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Integrated optimization of hybrid-stiffness stiffened shells based on sub-panel elements

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ABSTRACT

A concept of hybrid-stiffness stiffened shell is proposed based on sub-panel elements to achieve a simultaneous buckling pattern, which can provide enhanced design flexibility to fully explore the load-carrying capacity of structures. Then, a novel hybrid model is established to improve the computational efficiency of post-buckling analysis for stiffened shells, where the Numerical Implementation of Asymptotic Homogenization Method is utilized to smear out the stiffeners. On this basis, an integrated optimization framework of sub-panel configurations and weld lands for stiffened shells is presented. Illustrative examples with single and multiple cutouts demonstrate the effectiveness of the proposed framework based on the concept of hybrid-stiffness stiffened shell.

1. Introduction

Due to the high specific strength and stiffness, stiffened shells have been widely used in various branches of aerospace structures under axial compression to resist buckling, such as aircrafts and launch vehicles, etc. Regarding the buckling and post-buckling behaviors of stiffened shells, a large number of related studies have been conducted. An analytical-numerical procedure was developed by Sheinman and Frostig [1] to investigate the post-buckling behavior of stiffened panels. Savoia and Reddy [2] performed the post-buckling analysis of stiffened shells based on the layerwise shell theory of Reddy. Then, the finite strip method was successfully applied to the prediction of buckling loads of wing box structures by Riks [3]. Moreover, four different types of finite element analyses of composite panels were compared by Lanzi [4], including eigenvalue analysis, non-linear static analysis with modified Riks method, both implicit and explicit dynamic analyses, and then the experimental validation was also carried out. To identify the full post-buckling response of panels, Zhou et al. [5] developed a combined procedure of the arc-length and branch switching methods. Moreover, the degradation was taken into account in the post-buckling regime of composite stiffened panels by Degenhardt et al. [6], and a good agreement with experimental results was observed. To release the computational burden, Bisagni and Vescovini [7] presented an analytical formulation for the local buckling load and nonlinear post-buckling behavior of stiffened panels. The post-buckling behavior of stiffened plates with uncertain initial deflection was investigated by Qiu et al. [8] based on interval analysis. In addition, the elastic buckling strengths of cylindrical shells with weld lands were examined by Rotter and Teng [9]. Thornburgh [10] investigated the effects of axial weld lands on the buckling response of cylindrical shells, and it was found that the buckling load is very sensitive to the specific location and geometry of stiffeners near the axial weld lands. Recently, the influence of imperfection distributions considering manufacturing characteristics was studied by Hao et al. [11], and several general instructions about imperfection-critical areas for axially compressed stiffened shells with weld lands were derived. Besides, the effects of welding-induced residual stresses on the buckling and collapse behaviors were studied by Murphy et al. [12]. Furthermore, the influence of different welding sequences was compared by Tekgoz et al. [13].

To achieve an ever higher load-carrying efficiency, various design optimizations have been performed for stiffened shells. For example, the minimum-weight design optimization of stiffened panels was carried out based on PANDA2 and validated by STAGS [14]. Hao et al. [15] and Wang et al. [16] presented the optimization framework of stiffened shells considering both load-carrying capacity and imperfection sensitivity. Based on measured imperfections, the optimization and antioptimization of buckling loads were conducted for composite cylindrical shells by Elishakoff

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et al. [17]. Hao et al. [18] presented an efficient framework for the reliability-based design optimization of stiffened shells under multi-source uncertainties. Bacarreza et al. [19] proposed a robust multi-objective approach for composite stiffened panels. In addition, a non-parametric shape optimization method for stiffeners was developed by Liu and Shimoda [20,21]. The optimum design of stiffened shells with weld lands was obtained by Bushnell and Thornburgh [22]. However, since nonlinear post-buckling analysis of stiffened shells is usually time-consuming, global optimization of stiffened shells is almost not affordable if detailed FE models are employed. On this account, various types of equivalent stiffness models have been developed for close-spaced stiffened shells. Typically, Smeared Stiffener Method (SSM) together with Ritz method were utilized to predict the buckling load of stiffened shells for preliminary design [23], and the computational time is reduced remarkably. Hao et al. [24] proposed a hybrid optimization framework of stiffened shells by combining the efficiency of SSM with the accuracy of FEM. Compared to SSM, asymptotic homogenization method (AHM) has a higher prediction accuracy of effective stiffness, which is based on the rigorous mathematical foundation [25,26]. Nevertheless, the programmatic implementation of this method is very difficult, which severely limits its uses in practical design. In recent years, Cai et al. [27] developed a novel numerical implementation of the asymptotic homogenization (NIAH) method for periodic plates, which can easily be implemented in commercial FEM software. After that, this method was extended to periodic heterogeneous beam structures, and a good prediction accuracy was also achieved [28]. Based on the NIAH method, Wang et al. [29] presented a hybrid analysis and optimization framework for hierarchical stiffened plates under buckling constraints. Hao et al. [30] proposed an efficient optimization framework of cutout reinforcement for stiffened shells by utilization of the NIAH method.

In addition, variable-stiffness design of composite structures becomes a hot issue in recent years, since a superior structural performance can be achieved when compared to the constant-stiffness design. Setoodeh et al. [31] demonstrated that a significant improvement of buckling loads can be gained by utilization of variable-stiffness panels. Furthermore, a detailed comparison of surrogate models for the optimization of variable-stiffness composite panels was reported by Nik et al. [32]. With regard to metallic stiffened shells, several sub-panels are manufactured separately, and then assembled to large barrels by welding, which enhances the flexibility in the selection of stiffener configurations [33]. Hao et al. [34] presented a bi-step surrogate-based optimization framework for stiffened shells under non-uniform loading, where stiffener sizes (rather than stiffener types) can be different in each sub-panel. Actually, even for uniform loading, the buckling deformations mainly occur at the mid-length of shell along axial direction for the elastic buckling, while the buckling deformations usually evolve from the both ends of shell for the plastic buckling [35]. Therefore, the concept of non-uniform designs was also extended to composite stiffened panels under uniform loading by performing the layout optimization of circumferential stiffeners [36]. Besides, cutouts or openings are another primary source that may cause non-uniform stress distribution in stiffened shells, which are usually inevitable in aerospace structures, for the purpose of easy access, inspection and electric lines [37–41]. The orthotropy, thickness and size of cutout reinforcement were tailored to achieve improved buckling responses by Hilburger and Starnes [37]. Huang and Haftka [38] performed the optimization of fiber orientations near the cutout to increase the load-carrying capacity of composite plates, which provides a significant insight into the cutout reinforcement of composite structures. Hao et al. [30] proposed a novel method to determine the division of near field and far field, and then performed the optimization of curvilinear stiffeners in the near field. Nevertheless, the effects of far field away from the cutout were neglected in most of these previous works, which may significantly affect the stiffness distribution and loading path of the whole structures. Besides, the practical design of weld lands for metallic stiffened shells usually relies on previous experiences. Therefore, it is very crucial to perform the integrated optimization of near field and far field for stiffened shells, as well as weld lands. However, how to improve the computational efficiency and convergence rate of this type of integrated optimizations still remains as a challenging issue.

In order to achieve a simultaneous buckling pattern, a concept of hybrid-stiffness stiffened shell based on sub-panel elements is proposed in this study. Several commonly used stiffener types can be considered, including orthogrid, triangle grid, rotated triangle grid and diamond grid shapes. The NIAH method is utilized to smear out the stiffeners, and a novel hybrid model is established to improve the computational efficiency of post-buckling analysis with little sacrifice of prediction accuracy. Then, the confidence of the hybrid model for post-buckling analysis of stiffened shells is rigorously verified by comparison of detailed FEA. After that, an integrated optimization framework of each sub-panel configuration and weld lands for stiffened shells is presented based on the hybrid model, which can increase the design flexibility and computational efficiency. Finally, two 5-m-diameter cylindrical stiffened shells with single and multiple cutouts demonstrate the effectiveness of the proposed framework based on the concept of hybrid-stiffness stiffened shell, since both the structural efficiency and computational efficiency are increased when compared to traditional optimizations.

2. Design methodology

2.1. Numerical implementation of asymptotic homogenization (NIAH) method

To fully explore the potential of load-carrying capacity, stiffened shells under axial compression are usually served in nonlinear post-buckling regime until collapse occurs [42]. The cutouts further increase the nonlinearity of buckling and collapse behaviors of stiffened shells, which would result in non-convergence issues. In this case, the explicit dynamic method should be employed to solve the problem of convergence. However, since nonlinear post-buckling analysis of stiffened shells based on the explicit dynamic method is generally time-consuming, global optimization of stiffened shells based on detailed FE models is almost not affordable. In this study, the NIAH method is used to convert the stiffened shell into an unstiffened shell with anisotropic or isotropic property for post-buckling analysis, and thus the computational cost of nonlinear post-buckling analysis based on the explicit dynamic method can be reduced significantly. To be specific, unstiffened shell is established to substitute the stiffened shell, and the equivalent stiffness matrix is then assigned to the unstiffened shell. The NIAH method can be summarized as Fig. 1.

As was mentioned in Ref. [27], the effective stiffness coefficients $\boldsymbol{A}_{ij}$, $\boldsymbol{B}_{ij}$ and $\boldsymbol{D}_{ij}$ of the periodic unit cell Ω can be obtained by traditional implementation of AH method as

$$A_{ij} = \frac{1}{|\Omega|}\int_{\Omega}\left(\boldsymbol{\epsilon}_i^0 - \boldsymbol{\epsilon}_i^*\right)^{\mathbf{T}}\mathbf{c}\,\left(\boldsymbol{\epsilon}_j^0 - \boldsymbol{\epsilon}_j^*\right)\,d\Omega$$

$$B_{ij} = \frac{1}{|\Omega|}\int_{\Omega}\left(\boldsymbol{\epsilon}_i^0 - \boldsymbol{\epsilon}_i^*\right)^{\mathbf{T}}\mathbf{c}\,\left(\bar{\boldsymbol{\epsilon}}_j^0 - \bar{\boldsymbol{\epsilon}}_j^*\right)\,d\Omega$$

$$D_{ij} = \frac{1}{|\Omega|}\int_{\Omega}\left(\bar{\boldsymbol{\epsilon}}_i^0 - \bar{\boldsymbol{\epsilon}}_i^*\right)^{\mathbf{T}}\mathbf{c}\,\left(\bar{\boldsymbol{\epsilon}}_j^0 - \bar{\boldsymbol{\epsilon}}_j^*\right)\,d\Omega \tag{1}$$