Composite Structures 108 (2014) 711–719

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Computational structural tailoring of continuous fibre reinforced polymer matrix composites by hybridisation of principal stress and thickness optimisation

Thomas Rettenwander [a,*], Michael Fischlschweiger [b], Georg Steinbichler [a]

[a] Johannes Kepler University, Institute of Polymer Injection Moulding and Process Automation, Altenbergerstr. 69, 4040 Linz, Austria
[b] Center for Lightweight Composite Technologies, ENGEL AUSTRIA GmbH, 4300 St. Valentin, Austria

ARTICLE INFO

Article history:
Available online 16 October 2013

Keywords:
Structural optimisation
Finite element modelling
Principal stress optimisation
Thickness optimisation
Tape laying

ABSTRACT

Anisotropic composite material properties require special designing capabilities to fully exploit the remarkable properties in longitudinal fibre direction for stiffness and strength improvement. Therefore an optimisation scheme with hierarchical structuring of an optimality criterion based orientation optimisation and a gradient based technique for thickness optimisation is presented. The procedure is applied on two different space scales. Orientation optimisation based on principal stress directions is applied on a local laminate position. There fibre directions are affixed throughout the laminate until convergence is reached. On a local ply position thicknesses are determined in an iterative procedure. It is switched between both algorithms until global convergence is achieved. The application of algorithms on two different space scales leads to a robust engineering approach. The ability of the presented algorithm is tested with a numerical example and a structural optimisation of laminated composites is shown.

1. Introduction

Composites based on continuous fibres placed in a polymer matrix show remarkable potential to substitute metallic as well as pure polymer components in current engineering applications due to their low weight and mechanical properties. One example which demonstrates the strong need on high performance composite structures is the automotive industry which puts focus on weight reduction to increase fuel efficiency and consequently reduce CO_2 emission. In that point of view especially the substitution of current pure metallic components in the car by composite structures promises to be a key factor for reducing weight.

A successful implementation of this material class is strongly dependent on several factors. Besides manufacturing improvements even lighter composite structures seem essential. The ability to deal with anisotropic material properties in an optimum way promises further potential of weight reduction, because so far the high strength and stiffness in fibre direction is not fully exploited in structural applications. Several ideas and concepts for using spatially varying fibre directions for stiffness and strength improvement have been proposed in the past. In 1904 Michell and Melbourne [1] gave a theoretical background regarding minimum weight and maximum stiffness and strength of structures which can be useful to the design of composites. Hyman et al. [2] were among the first who tested locally varying fibre orientation in a structure. They subjected a plate with a hole with optimised fibre orientation to tension, however results were rather insignificant. Further research was done in [3], where maximum stiffness was accomplished by aligning the fibres according to local stresses. Cooper [4] tested a variable stiffness design for orthotropic materials. There an energy method was applied for defining principal stress or strain trajectories. A geometry, which is often used for evaluating the capability of tailoring strategies, is a plate with a hole, where for example a pin load can be acted. Experimental data for such a geometry were determined in [4] and it could be shown that aligning the fibres according to the load trajectories in the plate leads to remarkable improvements in strength of the structure with also feasible structural stiffness values. Later Khot et al. [5] presented optimisation strategies for variable stiffness design. In this work an algorithm based on a strain energy optimality criterion was used to update thickness values of a preexisting laminate with different fibre angles. Leissa and Vagins [6] also proposed a method for variable stiffness design with the aim to achieve equally distributed loading throughout the structure.

The above mentioned works were the starting point of a vivid research field for composite optimisation strategies. The speciality of composite optimisation regarding stiffness and strength is the large number of design variables, e.g., local orientation and also

---

* Corresponding author. Tel.: +43 73224686604.
E-mail address: thomas.rettenwander@jku.at (T. Rettenwander).
URLs: http://www.jku.at/ipim, http://www.engel.at (T. Rettenwander).

0263-8223/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2013.09.063

local thicknesses. Today a variety of optimisation approaches are used to determine local material orientation for tailoring structures with anisotropic material properties. According to Ghiasi et al. [7] optimisation strategies can be classified as:

- Optimisation with a gradient based technique.
- Optimisation with direct search methods.
- Optimisation with optimality criterion methods.
- Optimisation with hybrid methods.

The gradient based technique requires the calculation of the gradients of the objective function and therefore computation time increases exponentially with the number of design variables. For example Jorgensen [8] updated the local material orientation in each element by calculating the gradient of the objective function (optimising the flutter load), which was further used to update the design variables. A similar methodology was used by Cho and Rowlands [9]. The method of feasible direction was in charge to control local fibre orientation for minimisation of tensile stresses in the composite. Hyer and Lee [10] used a gradient-search technique to vary fibre orientation for increasing the buckling load in a compression loaded plate with a hole. In [11] an extended gradient technique is used to efficiently handle a patch design. This means for limiting the number of design variables regions of constant material angle, so called patches, are defined.

To minimise the computational effort an approximation of the original objective by a functional e.g. the first or second order Taylor series can be applied. These problems can then be solved in terms of traditional optimisation techniques. Such approximation technique is applied by e.g. [12–14].

Direct search methods are an alternative optimisation scheme for finding an optimal local orientation information for a given objective function. Direct search methods are not explicitly using derivatives for finding the optimum, however they use the functional as information only. Especially stochastic methods are known for finding a global optimum and for their robustness regarding the application to different optimisation problems. Among direct search methods for tailoring fibre directions in laminate structures genetic algorithms are most commonly used. Legrand et al. [15] used a genetic algorithm to optimise directly the local material orientation in each element. In [16] the before mentioned algorithm was optimised to provide faster computation times. The number of design variables is still high in this problem and makes computation expensive. In [17] a multi-objective optimisation was used to get the best balance between mass reduction and torsional stiffness. Therefore a genetic algorithm was applied. Wu et al. [18] also used a genetic algorithm to improve postbuckling behaviour of a laminated composite.

In [19–22] a simplification of the original local material orientation to a patch orientation optimisation problem is used and solved based on genetic algorithms. Adams et al. [23] also used a genetic algorithm which was applied to a patch design and furthermore incorporated blending rules. This code was further developed in [24,25].

To further enhance optimisation algorithms more effective hybrid algorithms are developed. Hybrid algorithms are combining global optimisation techniques (e.g. genetic algorithms, evolutionary algorithms, etc.) with faster traditional methods (gradient method, hill climbing, etc.). This combination provides convergence to global optimum and allows to find the optimum with faster methods. For further details the reader is referred to [26–28].

Optimality criterion methods based optimisation received the most attention in variable stiffness design. Within this field, optimality conditions based on strain energy or stress fields can be derived but also optimality conditions taking principal stress/strain directories or load path vectors as optimal directions are applied.

Strain energy based criteria can be found in [5], where the ply thickness of different straightline fibre formats with different fibre angles (e.g. 0/−45/+45/90) are updated according to a constant strain energy level throughout the structure. Pedersen [29] also derived an approach for optimal fibre orientation according to energy density minimisation for maximum stiffness of the structure. Duvaut et al. [30] used the strain energy level to update the fibre density and fibre orientation in each element of a structure. Setoodeh et al. [31] defined the material orientation problem as a minimum compliance problem. In the fibre orientation update algorithm a gradient based minimiser is used, computing a new candidate fibre orientation in every iteration cycle. If the new angle provides a lower value of complementary strain energy, then the new configuration is used. The fibre orientation optimisation is coupled with a Solid Isotropic Material with Penalization (SIMP) approach for density optimisation using cellular automata. In [32] Khosravi and Sedaghati a strain energy based criterion to update the fibre direction on a first level and the layer thickness on a second optimisation level was developed. Other strain energy based approaches can be found in: [33–36].

The theory behind principal stress optimisation is to predominantly subject fibres to tensile and compressive loads and therefore to match fibre directions with the principal stress vectors. Consequently shear stresses will disappear in the composite and failure due to excessive shearing is omitted. Pedersen [29,37,38] and Cheng and Pedersen [39] illustrated that for shear weak materials always a global extremum energy solution exists if fibres are co-aligned with principal stresses or strains. In this case directions of principal stresses, principal strains and fibre directions are equal and a global minimum for strain energy or also global complementary strain energy is reached. For shear strong materials also a nontrivial solution exists, where principal stresses and principal strains and the optimum fibre direction are not equal. For the definition of shear strong and shear weak materials the authors refer to [37,39]. Thomsen [40] as well as Landriani and Rovati [41] presented a similar approach and also found the co-alignment of principal stresses, principal strains and local fibre directions. Pedersen showed different examples of density, orientation and shape optimal composite structures in [42]. Hyer and Charette [43] incorporated a layer with variable fibre directions derived from principal stress optimisation in a straightline fibre laminate. Better results regarding buckling forces can be achieved in tension and equal results in compression. There are numerous other authors dealing with fibre alignment following principal stress/ strain directions [44–51]. Tosh and Kelly [52] showed that fibres aligned orthogonal to the first principal direction can improve the strength of the structure. As one result of their research they concluded that for bearing or highly multiaxial load cases where tension and compression are present, both, major and minor principal stress trajectories, have to be used to achieve highest load levels. In before mentioned publication [52] also fibre steering following the direction of the load path is suggested. This approach can also be found in [53,54].

Optimisation of composite materials requires besides the optimisation of local fibre orientation also the optimisation of material distribution (thickness or density) for ensuring to reach highest stiffness and strength levels. For anisotropic materials the same optimisation methods as for isotropic materials are applicable [55–57]. In [7] a thorough review of variable stiffness design of composites is given, including approaches combining orientational and material distribution optimisation. This is predominantly done in multi-level optimisation approaches, where the two approaches can be decomposed in a hierarchical or a non-hierarchical way. A thickness optimisation according to a strain energy density method and co-alignment of principal directions is done e.g. by Pedersen [29,37,38,42]. In [32] an energy based method was also used