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Optimal design and testing of laminated light-weight composite structures with local reinforcements considering strength constraints part I: Design

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ABSTRACT

The paper reports on a strength improvement method based on the recently published Ghost-Layer concept by Schläpfer and Kress [1] for identifying local reinforcements to a composite structure which is simulated with the finite element method. A pseudo-strength function (PSF) unifies the failure indices of the laminate layers of each finite element and allows for semi-analytical calculation of sensitivities with respect to layer thickness changes. Local reinforcements are generated by assigning a thickness value to parts of the virtual Ghost-Layers based on the sensitivity information. The method, manufacturing of test specimens, and validation are presented. High strength increase can be achieved with small amounts of additional mass. Details of the measurement techniques are presented in part II of this paper.

1. Introduction

Laminated composite materials are today well-established for the design of light-weight components. Their mass-specific mechanical properties exceed the properties of common metallic materials. Besides the aerospace industry, they are increasingly used in the automotive and sports sector. The layer-wise building technique enables to easily tailor the mechanical properties at a specific location to the mechanical requirements which enhances the potential for finding weight-minimal solutions. This becomes evident for regions near cut-outs or load introduction points. There, stress concentrations occur which reduce the global strength and stiffness of the structure. Layers can be added which only cover the highly loaded regions. Thus, mass is saved in regions where the individual loads do not call for additional reinforcements. Due to the anisotropic material behavior of the individual layers, the design of laminated composites is complex. The large number of design parameters impedes finding solutions intuitively which match the requirements optimally. In order to find an optimal solution in reasonable time, the preliminary design process is usually supported by computer based systems.

The material strength properties of unidirectional reinforced composites are highly anisotropic. Stress limits in fiber direction are one or two orders higher than perpendicular to it. This makes dimensioning more complicated, since the stress state has to be compared to the particular strength values. There exist many criteria for predicting failure events. The criteria of Tsai–Hill [2,3], Tsai–Wu [4,5] and Hoffman [6] are well-known. This is because of their simplicity in application rather than of their reliability. Their physical basis is rather weak. However, they are formulated with a quadratic closed-form expression and thus implemented in all common commercial finite element packages. Besides, the number of needed strength parameters is low. The recent and more sophisticated criteria do not only indicate a damage event but they distinguish also between fiber and matrix cracking, e.g. Hashin [7], Puck [8] or Cuntze [9]. They are based on physical models, but their application is more expensive since the failure indices for the several fracture modes have to be evaluated and distinguished. For Puck, additional strength properties are required. Another approach for dimensioning composite structures is to limit the maximal allowed strains. The threshold is set to the minimal breaking strain in material principal coordinates. This is reasonable when first matrix cracking cannot be tolerated, e.g. in aircraft industry.

All the mentioned criteria are able to predict first ply failure. Considering multiaxial laminates, this is most often matrix cracking, which leads not necessarily to a total failure of the structure. The ultimate strength of the structure may be significantly above the first-ply-failure load.

Strength-optimal layups of laminated composites can be found as long as the geometric design and the load cases are simple.

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However, with increasing complexity, the application of computer based systems in the design process becomes necessary. There is a group of publications [10–14] reporting on optimal design of a laminated plate for a given global stress state using mathematical programming or optimality criteria. The layer thicknesses, the layer orientations, or both are taken as design variables to find weight-minimal solutions considering strength constraints. With the increasing capacity of computer systems, genetic algorithms have become more popular for solving the problem. They allow to enhance the design space using discrete design variables such as the stacking sequence (e.g. Callahan and Weeks [15], Gürdal et al. [16], Park et al. [17], Walker and Smith [18]).

Haftka and Starnes [19] propose an optimization procedure for improving the compressive strength of composite plates with holes. The design domain is separated and the laminate around the hole is designed of a softer material system with higher failure strain which increases the loading capacity.

Another group of methods address the problem of finding locally varying laminates to tailor the properties of more complex structures having a non-homogeneous stress field. Hansel and Becker [20] propose an adaptive topology optimization method where material is removed layerwise considering element stresses and principal stress directions. The algorithm is later enhanced with a genetic algorithm [21]. Soremekun et al. [22] split a panel into sections and optimize the stacking sequence within each using a genetic algorithm. Keller [23] employs a genetic algorithm with a graph-based parameterization scheme for a global optimization with strength constraints.

Some approaches optimize the strength by locally varying the fiber orientations. Huang and Hafka [24] increase the load-carrying capacity for plates with holes. Kočvara and Stingl [25] enhance the Free Material Optimization method [26] for strength optimization. Khani et al. [27] take advantage of laminates with locally varying stiffness. The manufacturing process of these promising solutions may be expensive since fiber-placing machines are required.

1.1. Automated design process

The present study provides an alternative approach to tailor the laminate properties to the local strength requirements. The basic concepts, namely the parameterization scheme and the adaption process, have already been introduced in [1] on the example of eigenfrequency problems. Here, the method is enhanced to problems concerning strength. The approach is finite-element-based and takes advantage of the sensitivities of an objective function with respect to the thicknesses of the layers of the finite elements. Consequently, the number of design variables may become large and the sensitivities, which are from the mathematical perspective the gradients of the objective function, have to be derived analytically in order to provide an efficient evaluation. Sensitivities can be seen as linear extrapolation of the objective function changes with respective infinitesimal changes of the design variables. Taking them with respect to the layer thicknesses in the elements, they provide information where the structure should be adapted in order to modify the objective value most efficiently in terms of additional material needed. In case of multiple-objectives, which could for example be the strength with respect to different load cases, a search direction $\mathbf{s}$ is defined as a weighted sum of the sensitivities of the respective sub-objectives f.

$$\mathbf{s} = \sum_i w_i \frac{df_i}{d\mathbf{t}} \tag{1}$$

The weighting factors w_i are chosen by the designer. The search direction is a vector in the search space which points into the direction of optimal design improvement. Going back to the element-level, it indicates the influence of the element-layer thickness change considering different objectives f_i.

The employed parameterization scheme is based on the *Ghost Layer Concept* which has originally been presented in [1]. A number of layers with given material, thickness and material orientation is predefined for a specific design domain. In addition to the real layers, so-called *Ghost Layers* are defined which carry the information on material properties and material orientation but whose thickness is specified to zero. Since these layers are virtual, they have no influence on the structural behavior. However, sensitivities with respect to thickness changes can be calculated conventionally. Adding a predefined set of these *Ghost Layers* at the interfaces of the real layers provides additional information on how the structure is to be reinforced most efficiently. The existence of a layer is defined with a so called thickness control factor $\boldsymbol{t}_{ctrl}$ which can be interpreted as a weighting factor. Setting its value to zero or one determines whether a layer remains in its virtual state or has joined the set of real layers. A reinforcement layer is generated by assigning a real thickness to regions of a *Ghost Layer* where the values of the search direction or the sensitivities, respectively, are maximal. Theoretically, the thickness control factors $\boldsymbol{t}_{ctrl}$ could also have continuous values which would result physically in continuous layer thicknesses. With respect to the manufacturing process, continuous thickness values are not allowed here. The parameterization scheme is strongly related to the manufacturing process. A predefinition of the allowable basic and reinforcement layers delimits the design space and thus the freedom of potential solutions. However, it ensures that the obtained solutions can be manufactured. Since the sensitivities provide a linear assumption of the non-linear objective function, the thickness adaption process is carried out iteratively. The sensitivities are re-evaluated after the adaption of a given number of element-layers. The number of elements changed within on iteration loop is usually defined by a threshold which is set by percentage of the occurring minimal and maximal values of the search direction vector. In particular, the bandwidth of the sensitivities of all element-layers is evaluated. If, for instance, choosing a threshold of 5%, a real thickness value is assigned to all element-layers whose sensitivity value is in the top 5% range. Even if this process is quite simple, it has turned out to be robust and the solutions are obtained in reasonable time and have satisfying quality. Generally, the solution quality is increasing with decreasing step sizes which will, however, also extend the process time. In fact, this automated design process has been applied to the generation of local reinforcements regarding different design criteria. A more sophisticated example for the specific design regarding the dynamic behavior has been presented in [28]. Here, the process is enhanced and demonstrated for strength problems. Thereby, the same process is applied with other design criteria but the underlying objective function and the sensitivities are different.

2. Pseudo strength function (PSF)

2.1. General formulation

The automated design process for the generation of locally reinforced composite structures is enhanced to strength problems. In order to employ the proposed optimization procedure, the gradient field that expresses the influence of an element-layer thickness change on the objective function is needed. This presumes that the objective function is at least once differentiable. In contrast to the potential energy, eigenfrequencies or buckling load factors, there exists no closed-form expression that characterizes the strength of a structure since this is a very local property. The strength is limited by the occurring stresses or strains at the critical