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Minimum-weight design for three dimensional woven composite stiffened panels using neural networks and genetic algorithms

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The paper describes a modeling strategy for multi-scale analysis and optimization of stiffened panels, made of three-dimensional woven composites. Artificial neural network techniques are utilized to generate an approximate response for the optimum structural design in order to increase efficiency and applicability. The artificial neural networks are integrated with genetic algorithms to optimize mixed discrete–continuous design variables for the three dimensional woven composite structures. The proposed procedure is then applied to the multi-objective optimal design of a stiffened panel subject to buckling and post-buckling requirements.

1. Introduction

Stiffened panels are extensively used in the aeronautical field, and are often subjected to buckling phenomena under a certain level of compression load. The buckling load does not represent the maximum load that the structure can carry, and indeed, on the contrary, failure may not occur until the applied load is several times the buckling load [1,2]. Consequently, the post-buckling strength capacity has significant potential for further weight saving.

For this reason a large number of researchers [3–8] focused their attention on optimization procedures concerning buckling load maximization or weight minimization under buckling and post-buckling constraints.

Bisagni and Lanzi developed a global approximation strategy for a post-buckling optimization procedure for laminated composite stiffened panel combining neural network and genetic algorithms (GA) to reduce the cost and computation time [3]. Rikards et al. [9] developed an optimization approach based on building surrogate models and genetic algorithms. Kang and Kim [6] implemented a parallel computing scheme using GA, considering buckling and post-buckling behaviors, to obtain minimum-weight design. Bisagni and Vescovini [10] proposed an optimization strategy of a fuselage composite stiffened panel relied on a semi-analytical approach for the analysis and on GA for the optimization. Todoroki and Ishikawa [11] described a new strategy for Design Of Experiment (DOE) to obtain a response surface of buckling load of laminated composites, and then implemented the stacking sequence optimizations with GA using the response surface approximation.

Three common main characteristics can be identified in literature for the optimization of composite stiffened panels. Most of the researchers make use of meta or surrogate models to approximate the response of the stiffened panels in order to reduce the computational resources needed for the optimization. The solution of the optimization problem of composite stiffened panels is generally obtained with genetic algorithms. Most of the examples reported in literatures investigated laminated composite stiffened panels, while few investigations consider the weaving optimization of 3D woven composite stiffened panels.

The internal architecture of 3D woven composites is more complicated compared to laminated composites, but also more benefits could be obtained. Besides, the weaving parameters and routes of 3D woven composites can significantly influence the mechanical performances [3,9–13]. A large number of researches were performed to predict the mechanical properties of 3D woven composite via experimental [12,13], numerical [12,14,15] and analytical approaches [13,15]. The limited analytical solutions for composite structures, especially for complex topological and geometrical woven composites, prevent their use in the design optimization. Numerical approaches are a good choice for optimizing existing fabrics and for creating new textile model, but the optimization based on numerical approaches can result computationally expensive for analyzing complex structures. Besides, the time dedicated to the geometry preparation and mesh generation,

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to the definition of the weaving architecture and the application of the appropriate boundary conditions, must be added too.

The surrogate and approximated modeling techniques are a promising solution because, when the approximated models are properly built, these models mimic the behavior of the numerical analysis accurately and, at the same time, are computationally cheaper. For this reason the optimization strategy is generally based on combining a global approximated technique with genetic algorithms [3,6,9,11,16,17].

Typically, the optimization problems of composite stiffened panels are characterized by the combination of continuous and discrete design variable, e.g. the number and kind of stringers, the selection of material, the number of strands in weaving architectures and the number of plays. The genetic algorithms are a reliable tool to address discrete variables optimization problem [18]. They use implicit enumeration procedures, based on Darwin's theory of survival of the fittest [19]. The main advantage of this approach is that no derivative information is needed. Three operators including reproduction, crossover and mutation are usually adopted and these three steps are carried out for successive generations of the population until no further improvement in the fitness is attainable.

In the present paper, GA are combined with neural networks to solve the continuous and discrete optimization of the 3D weaving composite stiffened panels. At first, the paper focuses on the development of multi-scale analysis models for 3D weaving composite stiffened panels, starting from the fiber, through the models of yarn and textile, till the complete model of the structure. This is done by a dedicated Python script able to manage both discrete and continuous variables and to create all the requested models for the successive analysis and optimization phases. The DOE technique, coupled with the finite element code ABAQUS, is then used to reduce the number of sample points to create an accurate approximate model based on neural networks capable of reproducing the structural responses. Finally, the neural network-based approximate model is integrated with the GA module to setup and solve the optimization problem of stiffened panels, aiming at the minimum weight structure in presence of buckling and post-buckling requirements. Details of the implemented procedures together with an application example are reported in the following sections.

2. Multi-scale modeling of 3D woven composites

Textile composites are based on the combination of a resin system with a reinforcement, that is usually composed of thousands of fibers bundled into yarns which can be woven, braided or knitted into two dimensions (2D) or three dimension (3D) textiles. In particular, three-dimensional composites utilize fiber preforms constructed from yarns or tows arranged into complex three-dimensional structures. While they date back to 1960s, the increased global interest in recent years in 3D fabrics for resin, metal and ceramic matrix composites has led to the current expansion of their application from secondary to primary load-bearing applications in various engineering structures.

The modeling technique here adopted is based on a multi-scale simulation process including micro, meso and macro scale, as shown in Fig. 1. In order to predict macro scale behavior of 3D woven composite, it is necessary to know the weaving fabric characteristic and the yarn's profile.

The micro-scale modeling involves the study of the orientation and mechanical properties of the constituent yarn. The meso-scale modeling is based on the concept of homogenization and evaluates the mechanical properties of a fabric Representative Volume Element (RVE), which is typically used to determine the effective stiffness of textile fabrics. The macro-scale modeling deals with predicting the mechanical behaviors of completed textile structure under complex deformation state, assuming the fabric to be a continuous medium. The homogenization techniques provide the response of a RVE (global level) given the properties or response of the structure constituents (lower level). Since textile materials are heterogeneous and periodic, a RVE is adopted to account for the microstructure, which results in significantly reducing the size of the problem of numerical modeling. The reason for emphasizing the concept of the RVE is that it appears to provide a valuable discriminator between continuum (macroscopic) theories and microscopic theories: for scales larger than the RVE one can use continuum mechanics and reproduce properties of the material as a whole [20]. The modeling hierarchical strategy adopted for textile composite in this work integrates the three different modeling stages (see Fig. 1). Homogenizing techniques are then applied to link the different scale analyses.

A square-arrangement RVE is used to represent the unidirectional material behavior of the Twintex 1398, the material adopted in this study, and loop yarn, as shown in Fig. 1. It is assumed that the fibers are arranged in an even distribution with the measured volume fraction and same-average-filament diameter. Based on the hypothesis of square packing array, fiber and matrix are assumed to be in a perfect bonding condition. Fiber within the yarn cross-section can be packed into rectangular packing arrays; the circular shape is used to describe the fiber cross-section in yarn.

The effective elastic properties of RVE with right periodic boundary condition can be calculated through ABAQUS simulating six independent load cases. The basic principle and calculating process of RVEs effective elastic properties are obtained applying generalized concentrated forces with dimension of force per length, to the different degrees of freedom of RVE [21]. It corresponds to apply macroscopic stresses to the unit cell and the macroscopic stresses are related to these concentrated forces from a simple energy equivalence consideration. For example, if a force F_x is applied to the degree of freedom ε_x^0 of a unit cell while all the other extra degrees of freedom are free from constraints, the work done by the force is:

$$W = \frac{1}{2} F_x \varepsilon_x^0 \tag{1}$$

The strain energy can be written as

$$E = \frac{1}{2} \int_0^V \sigma_x^0 \varepsilon_x^0 dV = \frac{1}{2} \sigma_x^0 \varepsilon_x^0 \tag{2}$$

where V is the volume of the unite cell. Equating W to E yields a relationship between the concentrated force and the macroscopic stress applied:

$$\sigma_x^0 = F_x/V, \quad \sigma_y^0 = F_y/V, \quad \sigma_z^0 = F_z/V \tag{3}$$

$$\tau_{yz}^0 = F_{yz}/V, \quad \tau_{zx}^0 = F_{zx}/V, \quad \tau_{xy}^0 = F_{xy}/V \tag{4}$$

Once obtained the macroscopic stresses, the elastic properties are then easily recovered.

The multi-scale modeling procedure, sketched in Fig. 2, has been developed combining already available codes with ad-hoc developed pieces of software. The open source software TexGen, developed by University of Nottingham for modeling the geometry of textile structures [22], was used to pre-process input files for ABAQUS/CAE. Combining ABAQUS with TexGen was proven as a useful strategy to deal with textile composite modeling and structural analysis problems, since they both have an application programming interface (API) accessible through the Python programming language, allowing for an easy methodology to link the two codes. Hence, a Python script can be executed within ABAQUS/CAE interface, which is able to call TexGen library