adjustment of model inputs in order to match the experimental response, is only completed to prove deficiencies in the model and direct future efforts. The primary metric for comparison is the change in kinetic energy calculated before and after the impact event using the initial and rebound velocities of the indenter fixture, respectively. The experiments are conducted on a 12 layer laminate constructed of an 8-harness satin weave carbon fiber reinforced polymer (CFRP). The material is minimally characterized, leaving many model inputs unknown. Additionally, the force time histories and pre- and post-impact ultrasonic scans are utilized as validation metrics. A project status report documents some preliminary aspects of this study in greater detail [25].

2. Experiments

2.1. Materials and apparatus

The CFRP material used for this investigation consists of an 8-harness satin weave prepreg with an epoxy based resin. Laminates are hand layed up from precut ply kits. The material is cured in the form of flat plates using a standard autoclave process under vacuum at a temperature of 177 C and a pressure of 310 kPa. Specimens are then cut from consolidated laminates using a wet diamond saw to the dimensions shown in Table 1. For the textile architecture used in this study, one ply is denoted as (0/90) representing the warp and fill directions in the 0° and 90° directions, respectively. Therefore, the laminates used in this investigation are composed of 12 plies of textile material with the warp direction oriented along the specimen's length.

A gravity accelerated drop weight impact tester is used to perform instrumented impact experiments on the flat specimens. Below the pin located flat specimen there is an unsupported central region measuring 76 mm by 127 mm, corresponding to the width and length directions of the specimen, respectively. The specimen is not securely clamped; rather a pair of toggle clamps is closed with negligible force to only constrain vertical displacement of the specimen edges. The incident kinetic energy of impact, which is controlled with the mass of the crosshead and its drop height, is set at 50 J and 25 J for this investigation. The impact tip is a 19 mm diameter cylinder with a flat face made of stainless steel. The total mass of the crosshead assembly is 5.42 kg. A light sensor is used to determine the velocity just prior to and after impact. The force during impact is measured with a strain gage based load cell integrated in the tup. The force response is filtered at 12 kHz and data is collected at a frequency of approximately 820 kHz for the entire duration of the impact event. After the rebound velocity is measured, pneumatic rebound brakes are activated to prevent a second impact event onto the specimen.

Table 1
Typical dimensions for impact specimens.

Width (mm)	Length (mm)	Thickness (mm)	Stack sequence
102	155	4.49	$[(0/90)_6]_s$

In order to visualize, measure, and delineate between damage form and location, pre and post-impact specimens are ultrasonically scanned and then imaged with 3-dimensional computed tomography (CT). These methods provide metrics for the qualitative validation of finite element simulations.

CT is commonly used is non-destructive evaluation in order to visualize matrix cracks, delaminations and fiber breaks in carbon reinforced polymer composites. In fact, certain CT technologies can effectively delineate sub-micron damage in composites [26–28]. These studies have shown CT to provide insight into the spatial distribution of damage and the specific form of damage. CT scanning for this study is performed using a 225 keV energy level and a target power of 54 W.

While CT provides high resolution insight into the form and distribution of damage, it requires substantial time and effort in order to delineate damage for model validation purposes. A simpler approach that has been proved useful in visualizing damage in CFRP laminates is Ultrasonic scanning. For example, Aymerich and Meili compare ultrasonic to CT visualizations and show ultrasonic scans can provide comparable resolution to CT [28]. Ultrasonic scans measure signal attenuation in a damaged specimen. The result is a 2D representation of the damage profile. The amplitude of the back face reflection is plotted in these images and a corresponding scale is shown to quantify the degree of attenuation. A color coding with a large value of AMP (%) can be attributed to undamaged and well coupled material, allowing the input sound wave to pass through the specimen and return back to the transducer with virtually no losses. Conversely, low values of returned signal amplitude are attributed to attenuation of the signal to regions where damage is present, i.e. delamination, cracking, etc. Ultrasonic scanning is performed using a 5 MHz transducer with a focal length of 2 inches with specimens submerged in water to act as a coupling agent. All specimens are adequately baked out after water exposure before mechanical testing.

2.2. Experimental results

Specimens are impacted at an incident kinetic energy of approximately 50 J. A second set of impact experiments with 25 J of incident kinetic energy are conducted to validate the model after necessary adjustments. Both measured force time history data sets are shown in Fig. 1. The impact event consisted of a combination of elastic deformation and rebound as well as energy absorbing damage, with the entire event occurring in approximately 5 ms. A summary of the results is shown in Table 2.

The specimens underwent pre and post-impact scans using ultrasonics and 3D computed tomography. Typical CT results are shown in Fig. 2. The top-down view slices through the specimen reveal the extent of shear cracking and gross delamination. This top-down view is not able to detect delaminations that are in contact as well as the ultrasonic scans. However, slices along the length of the specimen reveal at which interfaces delamination has occurred and the extent at which it has grown.

3. Numerical model

3.1. Finite element code and mesh

The finite element mesh consists of the lower impactor geometry, a lumped mass, a fixed holder and base, and the specimen. The experiments consistently showed crack preference towards one side of the test fixture; indicating skew impact of the tup on the