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Tailoring the optimal load-carrying efficiency of hierarchical stiffened shells by competitive sampling

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ABSTRACT

The hierarchical stiffened shell is a promising aerospace structure configuration with high load-carrying capacity, however, it is challenging to fully explore its optimal load-carrying efficiency. Therefore, a bi-level optimization framework is proposed for hierarchical stiffened shells. In the first level of the optimization framework, a parallel computing numerical-based smeared stiffener method (NSSM) is first introduced for the fast prediction of critical buckling load and mode, by combining the numerical implementation of asymptotic homogenization (NIAH) method with the Rayleigh-Ritz method. Then, a large-scale Latin hypercube sampling (LHS) is performed in the entire design space based on NSSM, and a set of competitive sampling points is collected from the Pareto front of LHS results according to a screening criterion of load-carrying efficiency. In the second level, a surrogate-based optimization using radial basis function (RBF) technique is performed based on generated competitive sampling points with high load-carrying efficiency. Finally, detailed comparisons between optimal results of the proposed optimization method based on the competitive sampling method and the traditional surrogate-based optimization method based on the RBF technique and the LHS sampling method are made from the viewpoint of computational efficiency and global optimizing ability. Spending an approximate computational time, the optimal buckling result of the proposed method increases by 23.7% than that of the traditional method. In order to achieve an approximate global optimization result, the proposed method is able to reduce the computational time by 74.4% than the traditional method. By evaluating competitive sampling results, it can also be concluded that the partial global buckling mode and global buckling mode are most dominant buckling modes for hierarchical stiffened shells with the thick skin and closely-spaced stiffeners, which are prone to obtain a higher load-carrying efficiency.

1. Introduction

Owing to the high specific strength and stiffness, stiffened shells have been widely used in aerospace engineering [1,2]. Under the axial compression loading condition, buckling is the major failure mode for stiffened shells. In order to improve the load-carrying capacity of stiffened shells, diverse stiffener patterns have been developed [3–8], including isogrid stiffeners, curvilinear stiffeners, orthogrid stiffeners, Kagome stiffeners, Omega stiffeners, etc. Another promising stiffener pattern is hierarchical stiffeners, which are composed of major stiffeners (in larger stiffener size) and minor stiffeners (in smaller stiffener size). Based on numerical and experimental methods, Quinn et al. [9–11] and Houston et al. [12] studied the excellent mechanical performance of hierarchical stiffened panels by comparison against traditional stiffened panels with the same weight. The low imperfection sensitivity of hierarchical stiffened shells was verified by Wang et al. [13], which indicates that the hierarchical stiffened shell is a more robust and safe design against imperfections than the traditional stiffened shell. Taking the imperfection sensitivity into consideration, Hao et al. [14] proposed an efficient hybrid optimization framework for hierarchical stiffened shells based on smeared stiffener method and finite element method. Inspired by the dragonfly wing, Wang et al. [15] developed a novel hierarchical stiffened shell reinforced by mixed stiffener patterns (composed of orthogrid major stiffeners and triangle minor stiffeners), which significantly expands the design space of hierarchical stiffened shells. Aiming at obtaining the optimal buckling load, Zhao et al. [16] performed optimizations for hierarchical stiffened shells based on linear buckling and nonlinear collapse analyses respectively. In order to improve the analysis efficiency of hierarchical stiffened plates and shells, Wang et al. [17,18] established an

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equivalent model to accelerate the buckling analysis and optimization. In addition, the blast-resistant capacity and thermal buckling capacity of hierarchical stiffened structures were investigated in Refs. [19,20]. Up to now, the hierarchical stiffened shell is still a theoretical concept. But currently it is being evaluated and designed for new-generation heavy lift launch vehicles.

Typical buckling analysis methods for stiffened shells and hierarchical stiffened shells can be mainly summarized as finite element method (FEM), smeared stiffener method (SSM) and hybrid model method. Rahimi et al. [21] used the eigenvalue buckling method in ANSYS software to analyze the effect of stiffener profile on linear buckling load in composite isogrid stiffened shell under axial loading. Wang et al. [17] performed the linear buckling analysis on hierarchical stiffened panels based on the Lanczos method. Aiming at capturing the nonlinear post-buckling path of stiffened shells, the explicit dynamics method is employed for the detailed FE analysis of stiffened shells [22] and hierarchical stiffened shells [13,14,15,18], showing a good agreement with experimental results [23,24]. SSM is based on an analytical method to smear the skin and stiffeners into an equivalent lamina, and then the equivalent stiffness coefficients are substituted into the Rayleigh-Ritz method to calculate the buckling load [25,26]. SSM has been used in the analysis and optimization of stiffened shells, indicating higher computational time-consuming efficiency than a detailed FEM model [27–31]. However, Wang et al. [32] pointed out that SSM is not accurate enough because the coupling stiffness cannot be obtained accurately in SSM. In comparison to the analytical equivalent method in SSM, the numerical-based Asymptotic Homogenization Method (AHM) shows higher prediction accuracy because of its rigorous mathematical foundation of perturbation theory [33]. By combining the AHM with the Rayleigh-Ritz method, a numerical-based smeared stiffener method (NSSM) was proposed for stiffened composite cylindrical shells [32]. Its high prediction accuracy has been validated for diverse stiffener patterns by comparison against the traditional SSM [32]. Due to the fact that SSM cannot consider the nonlinear post-buckling capacity of stiffened shells, Tian et al. [34] and Hao et al. [35–37] established an effective hybrid model by combining equivalent methods with the detailed FE analysis method for stiffened shells and hierarchical stiffened shells. Its core idea is to first calculate equivalent stiffness coefficients based on equivalent methods, and then assign them into stiffness properties in the finite element model. After the establishment of the equivalent unstiffened shell, the explicit dynamics method is used to calculate the collapse load. Remarkably, the hybrid model developed by Tian et al. [34] reduced the post-buckling analysis time of stiffened shells by 92% by comparison against the detailed FEM model. As one kind of thin-walled structures, stiffened shells are sensitive to imperfections. In the early stage, the NASA SP-8007 guideline [38] is used to predict the lower-bound buckling load for shell structures. As demonstrated by many experimental studies [24,39], NASA SP-8007 is overly conservative, resulting in excess structural weight. Many research groups are developing advanced, accurate and realistic imperfection analysis methods. One representative work is the Shell Buckling Knockdown Factor (SBKF) project by NASA, which developed, analyzed and validated new design criteria for grid stiffened shells [40,41]. Another outstanding work is the single boundary perturbation approach (SBPA) proposed by Wagner et al. [42–47] in German Aerospace Center. The SBPA can induce a physical meaningful and realistic buckling response in a cylindrical shell. The significant effectiveness and efficiency of SBPA have been extensively verified and validated for unstiffened cylindrical shells, stiffened cylindrical shells and unstiffened conical shells [42–47], which can be regarded as a promising and advanced prediction method of the knockdown factor (KDF) value for shell structures. Based on optimization techniques, the Worst Multiple Perturbation Load Approach (WMPLA) was proposed and developed by Wang et al. [48]. It uses a finite number of single dimple-shape imperfections to cover the realistic imperfection in practice. After optimizing the amplitude and location of the combination of multiple perturbation loads, the lower-bound buckling load can be determined. The effectiveness of WMPLA was validated by a full-scale buckling test of isogrid stiffened shells [23].

For the purpose of achieving a higher buckling load or a lighter structural weight, many efforts have been made for the design and optimization of stiffened shells and hierarchical stiffened shells. Major optimization variables for stiffened shells include the stiffener height, the stiffener thickness, the skin thickness and numbers of stiffeners along axial and circumferential directions [49]. Extra optimization variables for hierarchical stiffened shells are major and minor stiffener heights, major and minor stiffener thicknesses, and numbers of major and minor stiffeners along axial and circumferential directions [17,28]. In order to search out the global optimal result, heuristic optimization algorithms are good choices (for examples, Genetic Algorithm [50,51], ant colony optimization algorithm [52], particle swarm optimization algorithm [53,54] and Shuffled Frog-Leaping Algorithm [55]). It should be pointed out that, heuristic optimization algorithms need large-scale iterations, and thus analytical buckling analysis method is combined with heuristic optimization algorithms in most instances [50–55]. When solving the large-scale optimization problem based on detailed finite element method, the surrogate modeling approach is an efficient solution to accelerate the optimization process. Lene et al. [56] used response surfaces methodology (RSM) for the surrogate-based optimization of a composite stiffened cylinder. According to literatures [13–16], the traditional optimization method for hierarchical stiffened shells is the conventional surrogate-based optimization method based on the RBF technique and the LHS sampling method. Zhao et al. [16] proposed a surrogate-based optimization framework for hierarchical stiffened shells based on radial basis function (RBF) surrogate modeling technology, and the optimal hierarchical grid design contributed to avoiding the undesired local buckling. Furthermore, the hybrid model was integrated into the surrogate-based optimization framework to replace the detailed finite element model [15,17], which significantly improved the optimization time-consuming efficiency of hierarchical stiffened shells. According to the physical and geometric characteristics of the design parameters involved in the complicated optimization process of stiffened shells with a large number of variables, many authors proposed efficient multilevel or multistep optimization strategies to search for the optimum design [57]. Liu et al. [58] applied a bi-level strategy to the post-buckling optimization of composite stiffened panels, by dividing the optimization process into the laminate level and the panel level. The optimization objective of the panel level optimization is to minimize the structural weight by optimizing the cross-sectional geometry, and that of the laminate level optimization is to seek optimum stacking sequences satisfying laminate design rules. Considering the multi-scale features of nano-enhanced composite structures, Dormohammadi et al. [59] decomposed the complex optimization problem into three levels, including a macroscale structural optimization, a macro-scale material optimization and a micro-scale material optimization. Wang et al. [18] established a multilevel optimization framework by decomposing the entire optimization into a major-level sub-optimization and a minor-level sub-optimization, where the Fixed-Point Iteration method is integrated to accelerate the convergence of the optimization framework.

This paper is organized as follows. First, the formulae of NSSM are derived for the critical buckling analysis of hierarchical stiffened shells. Meanwhile, the parallel computing method is integrated into NSSM, which can further improve the prediction efficiency of NSSM. Then, a bi-level optimization framework is established. In the first level, a large-scale Latin hypercube sampling (LHS) is performed among the entire design space based on NSSM, in order to generate a Pareto front set according to a screening criterion of load-carrying efficiency. In the second level, the surrogate-based optimization is performed based on the generated set of competitive sampling points with high load-carrying efficiency. Finally, detailed comparisons between optimal results of the proposed method and traditional optimization methods are made