EFFICIENT METHODS FOR ADDRESSING COMPOSITE DAMAGE RESISTANCE AND TOLERANCE DURING DESIGN

MOTIVATION

Fiber-reinforced composites are prevalent in many industries where weight, strength, and stiffness are key drivers in material selection. Introduced roughly five decades ago, carbon fiber reinforced polymers now dominate as the material of choice in structures for new aircraft projects. Despite their popularity, major challenges remain with design and certification of carbon fiber structures. Much work remains to streamline design procedures given the plethora of variables and the resulting analytical complexity.

A major concern that has been traditionally difficult to evaluate early in a design program is a composite structure's resistance and tolerance to impact damage. Laminated composites are weak under transverse loading, making them particularly susceptible to impact damage. There are different levels of damage classified based on severity and detectability. Damage detectability can be broken down into discrete source, visible, and barely visible impact damage (BVID) [1]. Depending on location on the aircraft, this impact damage could be caused by a bird strike, runway debris, ground equipment collision, or tool drop. Low energy impacts such as a tool drop cause BVID, which consists of internal damage that is difficult or impossible to detect with visual inspections. A structure must be shown to perform with BVID up to design loads, and for the entire service life of the aircraft in fatigue. Because of a lack of suitable computational tools, certification for these aspects has historically done by extensive physical testing of the final point design. However, to promote efficiency and reduce overall costs, it is desirable to replace as much of this physical testing as possible with simulation and predictive tools.

While high-fidelity finite element models have been demonstrated to show reasonable correlation to experimental tests [2], their high computational expense and sensitivity to input parameters limits their utility in the design process. To mitigate the high-computational expense, the complexity represented in the model needs to be reduced. One way to accomplish this is by moving from solid to shell finite element formulations, using advanced techniques to maintain accuracy, such as in [3]. To mitigate the sensitivity to input parameters, a move from purely deterministic methods to methods which consider how the uncertainty of model inputs propagates to results is needed. By considering the probabilistic nature of these inputs, our confidence in the results can be greatly increased.

Reducing the computational cost of a structural damage simulation will greatly increase the feasibility of both uncertainty quantification and optimization – iterative processes critical to modern design that require many model evaluations.

METHODOLOGY

The methods proposed for this project primarily span three areas: computational damage prediction, uncertainty quantification, and uncertainty-based design optimization. The next subsections give background for each of these areas.

Computational Damage Prediction

There has been significant progress in models that serve as predictive tools for evaluation of damage resistance and damage tolerance in composite laminates. High-fidelity finite element models have been demonstrated with close correlation to experimental data in both damage prediction (ie. crack locations/paths/sizes, delamination locations/areas/shapes), and with errors in compressive residual strength within 10% of experimental results [2]. While promising, these models have not been shown to be conservative, frequently overpredicting strength, and no robust method of quantifying uncertainty has been developed. In addition, high computational cost mitigates some of the benefits of the digital testing, for instance, taking between 19-21 hours on a 32-core computing cluster for a simple low-velocity impact/compression strength after impact simulation [2].

The key to improving the computational efficiency of these finite element models is by reducing the complexity of the model, ideally by developing a model that yields accurate results with a coarser discretization. The biggest gain to be had is in moving from solid elements (many elements through the thickness for each ply) to shell elements (as little as one element through the thickness). When using shell modeling techniques to simulate composite damage, the decision must be made in how to represent out-of-plane damage modes (primarily delamination). It can either be represented discretely, with more elements [4], or stiffness must be degraded in a way that is equivalent to the weakening of the structure due to subregion buckling [5]. Since the second method is not physically meaningful, it may not be accurate for general loading cases, and damage propagation cannot be accurately predicted. Therefore, it is desirable to represent out-of-plane damage discreetly, but ideally updating the discretization as damage is detected. Models using this adaptive fidelity technique have shown promising results [4], [6], [7].

Uncertainty Quantification

One of the shortfalls in current composite damage modeling is the lack of consideration of the probabilistic nature of the model inputs such as material properties, geometric dimensions, and fiber orientations. To get a reliable prediction of strength from these models, it is imperative to conduct some type of uncertainty quantification or sensitivity analysis.

The most popular uncertainty quantification methods are the Monte Carlo and quasi-Monte Carlo methods. In the Monte Carlo method, a set of input parameters is randomly drawn from the probability density function of the parameters, then the model evaluated for the sample set. Thousands of samples are needed for convergence, so the method is impractical for computationally expensive models. Quasi-Monte Carlo methods reduce the number of samples needed but are still typically impractical for composite damage models. A more recent family of techniques are polynomial chaos expansions, which calculate the same statistical metrics as Monte Carlo methods, but typically with much fewer model evaluations. When the number of uncertain parameters is fairly low, polynomial chaos expansion techniques can reduce the number of model evaluations by one to three orders of magnitude [8].

Uncertainty-Based Multidisciplinary Design Optimization (UMDO)

The desired result of any design activity is a design that meets all requirements and is hopefully optimized for one or more objectives. With typical deterministic optimization, often the identified optimum design will need to be modified to account for uncertainties and ensure reliability and robustness. UMDO, however, is an advanced methodology that has been widely recognized to address competing objectives in aerospace design such as performance, cost, reliability, and robustness. Using this class of methodologies, it is possible to incorporate constraints on the reliability (minimal possibility of catastrophe) and/or robustness (minimal performance loss with small perturbation of design variables). Challenges of these methods include representing and modeling the uncertainty of inputs (coupled/uncoupled) and propagating the uncertainty through the model. The major drawback of these methods is the high computational cost from the “double-loop” nature of the process – an uncertainty quantification loop inside of an optimization loop. Therefore, it is extremely important that the objective being optimized, and the constraints are as computationally efficient as possible. For certain problems, methods have been demonstrated that approximate aspects of the process to reduce the number of model evaluations, such as in [9].

RESEARCH OBJECTIVES

The goals of this research are to (1) develop and validate a computationally efficient shell modeling technique for predicting damage resistance and tolerance of a composite structure, (2) explore the accuracy of damage predictions using uncertainty quantification techniques, and (3) demonstrate the usage of damage simulation as part of an uncertainty-based optimization procedure.

PROPOSED WORK

Objective 1

The first goal of this project is the development and validation of a computationally efficient finite element routine for predicting low velocity impact (LVI) damage and residual strength. The performance goal is an order of magnitude reduction in computational time over existing high-fidelity techniques with minimal sacrifice in accuracy of results. This seems to be within reach given our previous progress with adaptive-fidelity shell modeling [7]. Reasonable results have been obtained for delamination prediction for solid laminates subjected to low-velocity impact [7], [10]. Simulations have been conducted matching various experimental data obtained using the ASTM procedure for testing damage resistance [11]. Figure 1 shows a delamination prediction and structural response.

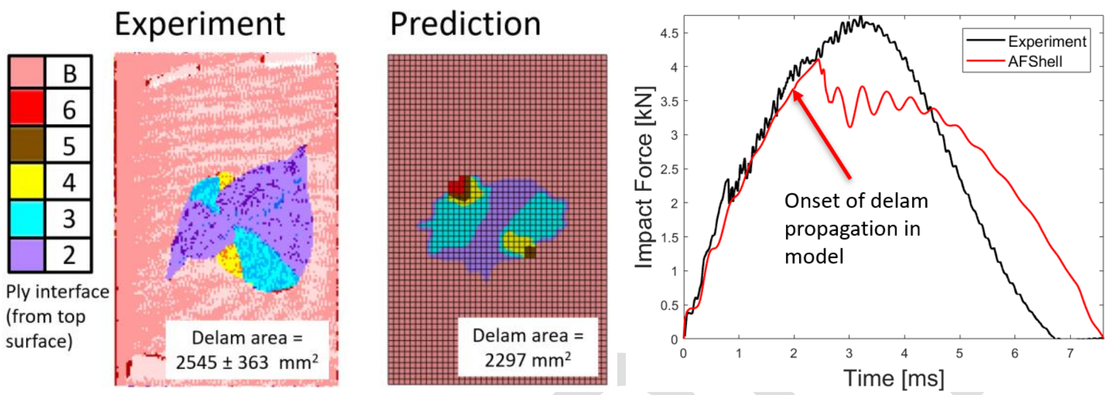

Figure 1. Delamination pattern from experiment and predicted by model (left), and structural response (right), from [7].

The projected delamination area is predicted well, and the damage geometry is similar to the experimental damage pattern. This model was computed on 1 processor in about 1.5 hours, making it many times more efficient than high-fidelity solid FEA techniques.

To better control all aspects of the model towards meeting Objective 1, I am developing a new model using FEniCS, an open-source computing platform that enables scientific models to be quickly translated into finite element code [12]. One benefit of using FEniCS is more freedom in all aspects of the problem formulation. Specifically, the ability to use an isogeometric analysis (IGA) basis in the finite element space, of which significant functionality has been implemented [13]. If the IGA functionality proves undesirable then the traditional finite element methods can still be used. If FEniCS itself proves undesirable, a model will be developed in a commercial finite element code such as Abaqus [14].

Objective 2

The second objective is to explore the accuracy of damage and residual strength predictions using uncertainty quantification techniques. This is needed to demonstrate the robustness of the model predictions. The model developed for Objective 1 will be evaluated with a framework such as [8] to determine sensitivity of input parameters and uncertainty in the predicted results.

To date, an uncertainty quantification procedure has been demonstrated on an example impact/residual strength test with a simplified finite element model and a subset of the input variables. The model and setup is described in [15]. Figure 2 shows the distribution of uncertain input parameters and a histogram of the residual strength predictions (population of 142 simulations). For this example, with the uncertainty of the in-plane strength parameters included, the standard deviation of the residual strength is 2.0 MPa.

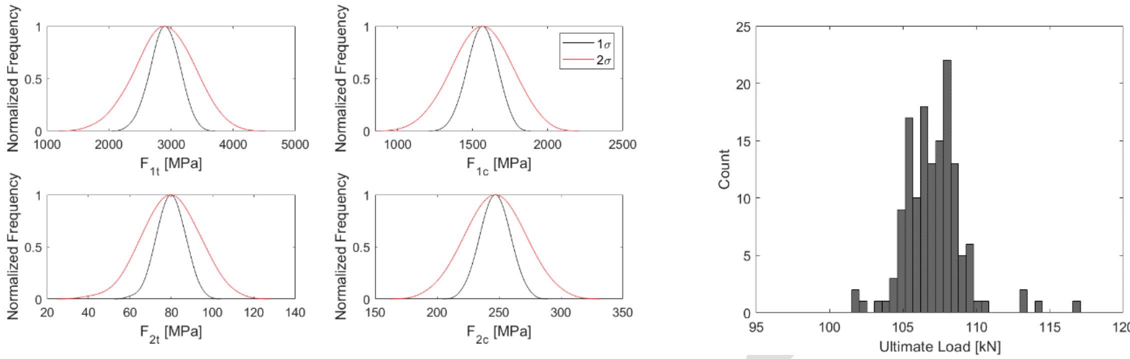

Figure 2. Input parameter distributions (left) and histogram of predicted strengths (right).

OBJECTIVE 3

The third outcome of this research is a UMDO framework for structural optimization considering damage resistance and tolerance. For structural optimization of a composite airframe, this will allow the structure's damage behavior to be accounted for when evaluating the contribution to system reliability. As it is typically the limiting factor in the design, this behavior should be modeled explicitly to increase precision over a standard strength/safety factor constraint. I propose to use the model developed in Objective 1 as part of a structural optimization procedure for a medium-complexity part, such as a stiffened panel, representative of a section of fuselage or wing. The procedure implemented will be similar to the UMDO procedure for a composite beam given in [16]. The predicted optimum will be compared with an optimum design predicted by a traditional strength-based approach.

TIMELINE

Activity	2019				2020							
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Objective 1												
Choose technology stack/modeling methods	X	X	X									
Collect data for model validation (from literature)			X	X	X							
Model develoment		X	X	X	X	X	X					
Model validation					X	X	X					
Objective 2												
Framework development/evaluation	X					X	X	X				
Evaluation with model from Objective 1								X	X			
Objective 3												
Framework development/evaluation							X	X	X			
Design exercise with realistic composite part									X	X		
Manuscript preparation and dissemenation						X	X	X	X	X	X	X

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