CURVED GRID STIFFENER LAYOUT OPTIMIZATION FOR REDUCING THERMALLY INDUCED OUT-OF-PLANE DEFLECTION OF COMPOSITE STRUCTURES

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ABSTRACT

Grid-stiffened composite structures are gaining increasing research attention due to its exceptional properties in specific stiffness, strength, and buckling resistance. If these structures are fabricated using additive manufacturing (AM) or automatic fibre placement (AFP), they inevitably need to withstand the influence of thermal residual stress and introduce unwanted out-of-plane deformation. In this work, we extend the previous proposed streamline stiffener patch optimization (SSP)) method to the cases under thermal loading in order to reduce the thermally induced out-of-plane deflection by optimally designing the curved stiffener paths. A square panel is used here as a numerical example to show the effectiveness of the proposed method.

1 INTRODUCTION

Grid-stiffened composite structures are attaching more and more attentions from both academia and industry due to their highly efficient open structural form with lightweight, high damage tolerance and high stability [1-3]. A conventional design has straight stiffener paths and is generated by periodically repeating an isogrid, orthogrid or anglegrid. As the development of additive manufacturing (AM) and automated fiber placement (AFP) technology, it is manufacturable for curved grid stiffeners using fiber-reinforced composite material. The work by Paschero and Hyer [4] shows that the axial buckling can be effectively enhanced by using elliptical lattices. However, it is quite challenging to design curved grid stiffener layout. Topology optimization using pseudo densities [5-7] and shape optimization using the stiffener path parameters [8, 9] are two common ways to deal with stiffener path optimization. However, topology optimization normally provides a concentrated distribution of bulk materials without clear grid stiffener intersection patterns, which can't make advantage of the high damage tolerance of grid stiffeners due to the redundancy of multiple stiffeners. Shape optimization is limited to the usage of a fixed stiffener topology. Since both the stiffener layout (topology) and the stiffener path (clear stiffener shape) are required, the problem of generating a curved grid layout can't be directly solved by the classical topology optimization or shape optimization methods. Besides, the equivalent stiffness of trusses is embedded into the background mesh to optimize the bar connections [10].

The authors and collaborators have proposed a Streamline Stiffener Path Optimization (SSPO) [11, 12] to use streamline functions to define curved stiffener paths and also a global/local model to optimize a topology varying grid layout on an unstiffened global model with a fixed mesh. The global model is established with the elemental material properties obtained from homogenization. When the grid stiffeners are sparsely distributed, the optimization effect using SSPO may be not effective. A data-driven model using Principal Component Analysis (PCA) [13] is proposed to do detailed design based on the optimal design from SSPO. Numerical examples using both SSPO and the data-driven model show the effectiveness of curved grid stiffeners.

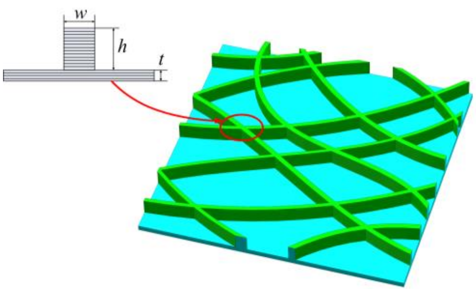
Due to the geometry complexity of curved grid-stiffeners, they can be manufactured using AM or AFP technology, which both require rapid heat release and cooling to achieve effective bonding between layers of composite materials. The thermally induced residual stresses will lead to out-of-plane distortion even before loading. In this paper, we are going to extend the published research work of SSPO to the applications of reducing the thermally induced out-of-plane deflection.

2 STREAMLINE Stiffener Path Optimization (SSPO)

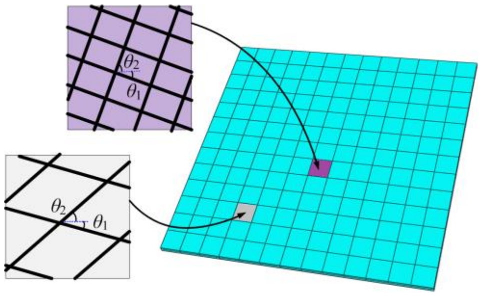
2.1 Curved grid stiffened composite structures and the global/local modeling strategy

We propose the concept of non-uniform curved grid stiffened composite structures (NCGCs) using curved grid stiffener paths and non-periodic distribution, as illustrated in Fig. 1(a), to explore the high efficiency of these novel structural types.

To cope with the optimization challenge, a global/local model is proposed to deal with the optimization on a global unstiffened model with the material properties are calculated from homogenization of the local grid distribution, as illustrated in Fig. 1(b).



(a)



(b)

Figure 1. The concept of NCGCs and the global/local modelling strategy. [1]

The strain energy of a representative cell configuration (RCC) is expressed as:

$$\Pi = \frac{1}{2}\mathbf{u}^T\mathbf{K}\mathbf{u} - \lambda^T(\mathbf{L}\mathbf{u} - \Upsilon\boldsymbol{\varsigma}_0) \tag{1}$$

where $\mathbf{u}$ is the displacement vector, and $\mathbf{K}$ is the stiffness matrix. $\boldsymbol{\varsigma}_0$ is strain and curvature vector with the subscript denoting the values at the mid plane. $\mathbf{L}$ and $\boldsymbol{\Upsilon}$ are the constraint matrices to coupling the displacement and strains, respectively, between the periodic boundaries.

At the same time, the strain energy of a RCC at the homogenized global model is expressed as:

$$\Pi = \frac{1}{2}\int_{\Omega} \boldsymbol{\varsigma}_0^T\,\bar{\mathbf{C}}\boldsymbol{\varsigma}_0 d\Omega \tag{2}$$

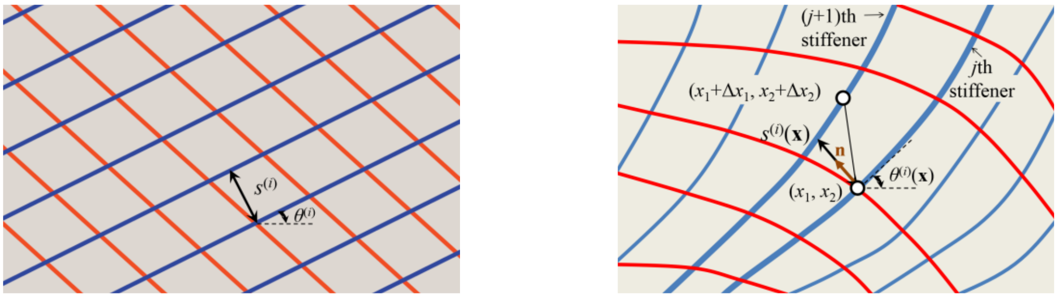
where $\bar{\mathbf{C}}$ is the equivalent material properties a RCC at the homogenized global model, which is calculated under the assumption of the same strain energy in the discrete model and the homogenized model with expression as follows.

$$\bar{\mathbf{C}} = \frac{1}{J}\mathbf{U}^T\mathbf{K}\mathbf{U} \tag{3}$$

where J is determinant of the Jacobin matrix of a RCC and $\mathbf{U}$ is the matrix made up of the displacement vector under unit strain.

2.2 Streamline functions for curved stiffener path definition

The grid stiffeners can be firstly classified into different groups with similar stiffener path orientations, as illustrated in Fig. 2 using blue and red colors to distinguish.



(a) Straight stiffener paths (b) Curved stiffener paths

Figure 2. Illustration of the stiffener path distribution of grid-stiffener structures. [1]

A streamline function for one stiffener path is defined as:

$$\varphi^{(i)}(x_1, x_2) = j \tag{4}$$

where the subscript (i) denotes the stiffener coming from the ith family, and j is an integer as the stiffener sequential number. Thus, its neighboring path is defined as:

$$\varphi^{(i)}(x_1 + \Delta x_1, x_2 + \Delta x_2) = j + 1 \tag{5}$$

where $(\Delta x_1, \Delta x_2)$ is the coordinate difference between the points on two different stiffeners. The left item of Eq. (4) can be expanded by using the Taylor expansion as:

$$\varphi^{(i)}(x_1 + \Delta x_1, x_2 + \Delta x_2) = \varphi^{(i)}(x_1, x_2) + \Delta x_1 \frac{\partial \varphi^{(i)}}{\partial x_1} + \Delta x_2 \frac{\partial \varphi^{(i)}}{\partial x_1} + \mathrm{O}(\Delta \mathbf{x}^2) \tag{6}$$

By combining Eqs. (4-6), we can obtain:

$$\Delta \mathbf{x} \cdot \nabla \varphi^{(i)} = 1 \tag{7}$$

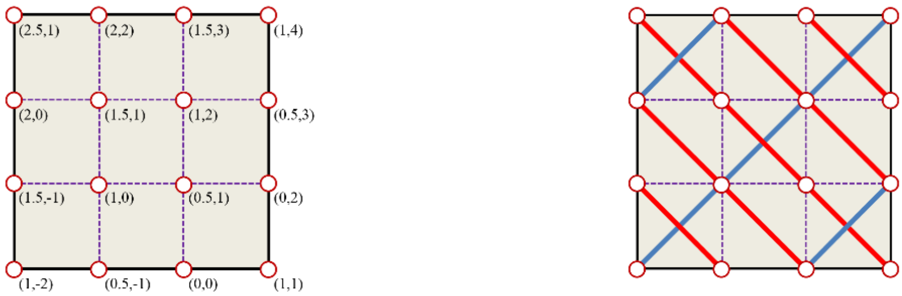
From the illustration in Fig. 2, the spacing between two stiffener paths can be expressed as:

$$s^{(i)} = \Delta \mathbf{x} \cdot \mathbf{n}^{(i)} = \frac{1}{\left\| \nabla \varphi^{(i)} \right\|} \tag{8}$$

At the same time, the stiffener orientations can be obtained using the following equations:

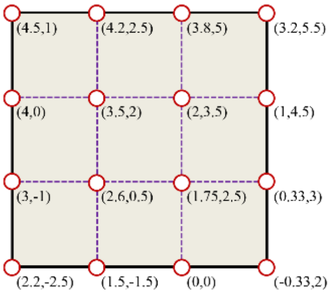
$$\begin{bmatrix} \sin \theta^{(i)} \\ -\cos \theta^{(i)} \end{bmatrix} = (-1)^i \mathbf{n}^{(i)} = (-1)^i \frac{\nabla \varphi^{(i)}}{\left\| \nabla \varphi^{(i)} \right\|} \tag{9}$$

Stiffener paths from the same group can be defined by the streamline function values (SFVs) attached to nodes on the global model. Nodes with the same integer SFV are located at the same stiffener path. Neighboring stiffener paths have the neighboring SFVs. The non-integer SFVs mean that the points are located between two neighboring stiffener paths.By reversely retrieving the stiffener paths, we can obtain a continuously distributed stiffener paths using a fixed number of SFVs.

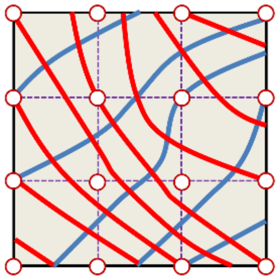


Distribution of SFVs Stiffener paths

(a) Straight grid stiffener paths



Distribution of SFVs


Stiffener paths

(b) Curved grid stiffener paths

Figure 2. Illustrations of straight and curved grid stiffener paths defined by streamline functions. [1]

2.3 Thermally induced out-of-plane deflections

When grid-stiffened structures are manufactured by AM or AFP, grids will be under a different thermal loading from the skin. The thermally induced residual stress will lead to out-of-plane deflections of the structure. To reduce this displacement, we extend the SSPO method to under thermal loading.

Under thermal loading both the displacement and the strain are made up of two parts: the mechanical part and the thermal part.

$$\mathbf{u} = \mathbf{u}_M + \mathbf{u}_T \tag{10}$$

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_M + \boldsymbol{\varepsilon}_T \tag{11}$$

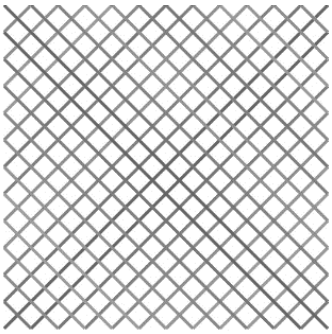
The strain energy can be calculated by substituting the above equation to the expression of the strain energy as below.

$$\Pi = \frac{1}{2}\mathbf{u}_M^T\mathbf{K}\mathbf{u}_M \tag{12}$$

Thus, the effective coefficient of thermal expansion introduced by the thermal residue stress can be derived by combining Eq. (12) with Eqs. (1) and (2).

3 A NUMERICAL EXAMPLE

When the skin and grid stiffeners are built from different materials, the thermal residual stress will lead to a bigger deflection. A numerical example with a composite skin and Aluminum grids under uniaxial compression is used here to illustrate the effect of optimizing the curved grid layout. As illustrated in Fig. 3, using optimal curved grid layouts, the thermally induced out-of-plane deflection is reduced by 25% compared to that of the initial straight grid layout. It is noticeably that both the structural stiffness and the structural weight are included in the optimization as design constraints to ensure the same structural load carrying capability at the given weight as the original structures with initial straight grid stiffeners.


(a) Initial straight grid stiffener layout

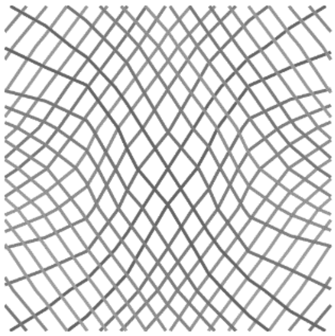

(b) Optimal curved grid stiffener layout

Figure 3. Illustration of initial straight and optimal curved grid stiffener paths for minimizing the thermally induced out-of-plane deflections.

4 CONCLUSION

The optimization of grid stiffener paths under thermal loading is discussed here. The method is developed based on the method of streamline stiffener path optimization (SSPO) for designing curved stiffener layout. A global & local model is established with the analysis is implemented on the global model with a fixed mesh and the local models will provide equivalent material properties for the global model. A numerical example of a square panel with an initial ±45o grid layout is provide to demonstrate the effectiveness of the proposed method in reducing the thermal-induced out-of-plane deflections.

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REFERENCES

[1] Huybrechts SM, Hahn SE, Meink TE. Grid stiffened structures: a survey of fabrication, analysis and design methods, in: Proceedings of the 12th international conference on composite materials (ICCM/12), 1999.

[2] Shroff S, Acar E, Kassapoglou C. Design, analysis, fabrication, and testing of composite grid-stiffened panels for aircraft structures, *Thin-Walled Structures* 119 (2017) 235–246.

[3] Hu Y, Li WX, An XY, Fan HL. Fabrication and mechanical behaviors of corrugated lattice truss composite sandwich panels, *Composites Science and Technology* 125 (2016) 114–122.

[4] Paschero M, Hyer MW. Improvement of axial buckling capacity of elliptical lattice cylinders, *AIAA Journal* 49 (2) (2011) 396–410.

[5] Wang W, Zhu JH, Zhang WH, Li SY, Kong J. Concurrent topology optimization design of structures and non-uniform parameterized lattice microstructures, *Structural and Multidisciplinary Optimization* (2018) 1–16.

[6] Wang Y, Zhang L, Daynes S, Zhang H, Feih S, Wang MY, Design of graded lattice structure with optimized mesostructures for additive manufacturing, *Materials & Design* 142 (2018) 114–123.

[7] Xia L, Breitkopf P. Recent advances on topology optimization of multiscale nonlinear structures, *Archives of Computational Methods in Engineering* 24 (2) (2017) 227–249.

[8] Mulani SB, Locatelli D, Kapania RK. Grid-stiffened panel optimization using curvilinear stiffeners, *AIAA paper* (2011-1895).

[9] Wang B, Tian K, Zhao H, Hao P, Zhu T, Zhang K, Ma Y. Multilevel optimization framework for hierarchical stiffened shells accelerated by adaptive equivalent strategy, *Applied Composite Materials* 24 (3) (2017) 575–592.

[10] Wei P, Ma HT, Wang MY. The stiffness spreading method for layout optimization of truss structures, *Structural and Multidisciplinary Optimization* 49 (4) (2014) 667–682.

[11] Wang D, Abdalla MM, Wang ZP, Su Z. Streamline stiffener path optimization (SSPO) for embedded stiffener layout design of non-uniform curved grid-stiffened composite (NCGC) structures. *Computer Methods in Applied Mechanics and Engineering*. 2019 Feb 1;344:1021-50.

[12] Wang, D., Abdalla, M. M., & Zhang, W. (2018). Sensitivity analysis for optimization design of non-uniform curved grid-stiffened composite (NCGC) structures. Composite Structures, 193, 224-236.

[13] Wang D, Yeo SY, Su Z, Wang ZP, Abdalla MM. Data-driven streamline stiffener path optimization (SSPO) for sparse stiffener layout design of non-uniform curved grid-stiffened composite (NCGC) structures. *Computer Methods in Applied Mechanics and Engineering*. 2020 Jun 15;365:113001.