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A REVIEW ON THE TOPOLOGY OPTIMIZATION OF THE FIBER-REINFORCED COMPOSITE STRUCTURES

According to the requirements of the aerospace industry for high strength, high stiffness, and lightweight structural parts, topology optimization has been proved to be an effective product design method. As one of the most conceptual and prospective structural optimization design methods, topology optimization intends to seek the optimal layout of materials in an allowed design region under a given load and boundary conditions. Thus, the object of study in the article is the method of topological optimization of aircraft structures. The goal of this article is to analyze the existing approaches, algorithms, as well as application of the method of topological optimization in the aerospace field in applied problems. The tasks are to describe the existing various approaches methods, features, and research directions of topological optimization as well as to study the possibility of application in the manufacturing process of composite structures. The following results were obtained. The optimization methods are briefly explained and compared, and the advantages and limitations of each approach are discussed. The various ways of simultaneous optimization of fiber orientation and structural topology were described and analyzed. The features of different methods of continuous fiber orientation optimization method were reviewed. The discrete fiber orientation optimization methods were represented. The possibility of multi-scale concurrent topological optimization was described. The combination of topology optimization and additive manufacturing was considered. Finally, the topology optimization of FRC structures which have been resolved in literature are reviewed and the potential research fields requiring more investigation are pointed out. Conclusions. In the article, a comprehensive review of the topology optimization design of FRC structures was presented. The promising way is to combine topology optimization with additive manufacturing techniques. However, these proposed methods may not suitable for other more complex problems, such as bucking stability and natural frequency. Hence, the topology optimization design of complex FRC components under complicated conditions is the main challenge in the future. This can be a new trend in the topology design of FRC structures.

***Keywords**: fiber-reinforced composite structure; additive manufacturing; simultaneous optimization; multi-scale optimization; topology optimization.*

Introduction

In recent years, fiber-reinforced composite (FRC) structures have been widely used in the automotive industry and aerospace engineering due to their high stiffness-to-weight ratio. For example, more than 50 % of the weight of the Airbus A350 XWB is made of composite materials. With the rapid development of additive manufacturing technique, continuous and spatially varying fiber paths are allowed to be used to fabricate FRC structures, which brings considerable design space and freedom for innovative design methods. Nowadays, topology optimization is admitted as an effective tool for lightweight and performance design, and it has been attempted to be used in the design of FRC structures to fully utilize the advantages of composite materials and new manufacturing technologies in recent years.

To date, a lot of studies focused on ply thickness, fiber orientations, and stacking sequence optimization of constant and variable stiffness composite laminates. It has shown that the various structural performances, e.g., structural stiffness, ply strength, local failure load, bucking stability and natural frequency, can be significantly improved by the fiber orientation optimization. The dedicated review work can be found in [1-4]. However, there is almost no dedicated review work on topology optimization of FRC structures, thus is also the motivation of this paper. Topology optimization is to seek the optimal layout of materials in an allowed design region under a given load and boundary conditions. The optimal configuration is the result of iterative processes, which includes the gradual removal of materials in areas with redundant materials and the addition of materials in the areas of structure where needed. In the past decades, topology optimization using isotropic materials has made remarkable progress in both theoretical research and practical application [5, 6]. Nevertheless, topology optimization of FRC structures is only studied in model and theory.

If the change of fiber orientation is ignored, the topology design of FRC structures can be simplified and the distribution of materials can be found by a classical topological method. Since the advantages of FRC can't be fully exploited without considering the material orientation, there are only a few examples in which using only pseudo-density as design variables. Stegmann and Lund [7] studied the topology design of stiffness problem for linear and geometrically nonlinear layered shell structures. Tong et al. [8, 9] proposed a design approach of compliant mechanism with laminated plates based on topology optimization. Dai et al. [10] presented a solution for the optimization of composite laminated plates with design-dependent loads. Hu and Vambol [11] designed the composite wing rib based on the topology optimization method, and the results show that the deformation of the optimized structure can be decreased by more than 20% compared with that of the non-optimized structure under the same material removal rate. The above results showed that the fiber orientation greatly affects the structural performances and topological shape.

In order to make full use of the anisotropic property of FRC, the material layout and fiber angle should be simultaneously designed in topology optimization of FRC. The difficulties and challenges for this kind of problem are as follows: firstly, the fiber orientation design variable may fall into local optima due to the trigonometric transformations; secondly, the computation cost is extremely high due to the large number of design variables, including fiber orientations, fiber and matrix material pseudo-density; thirdly, the iterative optimization process has poor convergence due to coupling between topological changes and fiber angles; fourthly, the complex topological geometry and the high spatial variation of fiber orientation make them hard to fabricate.

In this work, we categorize and compare different optimization problems and approaches in topology design of FRC structures. The review aims to provide a reference for designers to select the most applicable design method to solve given specific FRC structure design problems. For each optimization design methodology, its essence is described first, and then its advantages and shortcomings are discussed. The following sections describe the three kinds of optimization problems for FRC structures, and various optimization cases of FRC structures that have been dealt with in the literature are reviewed.

1. Simultaneous optimization of fiber orientation and structural topology

In the optimization of combining fiber angle and topology for FRC structures, the material pseudo-density is used as the design variable to design the material distribution, which is similar to the classical topology optimization. While the optimization of fiber orientation is a challenging problem. Generally speaking, there are two kinds of fiber orientation optimization methods: continuous fiber orientation optimization method and discrete fiber orientation optimization method. The first method is to select the optimal fiber orientation in a continuous scope of angles, and the latter is to select one of the given candidate fiber orientation as the optimal.

1.1. Continuous fiber orientation optimization method

To optimize the fiber orientation in a continuous scope of angle, a variety of optimization approaches have been proposed in recent years. In general, these existing approaches can be classified into four major classes: analytical method; multi-level optimization method; free material optimization method; specialized method.

1.1.1. Analytical method

To date, there are mainly three analytical methods to obtain the optimal fiber orientation, i.e., the strain-based method [12], the stress-based method [13], and the energy-based method [14]. The strain-based and stress-based methods can adjust the fiber orientation on the basic of the strain and stress state of elements. The analytical method has also been utilized for simultaneous optimization topology and fiber angle [15-18]. Nevertheless, Gea et al. [19] have proved that there are two different optimal orientations when the "repeated global minimum" appears in the strain-based or stress-based methods. In this case, both two methods can't determine the unique optimal material orientation. Therefore, the application scope of those methods is relatively limited. To avoid this shortcoming and improve computational efficiency, Yan et al. [20] proposed a hybrid strain and stress approach to obtain the unique optimal fiber orientation.

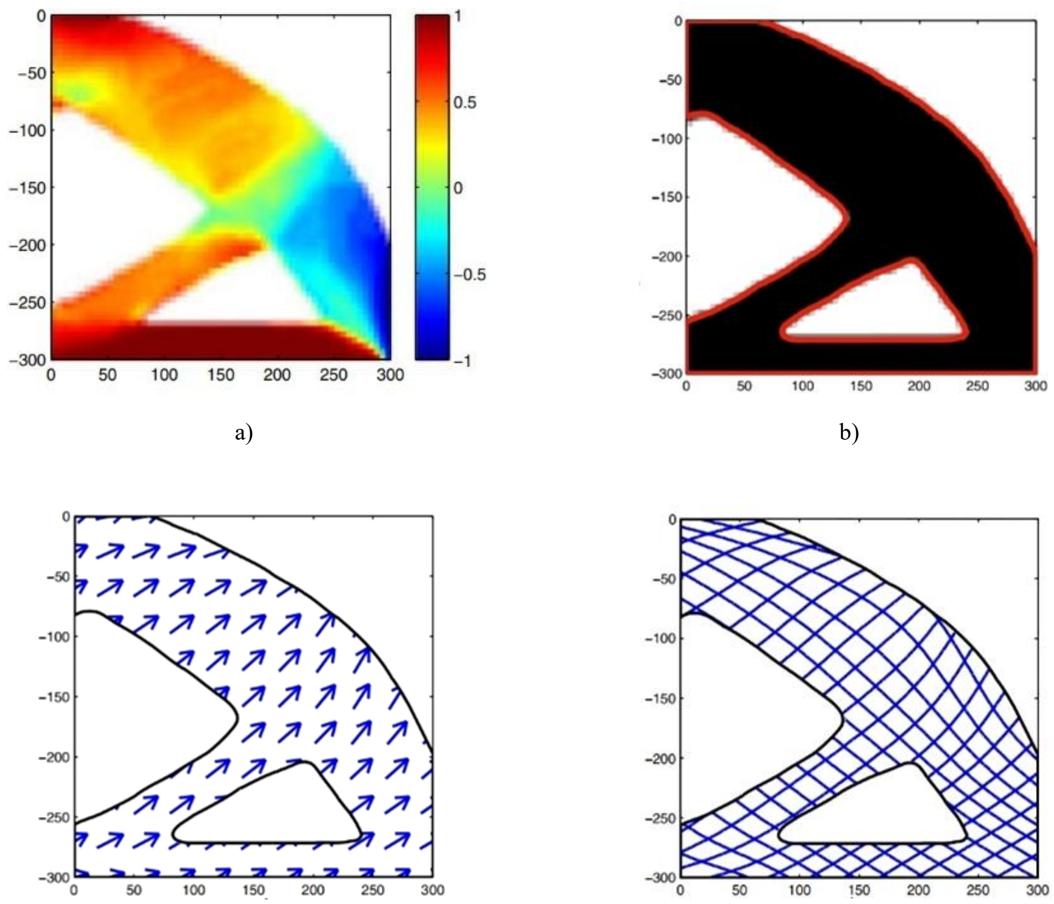
1.1.2. Multi-level optimization method

It is challenging to solve an optimization problem at one level that contains all the variables describing a complex structure. The multi-level optimization method is an effective way to deal with this kind of complex problem. The main idea of this method is to divide the optimization problem into several levels to cut down the complicacy of the problem and therefore improve the efficiency of the algorithm. In most research, the lamination parameters are often regarded as the transitional design variables, and the optimization problem is divided into two independent subproblems. Since lamination parameters are independent of the number of layers, the number of design variables is dramatically reduced. Meanwhile, each subproblem has a quite good convexity, which ensures the global optimal solution. Liu et al. [21] studied the simultaneous optimization of fiber distribution and layup configuration by using the multi-level optimization method. At the first level, the optimal lamination parameters with the minimum compliance were obtained by taking the layer thickness, fiber angle and fiber volume fraction as design variables. At the second level, the optimal lamination parameters were regarded as the design objective, the detailed layup configuration optimization is carried out considering the manufacturing constraints. Peeters et al. [22] studied a simultaneous design problem of structural topology and fiber path of the variable stiffness laminated plates by using a three-step approach. Fig. 1 shows the schematic diagram of this method. Tong et al. [23-25] studied the concurrent design problem of structural topology and fiber orientation for constant-stiffness composite laminated plates based on the multi-level optimization method. However, the Multi-level optimization method has the disadvantage of poor universality. The efficiency and the optimality of the solution of the optimization problem largely depend on the decomposition way. It is tough to determine the appropriate decomposition way for the complex optimization problem.

1.1.3. Free material optimization method

The most straightforward fiber orientation optimization is to use the angle itself as the design variable, and the optimal fiber orientation is solved by gradient-based algorithm [26-28]. However, this strategy will bring the optimization easily to fall into the local minimum, and the result is highly dependent on the initial value of design variables. To overcome the issue of multiple local minima, a more advanced methodology called Free Material Optimization (FMO) [29, 30] method is suggested. It uses the elements of the material elastic tensor as the design variable.

Therefore, it provides the maximum flexibility of the structure and material distribution. The advantage of this method is that it directly deals with the tensor itself, and there is no concept of rotation compared with other three-dimensional angle representations. Compared with using angle as design variable directly, the benefit of the method is that tensor representation may achieve a theoretically optimal structure. Nomura et al. [31] used the Cartesian vector components of the fiber angle as the design variables. Fig. 2 shows the optimized topologies for the short cantilever beam with different lengths, w_c=2, 3, 4. The proposed method supports both continuous angle design and discrete angle design.



a) b)

c) d)

Fig. 1. Schematic diagram of the three-step approach: a) step 1 – determination the optimal laminating parameters; b) step 2 – conversion the results of topological optimization into a geometric description by identifying the material boundaries; c) step 3 – obtaining a fully manufacturable design (fiber angle retrieval); d) step 3 – obtaining a fully manufacturable design (fiber path retrieval) [22]

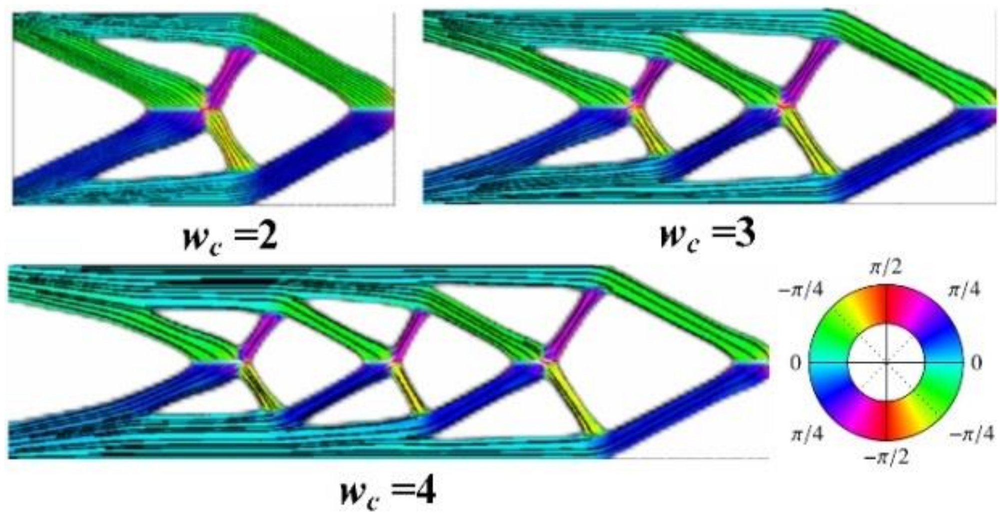


Fig. 2. Topological optimization for the short cantilever beam with different lengths, w_c=2, 3, 4 [31]

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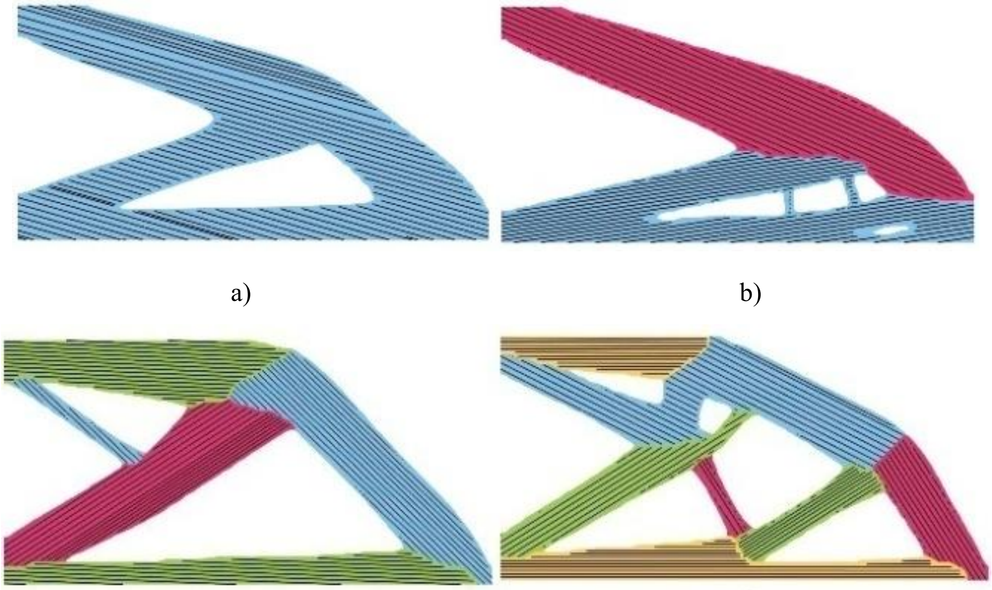
Lee et al. [32] appropriately extended upon the method [31] for the functionally graded FRC materials. A three-step consecutive optimization method was given, which involves, at first, structural topology of the matrix material, and thereafter, the fiber material distribution and angle, and finally, continuous and manufacturable fiber angle. However, the sequential optimization process may sacrifice the exploration of new topology optimization for anisotropic composites material.

Ranaivomiarana et al. [33] proposed a novel method for the concurrent topological optimization. The invariants of elastic tensors of composite materials were parameterized by the polar method. Zhou et al. [34, 35] proposed a design method for simultaneous topology and unidirectional (or curvilinear) fiber orientation. Fig. 3 shows the topological optimization with different number of components. Subsequently, the FMO method is further extended to solve three-dimensional problem [36, 37]. It should be noted that the approach may achieve optimal structure in theory, but it is usually not feasible in physics.

1.1.4. Specialized method

In this category, some specialized methods were developed for concurrent topology and fiber path optimization. For example, in order to deal with the local optima issue, Luo et al. [38] proposed an ingenious discrete-continuous parameterization (DCP) method. In the DCP method, the initial searching interval of fiber angle variable was divided into several sub-intervals averagely at first. Then, the initial continuous fiber angle optimization problem was transformed into a discrete sub-interval selection problem and a continuous fiber angle optimization problem in sub-interval. The discrete sub-interval selection problem can be transformed into a discrete material optimization problem, which can be optimized by the DMO etc. discrete material method. However, the main shortcoming of the DCP method is that only trial and error method can be used to determine the number of sub-intervals are needed in advance for a given problem.

Setoodeh [39] presented a novel cellular automata (CA) method for the combination design of fiber angle and topology for laminated composite structures. The numerical calculation costs can be greatly reduced by using massively parallel processor machines. However, the drawback of this method is that it can only be used to optimize a single layer, and there is no constraints on the change of fiber angle between adjacent points.



a) b)

c) d)

Fig. 3. Topological optimization with different number of components (different colors represent different components, and the line directions indicate the material orientations):
a) one component; b) two components; c) three components; d) four components [34]

While the results show the possibilities of simultaneous optimization of fiber angle and structural topology, the resulting fiber angle distribution varies greatly, which may limit the manufacturability of FRC structures. Fig. 4 shows the optimal topology and color-coded fiber angles with 50% volume fraction constraint. Li et al. [40] proposed a full-scale FRC structure topology optimization method to enable the simultaneous design of structure topology, continuous fiber path and its morphology (i.e., fiber thickness, volume and spacing).

Fig. 5 shows the compliance minimization problems of a Michell beam. Almost parallel and equidistant fibers are distributed in every part of the solid domain and basically along the direction of principal stress. The resulting design basically meets the requirements of engineering practice.

1.2. Discrete fiber orientation optimization method

The second class method for solving the fiber optimization problem is to choose from a discrete set of candidate fiber angles (for example, 0°, ±45°, 90° only). Due to manufacturability reasons, these prescribed discrete fiber angles are often preferred in the automotive and aerospace industries. To date, various optimization methods have been proposed and can be divided into two categories: 1) multiphase materials method; 2) hybrid method.

1.2.1. Multiphase materials method

Based on the ideology of multiphase materials topology optimization, Stegmann et al. [41] proposed the Discrete Material Optimization (DMO) method to realize the topology optimization of FRC structure. In this method, the fiber orientation was to choose one of the given finite number of angles as the optimal direction. The weighted sum of each candidate elastic tensor was taken as the effective elastic tensor, and the weights were set as the design variable. Niu et al. [42] studied the vibro-acoustic optimization of FRC structure by using the DMO method, and the design objective was to minimize the sound radiation. Hvejsel et al. [43] applied the DMO method to realize a simultaneous optimization of discrete fiber angle and structural topology for FRC structure.

Lund and Stegmann [44, 45] investigated the optimization problem of maximizing the stiffness, the natural eigen frequency and the buckling load factor of FRC structures. Sørensen and Lund [46] studied the large-scale topology and thickness optimization of FRC structures by using DMO method, and considered certain manufacturing constraints to achieve industrial relevance. As is known, the total number of design variables in DMO method is the number of candidate discrete fiber angles multiplied by the number of elements.

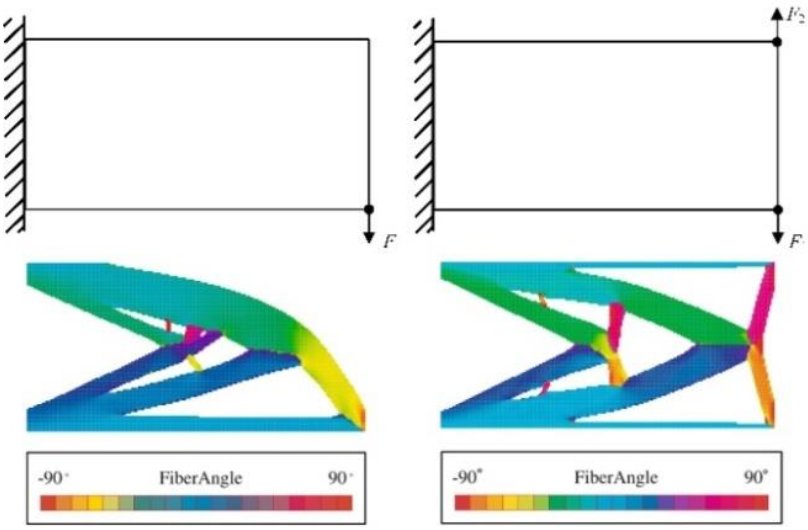


Fig. 4. Optimal topology and fiber angle distribution of the cantilever beam [39]

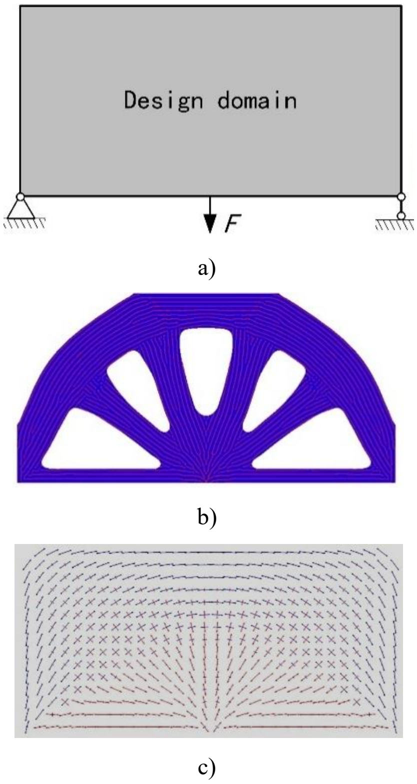


Fig. 5. Process of topological optimization: a) design domain and boundary condition of Michell beam; b) optimized topology and fiber path (the white, red and blue color denote the void, fiber material and matrix material, respectively); c) the direction of corresponding local principal stress (the blue and red lines denote compression and tension, respectively, and the length and direction of arrows represent the magnitudes and directions of the principal stress in each sub-region) [40]

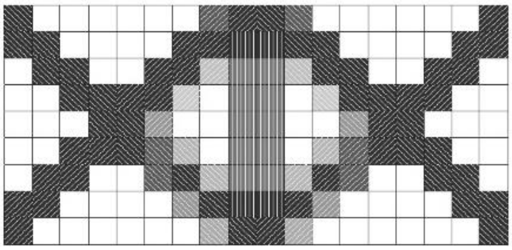
Hence, when the number of elements or candidate fiber angles is large, the scale of the optimization problem mightenlargea lot. This is a critical shortcoming of the DMO method. To solve the problem of the large number of design variables in DMO method, several variants were proposed later to reduce the degrees of design freedom and improve the computation efficiency. Bruyneel [47] proposed a shape function and parameterization (SFP) method. Based on the shape function of the finite element method, the material interpolation method constructed by the SFP method can effectively reduce the number of design variables. However, when the number of material phases is large, it is difficult to determine the shape function of the material interpolation method. To address this drawback, Gao et al. [48, 49] generalized the SFP method into Bi-value Coding Parameterization (BCP) method. The BCP method gives the interpolation method of any number of candidate fiber angles, and the candidate fiber angles can be parameterized with less design variables. In order to improve the convergence rate and obtain clear fiber ply angle choices, Duan et al. [50] proposed an improved Heaviside Penalization of Discrete Material Optimization (HPDMO) method by introducing continuous penalty strategy and Heaviside penalty function into the traditional DMO method. In order to extend the DMO method, Luo et al. [51] utilized the Heaviside projection method (HPM) to control the minimum length scale of fiber orientation. Sohouli [52] proposed a novel Decoupled Discrete Material Optimization (DDMO) method to optimize the thin-walled laminated composite structures. Fig. 6 presents the comparison between the optimal results of the two approximation methods in DDMO and the results of common DMO, and the study shows that the DDMO method is more robust and efficient compared to the DMO method. Because the topology optimization of FRC structures based on multiphase material method can be solved efficiently by gradient-based algorithms such as Method of Moving Asymptotes (MMA), Sequential Quadratic Programming (SQP).

Therefore, the advantage of the multiphase material method is that it is suitable for solving large-scale optimization problems. However, it is difficult to introduce manufacturing constraints into the optimization model, and numerical instability is easy to occur in the optimization process. So the design result often shows a discontinuous fiber path, which causes stress concentration and manufacturing difficulty.

1.2.2. Hybrid method

The hybrid method usually combines two or more different types of optimization approaches to benefit from the merits of them. In general, the hybrid method can cut down the size of the optimization problem, obtain faster convergence speed, produce a global optimum or make the optimization method more robust.

Hansel and Becker [53] proposed a stressed-based heuristic algorithm to design the laminated composite structures with minimal weight. Based on the same idea and methodology above, Hansel et al. [54] proposed to use the genetic algorithm (GA) to delete all the unnecessary layers and elements. The optimal topology shape and material distributions of a cantilever plate are shown in Fig. 7.



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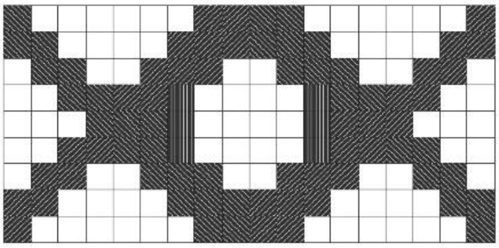

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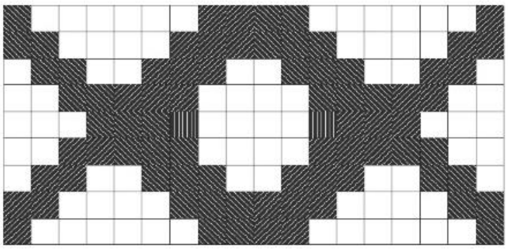

c)

Fig. 6. Optimal fiber angle and topology for the clamped-clamped beam (white: void; black: GFRP; gray: not converged): a) convergence of material for DMO; b) convergence of material for Diagonal Quadratic approximation; c) convergence of material for exponential approximation [52]

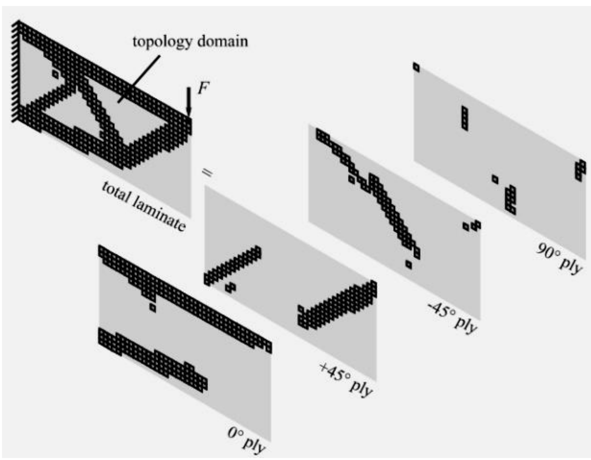

Fig. 7. The optimal topology shape and material distributions of the cantilever plate [54]

In order to solve the optimization problem with both continuous and discrete design variables, a hybrid multilevel approach for the topology optimization design of constant-stiffness laminated plates was proposed by Hu et al. [55]. At the first level, the MMA algorithm was used to get the optimal lamination parameters and structural topology, and then the IDSA (Improved Direct Simulated Annealing) algorithm was adopted to search for the optimal discrete fiber angle at the second level.

2. Multi-scale concurrent topology optimization

The pure structural optimization design or material design can improve the performance of the structure and achieve lightweight design, but it is also difficult to meet the technical needs of the current market. Exploring a more effective lightweight design method has become an important topic in automotive, aviation, aerospace and other fields. In recent years, multi-scale optimization has attracted more and more attention because of its larger design space and degree of freedom. Gao et al. [56] proposed a modified two-scale optimization model for the concurrent design of material microstructure orientation, macrostructure and microstructure topology. Coelho et al. [57] proposed a multi-scale topology optimization model for the design of bi-material composite laminates. The material model wasno longer a porous material, but it interpolates between two material components, matrix phases and reinforcing fibers. Yan et al. [20] proposed a method for simultaneous design of structural topology, material microstructure topology and material orientation based on the bi-direction evolutionary structural optimization (BESO) method. This methodology can further improve the stiffness of the structure. Fig. 8 shows the macro and micro topological structures and optimal fiber orientation for the cantilever beams.

On this basis, the concurrent optimization method was applied to the structural dynamic design problem to further improve the fundamental frequency of structures [58]. Kim et al. [59] applied the multi-scale concurrent topology optimization method to designing functionally

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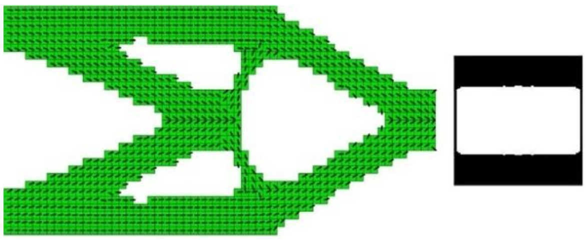
graded FRC structures. Because the multi-scale design approach can find the optimal result in a larger range, the design result is more likely better than that of single-scale structure.



a) b)

Fig. 8. The macro and micro topological structures and optimal fiber orientation for the cantilever beams [20]: a) topology of macrostructure (short black lines in each elements indicates the material orientation); b) topology of material microstructure

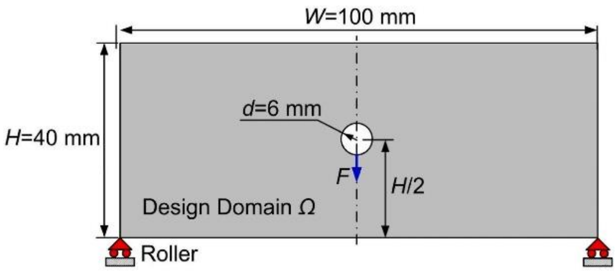
3. Combination of topology optimization and additive manufacturing

Currently, the FRC structures can be manufactured by open-mold and close-mold processes. The open-mold processes include spray lay-up, wet lay-up, vacuum bagging, filament winding, pultrusion, autoclave molding. The close-mold processes include compression molding and injection molding. These processes have some common shortcomings, i.e., high production cost, long cycle time, and difficulty to manufacture some complex and hollow structures. Hence, using conventional molding processes, there are obstacles in manufacturing the complex FRC topologies. While the additive manufacturing technique offers possible to avoid these limitations.

Additive manufacturing, also known as 3D printing, is a latest revolutionary transformation of design and manufacturing technique gaining great popularity in aerospace and automotive. In recent years, the FRC has been widely used in additive manufacturing technology because of its advantages in improving the mechanical properties of conventional isotropic parts [60]. Additive manufacturing techniques can not only construct complex hollow structure of FRC but also shorten the design and manufacturing cycle, thus reducing production costs.

It is well known that due to the anisotropy of the FRC, the deposition path significantly affects the structural properties. If the deposition path is not considered, only the non-optimal solution can be obtained. To overcome this issue, Liu and Yu [61] proposed a novel approach for concurrent optimization of deposition path orientation and the structural topology for additive manufactured parts. The concurrent optimization process was implemented based on a level-set method. However, the main disadvantage of this approach is that in order to make the fiber line fill the optimized area completely, some acute corners are inevitably appear, which leads to stress concentration and manufacturing difficulty. Subsequently, Papapetrou et al. [18] proposed the equally-spaced method, the offset method and the streamline method for fiber infill pattern to achieve the continuous fiber path and ensure manufacturability after the topology optimization. The energy-based method and the level-set based method were used to obtain the optimal orientation, respectively. Nevertheless, the fiber print paths generated by these three infill patterns have their own defects. Later, a load-dependent 3D print path planning method [62] was proposed to resolve the above issues. Li et al. [63] proposed a path-designed 3D printing method to manufacture the complex FRC structures considering the anisotropic property and load transmission path of the fiber. Jiang et al. [64] proposed a topology optimization method for continuous fiber angle optimization, which computed the optimal fiber layout and orientation for additive manufacturing structures. Chandrasekhar et al. [65] focused on the simultaneous optimization of the structure topology, build direction, and fiber orientation of short fiber reinforced polymers additive manufacturing components. Chen et al. [66] developed a multidisciplinary design method that combing topology optimization design, fiber reinforcement technique and additive manufacturing for the carbon FRC structures (Fig. 9).

Fig. 9, a gives the design region and boundary conditions of a three-point-bending beam. The topologically designed and actual fiber placement path for additive manufacturing is shown in Fig. 9, b. The continuous fiber placement paths for additive manufacturing were defined based on the average load transmission trajectories within the optimal topology.



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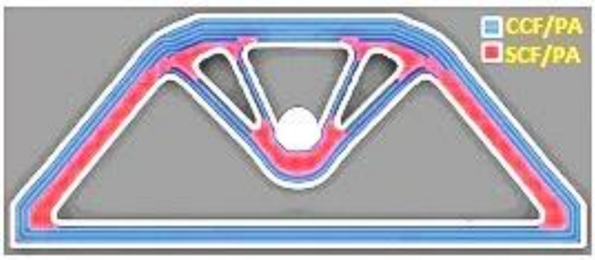

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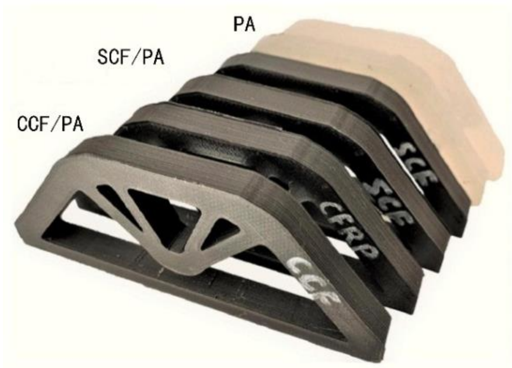

c)

Fig. 9. Process of topological optimization for additive manufacturing: a) design region and boundary conditions of a three-point-bending beam; b) topologically designed and actual fiber placement path for additive manufacturing; c) additive manufacturing specimens with different materials [66]

To ensure continuous printing, it is inevitable that there were enclosed areas without continuous carbon fiber (CCF) filament. Hence, the short carbon fiber (SCF)/ pure polyamide (PA) was used to fill in those enclosed areas. Using the same additive manufacturing method, the three-point-bending specimens made of different materials were printed accordingly, as shown in Fig. 9, c. However, this study did not solve the anisotropic behavior of continuous FRC in the process of topology optimization. To further reduce the potential weight, both the topology and the fiber orientation should be concurrently considered in further research.

Conclusion

In this work, a comprehensive review of the topology optimization design of FRC structures is presented. Particularly, the topology optimization problems of FRC structure are classified into three groups, i.e., simultaneous optimization of fiber angle and structural topology, multi-scale concurrent topology optimization, and the combination of topology optimization and additive manufacturing. The optimization methods dealing with continuous fiber orientation are categorized into four categories: analytical method, multi-level optimization method, free material optimization method and specialized method. How to avoid the locally optimal solution is a difficult problem in these methods. On the other hand, the optimization methods dealing with discrete fiber orientation are the multiphase materials method and hybrid method. Due to the limited number of candidate fiber orientations, the performance of structure is limited to a certain extent. A promising work is to combine topology optimization with additive manufacturing technique. In the current 3D printing technology, how to print continuous FRC with complex shape and excellent mechanical properties is still a huge challenge. Besides, the most used design objectives are to maximize the stiffness and minimize the weight of two-dimensional simple structural. However, these proposed methods may not suitable for other more complex problems, such as bucking stability and natural frequency. Hence, the topology optimization design of complex FRC components under complicated conditions is the main challenge in the future. This can be a new trend in the topology design of FRC structures.

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ОГЛЯД ТОПОЛОГІЧНОЇ ОПТИМІЗАЦІЇ ШАРУВАТИХ КОМПОЗИТНИХ КОНСТРУКЦІЙ

Чжен Ху

Вимоги, які пред'являються до елементів конструкції в аерокосмічній галузі це міцність, жорсткість та легкість і застосування методу топологічної оптимізації при проектуванні таких конструкцій є досить ефективним. Як один з найбільш концептуальних і перспективних методів оптимізації конструкції, метод топологічної оптимізації спрямований на пошук оптимального взаємного розташування шарів при заданому

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навантаженні і граничних умовах у дозволеній області проектування. Таким чином, об'єктом вивчення в наданій статті є методика топологічної оптимізації авіаційних конструкцій. Метою є аналіз існуючих підходів, алгоритмів, а також реалізація в прикладних задачах методу топологічної оптимізації в аерокосмічній галузі. Завдання – описати існуючі різні підходи, методи, особливості та напрямки досліджень топологічної оптимізації, а також вивчити можливість застосування в процесі виготовлення композитних конструкцій. В ході дослідження були отримані наступні результати. Пояснюються і порівнюються методи оптимізації, а також обговорюються переваги та обмеження кожного підходу. Були розглянуті та проаналізовані різні способи одночасної оптимізації орієнтації волокна і структурної топології. Описана можливість одночасної багатомасштабної топологічної оптимізації. Було розглянуто поєднання топологічної оптимізації та адитивного виробництва. Нарешті, розглядається топологічна оптимізація композитної конструкції, яка була вирішена в різних джерелах, і вказуються потенційні області дослідження, що вимагають додаткових досліджень. Висновки. У статті пропонується комплексний огляд топологічної оптимізації спроектованої композитної конструкції. Перспективним напрямком є поєднання топологічної оптимізації з методами адитивного виробництва. Однак, в разі, більш складних завдань, таких як стійкість і власна частота, запропоновані методи можуть бути неспроможні. Отже, топологічна оптимізація композитних конструкцій за умови складного навантаження є основним завданням в майбутньому. Це може бути новою тенденцією в проектуванні топологічних композитних конструкцій.

Ключові слова: шаруватий композит; адитивне виробництво; одночасна оптимізація; багато-масштабна оптимізація; топологічна оптимізація.

ОБЗОР ТОПОЛОГИЧЕСКОЙ ОПТИМИЗАЦИИ СЛОИСТЫХ КОМПОЗИТНЫХ КОНСТРУКЦИЙ

Чжен Ху

Требования, которые предъявляются к элементам конструкции в аэрокосмической отрасли это прочность, жесткость и легкость и применение метода топологической оптимизации при проектировании таких конструкций является достаточно эффективным. Как один из наиболее концептуальных и перспективных методов оптимизации конструкции, метод топологической оптимизации направлен на поиск оптимального взаимного расположения слоев при заданной нагрузке и граничных условиях в разрешенной области проектирования. Таким образом, **объектом** изучения в представленной статье является методика топологической оптимизации авиационных конструкций. **Целью** является анализ существующих подходов, алгоритмов, а также реализация в прикладных задачах метода топологической оптимизации в аэрокосмической области. **Задачи** – описать существующие различные подходы, методы, особенности и направления исследований топологической оптимизации, а также изучить возможность применения в процессе изготовления композитных конструкций. В результате исследования были получены следующие **результаты**. Кратко объясняются и сравниваются методы оптимизации, а также обсуждаются преимущества и ограничения каждого подхода. Были рассмотрены и проанализированы различные способы одновременной оптимизации ориентации волокна и структурной топологии. Описана возможность одновременной многомасштабной топологической оптимизации. Было рассмотрено сочетание оптимизации топологии и аддитивного производства. Наконец, рассматривается топологическая оптимизация композитной конструкции, которая была решена в различных источниках, и указываются потенциальные области исследования, требующие дополнительных исследований. **Выводы**. В статье представлен всесторонний обзор топологической оптимизации спроектированной композитной конструкции. Перспективным направлением является сочетание топологической оптимизации с методами аддитивного производства. Однако, в случае, более сложных задач, таких как устойчивость и собственная частота, предложенные методы могут быть не применимы. Следовательно, топологическая оптимизация композитных конструкций при условии сложного нагружения является основной задачей в будущем. Это может быть новой тенденцией в проектировании топологических композитных конструкций.

Ключевые слова: слоистый композит; аддитивное производство; одновременная оптимизация; многомасштабная оптимизация; топологическая оптимизация.

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