Graphical Abstract

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Highlights

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Topology Optimization strategies for continuous fiber-reinforced and functionally graded anisotropic composite structures: A brief review

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Abstract

Among all types of Additive Manufacturing (AM) technology,Continuous Fiber Fused Filament Fabrication (CF4) can fabricate high-performance composites compared to those manufactured with conventional technologies. AM provides the excellent advantage of a very high degree of reconfigurability, which is in high demand to support the immediate short-term manufacturing chain in medical, transportation, and other industrial applications. Additionally, the CF4 capability enables the fabrication of Continuous Fiber-Reinforced Composite (CFRC) materials and Functionally GRaded Anisotropic Composite (FGRC) structures. The current expedition in AM allows us to integrate Topology Optimization (TO) strategies to design realizable FRC and GFRC structures for a given performance. Various TO strategies for attaining lightweight and high-performance designs have been proposed in the literature, which exploits AM's design freedom. Therefore, the paper attempts to address works related to TO strategies employed to obtain optimal CFRC and FGRC structures. This review intends to overview, compare existing strategies, analyze their similarities and dissimilarities, and discuss challenges and future trends in this field.

Keywords:

1. Introduction

Additive Manufacturing. The cost-effective commercially available Additive Manufacturing (AM) or 3D Printing (3DP) technologies eliminate many limitations that previously plagued the manufacturing of highly tailored structural performance for multifunctional [] and multi-physics [] applications. Moreover, the short metamorphosis of AM technologies offers unique capabilities to realize the next-generation lightweight structure have brought great application potentials in several major industries such as aerospace [1, 2], automotive [] and medical[3]. First, AM's unique ability to fabricate a highly complex shape without a substantial increase in fabrication costs, along with the benefit s of reducing manufacturing preparation time, renders these technologies worthy investment for large-scale industries. Moreover, it offers the fabrication of lattice structures-a lightweight design comparative to the solid-filled parts. Thus, offer diversification of design to answers multifunctional material requirements in weight reduction, [4], their ability to dissipate energy [5, 6], heat [7] and vibration [8]. The printed polymer parts frequently consist of carbon nanotubes and short fibre to upgrade their mechanical performance. Still, it cannot outperform [9, 10], the mechanical strength offered by continuous fibre-reinforced composite laminate manufactured using conventional manufacturing tools. Hence, the shortcomings of 3D printed polymer composites aggravated the demand to develop Continuous Fiber Filament Fabrication (CF4) technology. CF4 technology provides a unique opportunity to reduce part distortion warping and support structures during printing, and fibre tension prevents nozzle clogging, a constant lookout with the polymer AM. Additionally, controlling the anisotropic properties of the fibre-reinforced composites can effectively distribute the loads throughout the laminate to maximize the structure's strength and stiffness. Recognizing these potentials of AM, returned a resurgent interest in utilizing the design strategies to exploit AM's performance-driven manufacturing technologies towards enhancing printed parts' overall functional performance. In contrast, to the geometric-driven or/and cost-driven manufacturing of components. The concept of performance-driven manufacturing is known as Design for Additive Manufacturing (DfAM) [11].

Topology optimization. Topology Optimization (TO), one of the DfAM methods, is an iterative design tool to optimize a quantifiable objective while being intended to sustains loads, constraints, and boundary conditions. Topology Optimization is frequently adopted to design structurally sound parts and has subsequentially surpassed optimization design tools such as shape and size optimization in isolation. The seminal work of Bendsøe and Kikuchi [12] introducing the concept of TO on the homogenization method; since then, TO has been developed rapidly. TO approaches can be summarized as follows: the homogenization method [12]; the Solid Isotropic Material with Penalization (SIMP) method [13, 14], the level set method [15, 16], the Evolutionary Structural Optimization (ESO) method [17]; Topology Derivatives [**? ?**] and Phase

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Field. The details of these approaches are discussed in the review papers [18, 19, 20] and some emerging TO methods for smooth boundary representation include the 'Metamorphic Development Method' (MDM) [21], and the 'Moving Morphable Method' (MMM) [22]. The general architecture of TO starts with the definition of maximizing or minimizing a single or multi-target-objective function to fulfil a set of constraints such as volume, displacement, or frequency [23]. Then, as part of an iterative process, design variables, Finite Element Analysis (FEA), sensitivity analysis, regularization, and optimization steps are repeated in this order until convergence is achieved [24].

Topology Optimization of fiber-reinforced composite materials. The optimization concept applied to composite materials allows finding the optimized geometric contours of the laminate, the optimized material distribution, the optimized orientation of fiber paths, as well as optimized mapping regions for the insertion of additional layers of material aimed, for example, to increase the strength of regions with distribution of intense loads. CF4 technology allows fabrication of FRC material with the continuous spatial in-plane variation of fiber angle and fiber volume fraction, thus expanding design space as opposed to variable [25] and constant stiffness laminate [25]. Moreover, CF4 technology can achieve out-of-plane variation of fiber angle due to the fiber-reinforced composite's self-supporting characteristics. Numerous studies have shown that fiber orientation optimization can significantly tailor structural performance such as stress concentration[26], stiffness [27], load-bearing capacity, buckling load, and the natural frequency [28]. Therefore, the design of the FRC structures requires optimization methods that reflect design freedom offered by CF4 technologies, including constraints, to thoroughly exploit the anisotropic properties of FRC material [29]. Amidst the ingredients of the optimization method for FRC structures with continuous fiber parameterization schemes and optimization algorithms have notable influences on the quality of the solution. The article on the optimization of topology and fiber path orientation and thus, only related works are reviewed.

2. Paramterization schemes for fiber orientation

The parameterization scheme implements a numerical description of fiber orientation patterns and defines variables for the optimization. It should ensure spatial continuity of fiber angle so that CF4 technology can produce the structure, and it should also provide enough design freedom so that optimization algorithm can consider more candidate designs.

Continuous Parameterization

The straightforward parametrization of fiber orientation design uses the angle itself as the design variable. The design variable is then the continuous and independent parameter at design points, for instance, at centers of finite elements. Handling the continuous fiber orientation design presents difficulties due to a fourth-order transform tensor, which rotates the tensor to a given angle composed of multivalued sine and cosine functions, rendering a non-convex optimization problem. Thus, optimizing the fiber orientation is susceptible to the initial fiber configuration and produces difficulties obtaining the optimized solution. In addition, the lack of fiber continuity in a large region puts a question mark on the realizability of the attained optimized solution. As illustrated in [30], suboptimal solutions [25, 29] are the persistent outcome of a continuous fiber orientation design problem. Various modifications in parametrization schemes and different optimization algorithm methods have been considered to handle the sub-optimal design issue for the continuous fiber orientation problem — one brute-force way to avoid it by relaxing the design space. For instance, free material optimization (FMO)[31, 32] further relaxed the design space by independently parameterizing each stiffness tensor element as the design variable. However, interpretation of the obtained stiffness tensor and linking it to the feasible physical design makes this approach challenging. Xia and Shi [33]

An alternative is employing curvilinear parameterization schemes that define fiber paths as the graphs of analytical function, which guarantee continuity of fiber angle and have a small number of design variables [34, 35, 36]. Nevertheless, the restrictive design search space will limit the tailorability of the fiber path, thus deteriorates the optimization problem's stability [37] and quality of the optimized solution. Adjectenly, the parameterization schemes can follow equidistant iso-contours of a level set function to represent curvilinear fiber paths [38, 39], thus naturally ensuring fiber continuity and being often parallel to the neighboring fiber paths. Furthermore, the optimization result becomes highly dependent on the initial configuration, and local solutions often appear [40].

Discrete Paramterization

The counter approach reduces the design search space to avoid multiple local minima issues where the optimized solution is highly sensitive to the initial fiber configuration. Thus, Stegmann and Lund [30, 41] stretched the design search space by choosing discrete fiber orientation candidates, define apriori, which parameterized the design space into the discrete material candidates. These transversely isotropic material models are defined for different fiber orientations for the same isotropic elasticity tensor and share some similarities with the multi-material optimization problem in [42, 43]. The suggested approach assigned weighting functions to different candidates and employed gradient-based optimization and penalization coefficient to force the weighting functions towards either zero or one to seek fiber convergence, i.e., one discrete material at each design point. This method is known as Discrete Material optimization (DMO). DMO laid the foundation for SFP (Shape Function and with Penalization) [44], BCP (Bi-value Coding Parameterization) [45] to perform discrete fiber orientation optimization . A comparison using various numerical examples on these methodologies on discrete fiber orientation optimization drawn in [46]. Contrarily to CFAO, it does not cover design problems for continuously varying orientation distributions. Thus, it permits a limited scope to fully exploit the potential of modern technology's continuously varying orientation in composites. [47, 27, 26]. Secondly, these methods fail to address the fiber convergence even against the significant penalization factor; hence, their benefit relies on an optimization algorithm to circumvent impractical mixtures of fiber angles. Third, the discrete parameterization scheme should further minimize the number of design candidates for efficient optimization.

Kiyono et al. [46] proposed a continuation of the computational approach suggested by Yin and Ananthasuresh [43] by utilizing the normal distribution function to guarantee fiber convergence, low sensitivity to the initial fiber configuration, and the continuity of the fiber orientation Salas et al. [48] proposed a Self-Penalization Interpolation Model for Fiber Orientation (SPIMFO) based on convergent Talyor series for sine and cosine functions and optimized the dynamic design of laminated piezo composite actuators combining SPIMFO with SIMP method. Nomura et al. [49]. proposed a general methodology for the simultaneous design of structural topology and continuous and discrete material orientation with the isoparametric projection method. In that study, the Cartesian components of the orientation vector were chosen as the orientation design variables. The 2π ambiguity stems from the periodic nature of the angular representation is addressed to yields better control on manufacturability. However, the simultaneous design will significantly change the orientations with a change in topology, potentially causing LOSS.

Optimization Algorithm

Analytical approaches

Analytical methods determined early studies of optimal fibre orientation that dates back to the pioneering work of Pedersen on strain-based method [50, 51, 52] and followed by the stress-based method. In the strain-based method, analytically derived equations study the sensitivity of strain energy with respect to material orientation for orthotropic material based on the assumption that the strain energy is invariant on material orientation. A similar analytical deduction can be derived for the stress-based method that except constant stress field with respect to material orientation. These methods eliminate the need for iteration during the design process and significantly increase computational efficiency compared with mathematical programming. In addition, the stress-based method produces a slightly stiffer structure than the strain method because strong couplings exist among the orientational variables when the strain field is used. In both scenarios, optimization proceeds towards convergence. The material orientation tends to coincide with the major principal stress/strain fields for relatively 'weak' shear and some shear 'strong' types of orthotropic materials. However, the methods are highly dependent on the initial fibre configuration, and the solution of both approaches will fail when the local and repeated global minima (more than one solution has the same global minimum value) occurs [53]. Nevertheless, these methods form the basis for future research on material orientation optimization for fibre reinforced composite materials. These methods' shortcomings were due to the assumption of constant stress or strain fields that was removed by the energy-based method introduced by Luo and Gea [54, 55]. The proposed hybrid framework estimates the strain fields' and stress fields' dependency on fibre orientation by introducing an approximate energy factor. Their research showed that an energy-based method produces numerically more optimal solutions to stress-based and strain-based methods. The method use inclusion model is used to analyze the variations of the strain and stress of one design cell due to the rotation of orthotropic material in that design cell. It assumes that the displacements are continuous at the interface of the design cell after the cell orientation changes. Thus, the strain of the design cell will not change because the cell is under the same displacement boundary condition. In contrast, the stress of the design cell will vary, suffer from stress discontinuity at the interface. Furthermore, the assumption to consider additional stress and strain fields for both the design cell and its surrounding resolves stress discontinuity caused at the interface. By introducing the concept of energy factor, Luo et al. evaluated additional stress and strain field.

Gradient-based approaches

[41] gradient based optimization of the buckling load of laminate composite structures considering fiber angle deisng variables. The optimization formualtion are based on either linear or geomterically nonlinear analysis and formulated as mathematical programming problems solved using gradient based techniques. Xia and Shi [56] First, a hierarchy of parameterizations are constructed. At each level of the hierarchy, one has a distinct parameterization for the fiber angle arrangement. From the top level to the bottom level of the hierarchy, the number and density of design points for the Shepard interpolation increase, thus the design freedom and the resolution of parameterization increase as well. Second, at each level of the hierarchy, an optimization problem is formulated, and these optimization problems are solved successively. After the optimization problem at a coarse level is solved, one goes to its neighboring finer level, using the solution of the former one to compute an initial design for the latter one. Again, the Shepard interpolation is used for the computation of initial design.

formulated cascadic multilevel optimization problem, where there results from coarse level serves as an initial design for finer level.

Heurstic-based approaches

Another outlook on approaching the LOSS problem is using an optimization solver better at global searching ability, such as the genetic algorithm [57] and simulated annealing algorithm [58]. The heuristic algorithm can find "global minimum" and allow handling a discrete variable, but this always sacrifices the computational cost. Sigmund [59] questions the usefulness of non-gradient approaches in TO, showing the inefficiency of non-gradient algorithm-based optimization problems with many design variables and constraints. As a result, gradient-based solver i.e. Method of Moving Asymptotes (MMA) [60] set the framework for the TO problem and has been pushed significantly to avoid the LOSS [61].

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References

References

[1] D. Kokkinis, M. Schaffner, A. R. Studart, Multimaterial magnetically assisted 3D printing of composite materials, Nat. Commun. 6 (2015) 1–10. doi:10.1038/ncomms9643.

[2] L. Berrocal, R. Fernández, S. González, A. Periñán, S. Tudela, J. Vilanova, L. Rubio, J. M. Martín Márquez, J. Guerrero, F. Lasagni, Topology optimization and additive manufacturing for aerospace components, Prog. Addit. Manuf. 4 (2019) 83–95. doi:10.1007/s40964-018-0061-3.

[3] A. D. Cramer, V. J. Challis, A. P. Roberts, Physically Realizable Three-Dimensional Bone Prosthesis Design With Interpolated Microstructures, J. Biomech. Eng. 139. doi:10.1115/1.4035481.

[4] N. A. Fleck, V. S. Deshpande, M. F. Ashby, Micro-architectured materials: past, present and future, Proc. R. Soc. A Math. Phys. Eng. Sci. 466 (2010) 2495–2516. doi:10.1098/rspa.2010.0215.

[5] P. Qiao, M. Yang, F. Bobaru, Impact Mechanics and High-Energy Absorbing Materials: Review, J. Aerosp. Eng. 21 (2008) 235–248. doi:10.1061/(ASCE)0893-1321(2008)21:4(235).

[6] I. Maskery, A. Hussey, A. Panesar, A. Aremu, C. Tuck, I. Ashcroft, R. Hague, An investigation into reinforced and functionally graded lattice structures, J. Cell. Plast. 53 (2017) 151–165. doi:10.1177/0021955X16639035.

[7] A. O. Aremu, J. P. J. Brennan-Craddock, A. Panesar, I. A. Ashcroft, R. J. M. Hague, R. D. Wildman, C. Tuck, A voxel-based method of constructing and skinning conformal and functionally graded lattice structures suitable for additive manufacturing, Addit. Manuf. 13 (2017) 1–13. doi:10.1016/j.addma.2016.10.006.

[8] L. Cheng, X. Liang, E. Belski, X. Wang, J. M. Sietins, S. Ludwick, A. To, Natural Frequency Optimization of Variable-Density Additive Manufactured Lattice Structure: Theory and Experimental Validation, J. Manuf. Sci. Eng. 140. doi:10.1115/1.4040622.

[9] P. Parandoush, D. Lin, A review on additive manufacturing of polymer-fiber composites (dec 2017). doi:10.1016/j.compstruct.2017.08.088.

[10] Y. Sano, R. Matsuzaki, M. Ueda, A. Todoroki, Y. Hirano, 3D printing of discontinuous and continuous fibre composites using stereolithography, Addit. Manuf. 24 (2018) 521–527. doi:10.1016/j.addma.2018.10.033.

[11] J. Plocher, A. Panesar, Review on design and structural optimisation in additive manufacturing: Towards next-generation lightweight structures, Mater. & Des. 183 (2019) 108164. doi:10.1016/j.matdes.2019.108164.

[12] M. P. Bendsøe, N. Kikuchi, Generating optimal topologies in structural design using a homogenization method, Comput. Methods Appl. Mech. Eng. 71 (1988) 197–224. doi:10.1016/0045-7825(88)90086-2.

[13] M. P. Bendsøe, Optimal shape design as a material distribution problem, Struct. Optim. 1 (1989) 193–202. doi:10.1007/BF01650949.

[14] G. I. N. Rozvany, M. Zhou, T. Birker, Generalized shape optimization without homogenization, Struct. Optim. 4 (1992) 250–252. doi:10.1007/BF01742754.

[15] M. Y. Wang, X. Wang, D. Guo, A level set method for structural topology optimization, Comput. Methods Appl. Mech. Eng. 192 (2003) 227–246. doi:10.1016/S0045-7825(02)00559-5.

[16] G. Allaire, F. Jouve, A.-M. Toader, Structural optimization using sensitivity analysis and a level-set method, J. Comput. Phys. 194 (2004) 363–393. doi:10.1016/j.jcp.2003.09.032.

[17] Y. M. Xie, G. P. Steven, A simple evolutionary procedure for structural optimization, Comput. Struct. 49 (1993) 885–896. doi:10.1016/0045-7949(93)90035-C.

[18] G. I. N. Rozvany, A critical review of established methods of structural topology optimization, Struct. Multidiscip. Optim. 37 (2009) 217–237. doi:10.1007/s00158-007-0217-0.

[19] N. P. Van Dijk, K. Maute, M. Langelaar, F. Van Keulen, Level-set methods for structural topology optimization: A review, Struct. Multidiscip. Optim. 48 (2013) 437–472. doi:10.1007/s00158-013-0912-y.

[20] J. D. Deaton, R. V. Grandhi, A survey of structural and multidisciplinary continuum topology optimization: Post 2000, Struct. Multidiscip. Optim. 49 (2014) 1–38. doi:10.1007/s00158-013-0956-z.

[21] J. S. Liu, G. T. Parks, P. J. Clarkson, Metamorphic Development: A new topology optimization method for continuum structures, Struct. Multidiscip. Optim. 20 (2000) 288–300. doi:10.1007/s001580050159.

[22] C. Liu, Z. Du, W. Zhang, Y. Zhu, X. Guo, Additive Manufacturing-Oriented Design of Graded Lattice Structures Through Explicit Topology Optimization, J. Appl. Mech. 84. doi:10.1115/1.4036941.

[23] H. Li, Z. Luo, M. Xiao, L. Gao, J. Gao, A new multiscale topology optimization method for multiphase composite structures of frequency response with level sets, Comput. Methods Appl. Mech. Eng. 356 (2019) 116–144. doi:10.1016/j.cma.2019.07.020.

[24] M. P. Bendsoe, O. Sigmund, Topology optimization: theory, methods, and applications, Springer Science & Business Media, 2013.

[25] H. Ghiasi, D. Pasini, L. Lessard, Optimum stacking sequence design of composite materials Part I: Constant stiffness design, Compos. Struct. 90 (2009) 1–11. doi:10.1016/j.compstruct.2009.01.006.

[26] K. Sugiyama, R. Matsuzaki, A. V. Malakhov, A. N. Polilov, M. Ueda, A. Todoroki, Y. Hirano, 3D printing of optimized composites with variable fiber volume fraction and stiffness using continuous fiber, Compos. Sci. Technol. 186 (2020) 107905. doi:10.1016/j.compscitech.2019.107905.

[27] A. V. Malakhov, A. N. Polilov, Design of composite structures reinforced curvilinear fibres using FEM, Compos. Part A Appl. Sci. Manuf. 87 (2016) 23–28. doi:10.1016/j.compositesa.2016.04.005.

[28] J. Zhang, W.-H. Zhang, J.-H. Zhu, An extended stress-based method for orientation angle optimization of laminated composite structures, Acta Mech. Sin. 27 (2011) 977–985. doi:10.1007/s10409-011-0506-0.

[29] Y. Xu, J. Zhu, Z. Wu, Y. Cao, Y. Zhao, W. Zhang, A review on the design of laminated composite structures: constant and variable stiffness design and topology optimization, Adv. Compos. Hybrid Mater. 1 (2018) 460–477. doi:10.1007/s42114-018-0032-7.

[30] J. Stegmann, E. Lund, Discrete material optimization of general composite shell structures, Int. J. Numer. Methods Eng. 62 (14) (2005) 2009–2027. doi:https://doi.org/10.1002/nme.1259.

[31] J. Zowe, M. Kocvara, M. P. Bendsøe, Free material optimization via mathematical programming, Math. Program. 79 (1997) 445–466. doi:10.1007/BF02614328.

[32] A. Ben-Tal, M. Kocvara, A. Nemirovski, J. Zowe, Free Material Design via Semidefinite Programming: The Multiload Case with Contact Conditions, SIAM J. Optim. 9 (1999) 813–832. doi:10.1137/s1052623497327994.

[33] Q. Xia, T. Shi, Optimization of composite structures with continuous spatial variation of fiber angle through Shepard interpolation, Compos. Struct. 182 (2017) 273–282. doi:10.1016/j.compstruct.2017.09.052.

[34] M. Bruyneel, S. Zein, A modified Fast Marching Method for defining fiber placement trajectories over meshes, Comput. & Struct. 125 (2013) 45–52. doi:10.1016/j.compstruc.2013.04.015.

[35] E. Lemaire, S. Zein, M. Bruyneel, Optimization of composite structures with curved fiber trajectories, Compos. Struct. 131 (2015) 895–904. doi:10.1016/j.compstruct.2015.06.040.

[36] P. Hao, C. Liu, X. Liu, X. Yuan, B. Wang, G. Li, M. Dong, L. Chen, Isogeometric analysis and design of variable-stiffness aircraft panels with multiple cutouts by level set method, Compos. Struct. 206 (2018) 888–902. doi:10.1016/j.compstruct.2018.08.086.

[37] H. Ghiasi, K. Fayazbakhsh, D. Pasini, L. Lessard, Optimum stacking sequence design of composite materials Part II: Variable stiffness design, Compos. Struct. 93 (2010) 1–13. doi:10.1016/j.compstruct.2010.06.001.

[38] C. J. Brampton, K. C. Wu, H. A. Kim, New optimization method for steered fiber composites using the level set method, Struct. Multidiscip. Optim. 52 (2015) 493–505. doi:10.1007/s00158-015-1256-6.

[39] V. S. Papapetrou, C. Patel, A. Y. Tamijani, Stiffness-based optimization framework for the topology and fiber paths of continuous fiber composites, Compos. Part B Eng. 183 (2020) 107681. doi:10.1016/j.compositesb.2019.107681.

[40] Y. Tian, S. Pu, T. Shi, Q. Xia, A parametric divergence-free vector field method for the optimization of composite structures with curvilinear fibers, Comput. Methods Appl. Mech. Eng. 373 (2021) 113574. doi:10.1016/j.cma.2020.113574.

[41] E. Lindgaard, E. Lund, Optimization formulations for the maximum nonlinear buckling load of composite structures, Struct. Multidiscip. Optim. 43 (2011) 631–646. doi:10.1007/s00158-010-0593-8.

[42] M. P. Bendsøe, O. Sigmund, Material interpolation schemes in topology optimization, Arch. Appl. Mech. 69 (1999) 635–654. doi:10.1007/s004190050248.

[43] L. Yin, G. K. Ananthasuresh, Topology optimization of compliant mechanisms with multiple materials using a peak function material interpolation scheme, Struct. Multidiscip. Optim. 23 (2001) 49–62. doi:10.1007/s00158-001-0165-z.

[44] M. Bruyneel, SFP—a new parameterization based on shape functions for optimal material selection: application to conventional composite plies, Struct. Multidiscip. Optim. 43 (2011) 17–27. doi:10.1007/s00158-010-0548-0.

[45] T. Gao, W. Zhang, P. Duysinx, A bi-value coding parameterization scheme for the discrete optimal orientation design of the composite laminate, Int. J. Numer. Methods Eng. 91 (2012) 98–114. doi:https://doi.org/10.1002/nme.4270.

[46] C. Y. Kiyono, E. C. N. Silva, J. N. Reddy, A novel fiber optimization method based on normal distribution function with continuously varying fiber path, Compos. Struct. 160 (2017) 503–515. doi:10.1016/j.compstruct.2016.10.064.

[47] M. Arian Nik, K. Fayazbakhsh, D. Pasini, L. Lessard, Surrogate-based multi-objective optimization of a composite laminate with curvilinear fibers, Compos. Struct. 94 (2012) 2306–2313. doi:10.1016/j.compstruct.2012.03.021.

[48] R. A. Salas, F. J. Ramírez-Gil, W. Montealegre-Rubio, E. C. N. Silva, J. N. Reddy, Optimized dynamic design of laminated piezocomposite multi-entry actuators considering fiber orientation, Comput. Methods Appl. Mech. Eng. 335 (2018) 223–254. doi:10.1016/j.cma.2018.02.011.

[49] T. Nomura, E. M. Dede, J. Lee, S. Yamasaki, T. Matsumori, A. Kawamoto, N. Kikuchi, General topology optimization method with continuous and discrete orientation design using isoparametric projection, Int. J. Numer. Methods Eng. 101 (2015) 571–605. doi:https://doi.org/10.1002/nme.4799.

[50] P. Pedersen, On optimal orientation of orthotropic materials, Struct. Optim. 1 (1989) 101–106. doi:10.1007/BF01637666.

[51] P. Pedersen, Bounds on elastic energy in solids of orthotropic materials, Struct. Optim. 2 (1990) 55–63. doi:10.1007/BF01743521.

[52] P. Pedersen, On thickness and orientational design with orthotropic materials, Struct. Optim. 3 (1991) 69–78. doi:10.1007/BF01743275.

[53] H. C. Gea, J. H. Luo, On the stress-based and strain-based methods for predicting optimal orientation of orthotropic materials, Struct. Multidiscip. Optim. 26 (2004) 229–234. doi:10.1007/s00158-003-0348-x.

[54] A. R. Díaz, M. P. Bendsøe, Shape optimization of structures for multiple loading conditions using a homogenization method, Struct Optim. 4 (1992) 17–22. doi:10.1007/BF01894077.

[55] H. C. Cheng, N. Kikuchi, Z. D. Ma, An improved approach for determining the optimal orientation of orthotropic material, Struct. Optim. 8 (1994) 101–112. doi:10.1007/BF01743305.

[56] Q. Xia, T. Shi, A cascadic multilevel optimization algorithm for the design of composite structures with curvilinear fiber based on Shepard interpolation, Compos. Struct. 188 (2018) 209–219. doi:10.1016/j.compstruct.2018.01.013.

[57] Z. Wang, A. Sobey, A comparative review between Genetic Algorithm use in composite optimisation and the state-of-the-art in evolutionary computation, Compos. Struct. 233. doi:10.1016/j.compstruct.2019.111739.

[58] O. Hasançebi, S. Çarbas, M. P. Saka, Improving the performance of simulated annealing in structural optimization, Struct. Multidiscip. Optim. 41 (2010) 189–203. doi:10.1007/s00158-009-0418-9.

[59] O. Sigmund, On the usefulness of non-gradient approaches in topology optimization, Struct. Multidiscip. Optim. 43 (2011) 589–596. doi:10.1007/s00158-011-0638-7.

[60] K. Svanberg, The method of moving asymptotes—a new method for structural optimization, Int. J. Numer. Methods Eng. 24 (1987) 359–373. doi:10.1002/nme.1620240207.

[61] Y. Shen, D. Branscomb, Orientation optimization in anisotropic materials using gradient descent method, Compos. Struct. 234 (2020) 111680. doi:10.1016/j.compstruct.2019.111680.