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Imperfection-insensitive design of stiffened conical shells based on equivalent multiple perturbation load approach

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ABSTRACT

Stiffened conical shells in launch vehicles are very sensitive to various forms of imperfections. As a type of equivalent imperfections, several perturbation load approaches are used to investigate the influence of dimple-shape imperfections on the load-carrying capacity of stiffened conical shells. Firstly, the effect of axial location of dimple is examined by single perturbation load approach (SPLA), since the stiffness of stiffened conical shells varies along axial direction. Then, worst multiple perturbation load approach (WMPLA) is employed to find the lower bound of the collapse load of stiffened conical shells, and also provides the knowledge to determine the number of dimples in the multiple perturbation load approach (MPLA). After that, the optimization of stiffened conical shells for imperfection-insensitive design is carried out, where the equivalent MPLA is adopted during the optimization process to reduce the computational cost. Illustrative example indicates that stiffened conical shells exhibit more complicated imperfection sensitivity compared to cylindrical shells, and the proposed optimization framework can find an imperfection-insensitive design under structural weight constraint in an efficient manner.

1. Introduction

Conical shells are increasingly used in launch vehicles and other aerospace designs, and the primary design concern is the stability of the structure. Until now, there have been extensive studies on the buckling and collapse responses of conical shells under axial compression or/and external pressure [1–3]. In this context, Chang and Kazt [4] found that the buckling strength of conical shell under axial compression is mainly dependent on the boundary condition of the smaller end, which is distinct from the one observed from cylindrical shells or plates [5]. Tong and Wang [6] proposed a power series based solution for the buckling of composite conical shells by using Donnell-type theory. Then, buckling analysis of laminated conical shells was performed based on higher shear deformation theory by Pinto Correia et al. [7]. Shadmehri et al. [8] developed a semi-analytical approach to predict the linear buckling response of composite conical shells. The static analysis of functionally graded conical shells was then carried out by the generalized unconstrained third order theory coupled with the stress recovery [9]. Typically, the structural efficiency can be improved by stiffeners, which can increase the strength of conical shells against buckling [10]. Different buckling modes of stiffened conical shells were compared through linear eigenvalue analysis by Spagnoli [11], where local skin buckling between stiffeners, local stiffener buckling and global buckling were taken into account.

Despite these achievements, there still exist large discrepancies between experimental and theoretical predictions of load-carrying capacities for thin-walled structures, which are primarily attributed to initial geometric imperfections, i.e., small deviations from the perfect shape [12–21]. To partially explain the essence of imperfection sensitivity, notional load versus end-shortening curves of perfect and imperfect thin-walled cylinders are provided in Fig. 1. The theoretical behavior of the perfect cylinder is shown with a dashed line, and the imperfect structure is shown with a solid line. For the perfect geometry, the maximum load occurs at a bifurcation point, where unstable equilibrium states that are adjacent to the primary equilibrium path exist. Once initial geometrical imperfections are included, the structure would extend part way into the cusp and then exhibit a limit-point load, which is significantly lower than the one for perfect geometry [12]. For this case, the theoretical buckling load is inadequate to represent the load-carrying capacity of the as-built structure. In the previous studies, the important role of imperfections on reducing the

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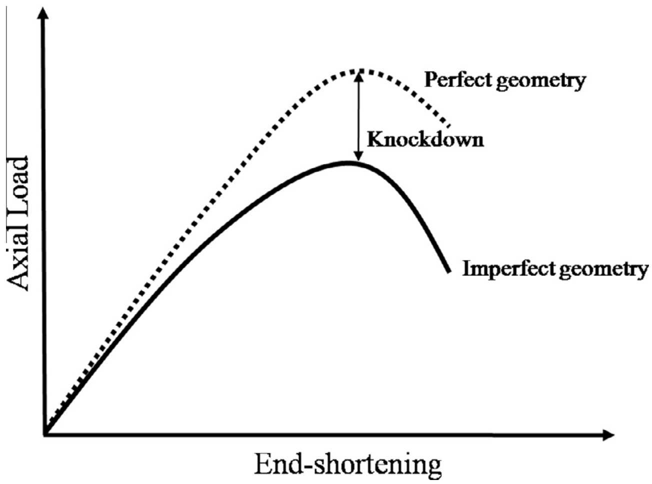

Fig. 1. Notional load versus end-shortening curves of perfect and imperfect thin-walled structures.

buckling load has been conducted for cylindrical shells, however, only few concerns are related to conical shells. Nonlinear buckling response of imperfect stiffened conical shells was predicted based on finite element analysis by Spagnoli and Chryssanthopoulos [22]. Also, Goldfeld [23] found that the cone vertex half-angle has a strong effect on the imperfection sensitivity of conical shells. Furthermore, the influence of imperfections with various forms for conical shells was examined by Blachut [24]. Jabareen and Sheinman [25] developed a general procedure to investigate the imperfection sensitivity of stiffened conical shells based on Donnell-type theory. Actually, stiffened conical shells are widely used in launch vehicles and other aerospace designs. It is very crucial to assess the load-carrying capacity and safety for practical conical stiffened shells in service.

In the practical design of thin-walled structures under axial compression, the theoretical buckling load is usually calculated based on perfect geometry, and the design load is then obtained by multiplying this theoretical buckling load with a so-called knockdown factor (KDF) [26–28]. Based on a large collection of testing data in 1960s, KDFs of cylindrical shells were proposed by NASA SP-8007 [29], which are still extensively used in the preliminary design of shell structures prone to buckling. However, according to recent experimental studies [26,30,31], these KDFs were demonstrated to be very conservative, and the shell structures designed by this guideline are redundant and overweighted, thus affecting the payload capacity of launch vehicles. To cope with this problem, as a type of realistic equivalent imperfections, Hühne et al. [30] suggested the single perturbation load approach (SPLA) for creating a single dimple-shape imperfection, which can produce physically meaningful response characteristics that are typically similar to the onset of real buckling process [31]. The SPLA was compared with four other methods commonly used to create geometric imperfections, including eigenmode-shape, geometric dimple-shape, axisymmetric and measured imperfections [32], and results indicate that the perturbation load approach is a promising method to predict improved KDFs. Then, the SPLA was applied to composite unstiffened conical shells, and detailed comparison with artificial measured imperfections was discussed [33]. Subsequently, a combined methodology of the SPLA and stochastic approach was proposed by Degenhardt et al. [34]. However, the probability density functions of the involved random variables need to be determined by a large collection of prior data, otherwise, small probability data error may cause large deviation of probability calculation and largely scattered KDFs. Moreover, because the determination of KDFs relies on the distribution of probability density, the value of KDF needs to be validated by a large number of experiments before it can be used with full confidence. To this end, one attempt of unified approach to determine the worst realistic imperfection for unstiffened cylinders was made by the present authors [35]. After that, the worst multiple perturbation load approach (WMPLA) was developed for stiffened shells with and without cutouts, aiming to provide references for improving KDFs [36].

Since structural efficiency is of great significance for aerospace designs, various optimizations have been performed for conical shells. The minimum-weight design of stiffened conical shells with natural frequency constraints was obtained by Rao and Reddy [37]. By utilization of response surface methodology, the optimization of composite conical shells for the maximum buckling load was carried out by Goldfeld et al. [38]. Then, Morozov et al. [39] performed the design optimization of anisogrid stiffened conical shells, and a significant weight reduction was finally achieved. However, although several optimizations of imperfect cylindrical shells have been carried out in recent years [18,40,41], there is still no consideration of the effects of initial imperfections in the previous optimizations of conical shells, which may produce conservative or risky designs.

This paper is structured as follow. In Section 2, several perturbation load approaches are introduced briefly. In Section 3, these methods are used to investigate the influence of dimple-shape imperfections on the load-carrying capacity of stiffened conical shells. Firstly, the effect of axial location of dimple is examined by the SPLA, since the stiffness of stiffened conical shells varies along axial direction, and is strongly dependent on the coordinates of the shell. Then, the WMPLA is employed to find the lower bound of the collapse load of stiffened conical shells, and also provides the knowledge to determine the number of dimples in the MPLA. In Section 4, the optimization of stiffened conical shells for imperfection-insensitive design is carried out, where the EMPLA is adopted during the optimization process to reduce the computational cost. Finally, detailed comparison with traditional optimization formulation is discussed through the illustrative example.

2. Perturbation load approaches

2.1. Single perturbation load approach (SPLA)

As a type of realistic equivalent imperfections, the SPLA was developed to produce a single dimple-shape imperfection for thin-walled structures. The implementation of the SPLA can be divided into three steps. Firstly, a concentrated perturbation load is applied to the half-way of cylinder surface, as shown in Fig. 2,

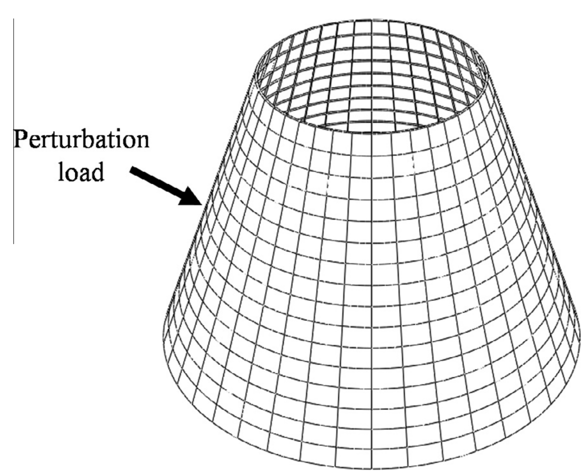

Fig. 2. Sketch of SPLA for stiffened conical shell.