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# Composite laminate failure parameter optimization through four-point flexure experimentation and analysis

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ABSTRACT

Fiber-reinforced composite materials offer light-weight solutions to many structural challenges. In the development of high-performance composite structures, a thorough understanding is required of the composite materials themselves as well as methods for the analysis and failure prediction of the relevant composite structures. However, the mechanical properties required for the complete constitutive definition of a composite material can be difficult to determine through experimentation. Therefore, efficient methods are necessary that can be used to determine which properties are relevant to the analysis of a specific structure and to establish a structure's response to a material parameter that can only be defined through estimation. The objectives of this study deal with demonstrating the potential value of sensitivity and uncertainty quantification techniques during the failure analysis of loaded composite structures; and the proposed methods are applied to the simulation of the four-point flexural characterization of a carbon fiber composite material. Utilizing a recently implemented, phenomenological orthotropic material model that is capable of predicting progressive composite damage and failure, a sensitivity analysis is completed to establish which material parameters are truly relevant to a simulation's outcome. Then, a parameter study is completed to determine the effect of the relevant material properties' expected variations on the simulated four-point flexural behavior as well as to determine the value of an unknown material property. This process demonstrates the ability to formulate accurate predictions in the absence of a rigorous material characterization effort. The presented results indicate that a sensitivity analysis and parameter study can be used to streamline the material definition process as the described flexural characterization was used for model validation.



## 1. Introduction

Computer simulations can be used to model the behavior of a loaded composite structure assuming the structure's materials are well defined. Specifically, sophisticated material models are being developed that will accurately simulate the complex progressive damage and failure behaviors commonly observed in fiber-reinforced composite materials. However, while these material models offer the capability for realistic simulations, their use requires the definition of numerous material parameters (i.e., elastic moduli and failure strengths in the different material directions). Ideally, these input parameters would be determined via a thorough experimental characterization program for the composite materials of interest. Unfortunately, given realistic time and cost constraints, the experimental determination of such a large number of material model parameters is not generally feasible. However, through the application of methods investigating the individual input parameter sensitivities and uncertainties, such thorough characterization techniques may not be necessary. A sensitivity analysis can be used to quantify the individual effect that each input parameter has on a simulation's output, effectively identifying those material parameters critical to the modeled response. Also, uncertainty quantification methods can be used to enumerate the influence of unknown input parameters on a simulated output response, allowing for reliable predictions in the absence of an exact material characterization.

Many examples exist in literature demonstrating the value of parametric sensitivity studies in the process of modeling various physical phenomena. The applications for this type of analysis have proven to be fairly far reaching with sampled references demonstrating relationships to many different scientific fields. For example, within the field of material science, Gunawan, et al.,

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utilized a sensitivity analysis to measure the activation energies most critical to computer simulations of boron diffusion in silicon [1]. In separate studies completed by Binici et al., Zheng, et al., and Bryson et al., parametric sensitivity analyses were shown as applicable to civil engineering applications. Specifically, Binici, et al., utilized sensitivity studies to determine which uncertain material parameters have the most profound effect on the behavior of reinforced concrete columns, Zheng, et al., studied the influence of model parameters in simulations of the long-term deflection of continuous, rigid frame bridges, and Bryson et al., applied a sensitivity study to computer models of soils and clays loaded in compression [2–4]. Similar studies have also been utilized for vehicular and automotive applications. Hua et al., measured the effect of geometrical parameter variations of a dynamically loaded vehicle frame and Huang et al., examined the effect of material input parameters in models simulating the presence of “squeal” in automotive brakes [5,6]. Additional relevant studies have also been found in composites research. Namely, Radebe, et al., and Daneshpayeh et al., demonstrated the use of sensitivity analyses in their studies of the effect of material property uncertainty on the performance of nanostructures and nano-composites [7,8], Vu-Bac et al., utilized a sensitivity analysis to assess the effect of uncertain material parameters on mechanical properties determined through multi-scale modeling [9], and Islam et al., utilized a sensitivity study in the process of optimizing manufacturing parameters for particleboards [10]. In another example from literature, Kenis, et al., demonstrated the usefulness of a sensitivity study to geological applications as simulations modeling the development of specific rock formations were completed within a parameter study [11]. Finally, Zhang et al., demonstrated the negative effect that material porosity and increasing void content can have on a composite's structural performance due to the variability that such material inconsistencies can create in the composite's mechanical properties [12]. This variability can be difficult to account for in finite element simulations when continuum methods are applied. Therefore, the application of uncertainty quantification techniques and parameter studies can be utilized to account for the inconstancies voids can create in a composite material.

Examples from literature have demonstrated the usefulness of parameter studies within diverse scientific fields. Therefore, the objectives of this study deal with the application of sensitivity and uncertainty quantification techniques within the structural analysis of composite parts. Specifically, a sensitivity analysis will be completed for simulations of a carbon fiber composite material loaded in four-point flexure. The corresponding simulations will utilize a phenomenological composite material model that was recently developed and implemented into the production version of the Sandia National Laboratories' solid mechanics finite element analysis code. This model is capable of capturing such important composite material behaviors as progressive damage and post-failure softening, but requires the input of 77 separate material parameters. Therefore, the sensitivity analysis will be used to determine which of the material inputs are most critical to predictions of failure and only those critical parameters will be rigorously defined using experimental methods. Then, uncertainty quantification will be used to propagate any input parameter unknowns through to the predicted output response effectively predicting the material's flexural behavior in the absence of a complete experimental characterization of the model's 77 separate input parameters. Furthermore, the modeling methods verified with the uncertainty quantification simulations will be used to develop a surrogate, or approximation, model that can be used in conjunction with the experimental data to determine unknown material properties of interest.

## 2. Flexure experiments

To demonstrate the proposed techniques and to provide validation data for the simulations, experiments were completed to characterize a carbon fiber/epoxy composite material in four point flexure. The flexural loading scheme was deemed desirable as the applied bending conditions provide for a complex and interesting response, which offer a good measure of the proposed technique's value through the planned computer simulations. Furthermore, experiments of this type are easily prepared for and conducted.

### 2.1. Composite materials and specimen preparation

The flexural test specimens were composed of a carbon fiber reinforced polymer (CFRP) material consisting of an 8-harness textile, pre-impregnated carbon fabric with an epoxy based resin. Laminates for testing were manufactured with a hand lay-up process with precut ply kits, which were prepared with a CNC cutter in order to control the geometry and fiber orientation. The flat laminates were cured with a standard autoclave process under vacuum with an applied temperature and pressure of 350 °F and 45 psig, respectively, as suggested by the manufacturer. Several specimens were cut from the consolidated laminates with a wet saw outfitted with a diamond blade. A total of four specimens were considered as part of this study and their average dimensions and stacking sequence are given in Table 1.

### 2.2. Experimental procedure

The described specimens were tested to failure in four-point flexure with an applied load span of 50 mm and support span of 100 mm (quarter-point loading). The tests were completed under displacement control with a crosshead descent rate of 5 mm/min and, throughout each test, displacement and load data were recorded directly from the testing machine crosshead and load cell with an acquisition rate of 10 Hz.

Upon testing completion, the measured specimen dimensions and recorded load-displacement data were used to determine the flexural stress and flexural strain as well as the flexural modulus. For this quarter point loading configuration, the maximum displacement and the crosshead displacement differences are accounted for, allowing the flexural strain, $\varepsilon$, and flexural modulus, $E_f$, to be expressed as:

$$\varepsilon = \frac{6t}{L^2} V_c \tag{1}$$

$$E_f = \frac{L^3}{8wt^3}\left(\frac{P}{V_c}\right) \tag{2}$$

where the thickness, $t$, width, $w$, and length, $L$, are all specified from the specimen geometry, and the crosshead displacement, $V_c$, and applied load, $P$, are directly measured during the experiment. The flexural stress, $\sigma_f$, can be computed from equations (1) and (2), and is independent of the crosshead displacement. Also, the stiffness of the experimental load frame and fixturing was taken into account with respect to the flexural rigidity of the specimen, allowing the crosshead displacement to be used in all calculations rather than a

**Table 1**
Typical dimensions for flexural specimens.

| Width (mm) | Length (mm) | Thickness (mm) | Stacking sequence |
|---|---|---|---|
| 24.57 | 135 | 2.93 | $[(0/90)_4]_5$ |