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Influence of imperfection distributions for cylindrical stiffened shells with weld lands

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ABSTRACT

The influence of imperfection distributions considering manufacturing characters on the buckling response of stiffened shells has not been satisfactorily understood. Stiffened shells with three types of weld lands were established, including axial weld lands, circumferential and sequential axial weld lands, as well as staggered axial weld lands. As a concept of equivalent imperfection, dimple-shape imperfections produced by perturbation loads were adopted to substitute the measured imperfections, in order to reduce experimental and computational costs. Firstly, the influence of imperfection positions on the collapse load was examined for single perturbation load. Then, the influence of imperfection distributions was investigated for multiple perturbation load based on Monte Carlo Simulation. Finally, detailed comparison of three types of weld lands was made from the point-of-view of load-carrying capacity and imperfection sensitivity. Results can provide general instructions about imperfection-critical areas for axially compressed stiffened shells, which are particularly crucial for the manufacturing process.

1. Introduction

Axially compressed stiffened shells are the major structural component of launch vehicles to resist buckling and collapse. However, there exists large discrepancies between experimental and theoretical predictions of collapse loads for thin-walled structures, and it has been generally recognized that initial imperfections (i.e., small deviations from perfect structures) are the main attribution, which can dominate the buckling and post-buckling behavior of real-world thin-walled structures. Thus, a great deal of research was put forward to investigate the influence of various forms of initial imperfections [1,2]. So far, the most frequently used guideline to handle the effects of imperfections is NASA SP-8007 [3], where knockdown factors (KDFs) for structural design were determined by the lower bound curve based on a large collection of experimental results in 1960s. With the rapid advances of material system and manufacturing technology, these KDFs were proven to be over conservative [4]. In this case, a project named as Shell Buckling Knockdown Factor (SBKF) was funded by NASA Engineering and Safety Center for buckling-critical launch vehicle structures [4–6], aiming to develop and validate new shell buckling design methods accounting for imperfection sensitivity. Later, a Framework Plan called New Robust Design Guideline for Imperfection Sensitive Composite Launcher Structures (DESICOS) was funded by European Commission [7–9], whose ultimate objective is to establish a new design approach for imperfection sensitive composite launcher structures. Recently, a National Basic Research Program of China called Lightweight Design Theory and Method of Stiffened Shells including Imperfection Sensitivity was approved for future heavy-lift launch vehicles [10–14], and this study is also part of this research program. Among these research projects, it should be noted that, compared to the experiment-based approach, analysis-based approach is considered as a promising tool to investigate the safety margins attached to structural stability designs from a point-of-view of economy, since the experimental cost is usually hard to afford, especially for large-diameter structures.

For thin-walled structures, geometric imperfections refer to deviations from the shape of perfect geometry, which are generally grouped into three broad categories: realistic, stimulating and worst imperfections [15]. Specifically, realistic imperfections can be determined by contact or non-contact optical measurement methods [4,16], and advanced imperfection measurement systems for unstiffened shells and stiffened panels have been developed by Degenhardt et al. [17]. Until now, a great deal of research has been carried out based on measured imperfections [18–21]. The essence of such a method is to associate characteristic imperfections with certain manufacturing processes, and then predict the nonlinear buckling phenomenon accurately by means of numerical analyses. In the

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established International Imperfection Data Bank, the measured initial geometric imperfections of unstiffened shells were decomposed into Fourier series for nominally identical specimens [22–25]. Unfortunately, the bottleneck of this method is that complete knowledge of the measured initial geometric imperfections is usually not available within the context of design process, let alone the accommodated mathematical model, moreover, measured imperfections of stiffened shells are desperately scarce in open literatures, due to the complex measurement method and extremely high expend. In addition, the measured imperfection sensitivity analysis may suffer from heavy computational efforts, especially for stiffened shells, because extremely refined meshes are required to describe and capture the nodal deviations from perfect geometry; stimulating imperfections can be considered as a type of artificial imperfection, leading to a characteristic physical buckling behavior. Typically, the incorporation of geometric imperfections using eigenmode shapes is a commonly applied technique [26,27]. Besides, Hühne et al. [28] developed the Single Perturbation Load Approach (SPLA) to create a local dimple-shape imperfection, which can produce a physically meaningful buckling behavior that is similar to the one observed in tests. Since the SPLA can be regarded as a type of equivalent imperfections, extremely refined meshes are not required, rather than measured imperfections, as discussed in Section 3.2. Then, the SPLA was extended to the design of composite conical structures under axial compression [29]. Furthermore, a combined methodology of the SPLA with a stochastic app roach was proposed by Degenhardt et al. [9]. As another significant supplement of the SPLA, the concept of Multiple Perturbation Load Approach (MPLA) was introduced by Arbelo et al. [8]; worst imperfections can be determined mathematically by means of optimization methods [30,31]. Based on a finite number of perturbation loads, an optimization framework to identify the worst realistic imperfection was presented by the authors for cylindrical unstiffened shells [11], aiming to provide references for the improved KDFs. More recently, Worst Multiple Perturbation Load Approach (WMPLA) was developed and extended to the design of stiffened shells with and without cutouts by the authors [13]. In addition, reliability-based method has been adopted to find more rational KDFs [32], where random geometric imperfections, material property and thickness variations, and even non-uniform axial loading were incorporated into the buckling prediction of cylindrical shells [33,34]. Also, a stochastic method using the first-order second-moment analysis was presented for unstiffened shells based on measured imperfections [19].

To the authors' knowledge, previous studies of imperfection sensitivity for thin-walled structures were mainly concentrated on the buckling response to various forms of imperfections. However, the influence of imperfection distributions considering manufacturing characters has not been studied intensively so far. Actually, establishing a correlation between imperfection distributions and structural performances is particularly significant for guiding the manufacture process and technology of stiffened shells. With regard to metallic stiffened shells, several segments are manufactured independently, and then assembled to complete barrels by welding, which adds the flexibility in the choice of stiffener configurations [35]. Rotter and Teng [36] examined the elastic buckling strengths of cylindrical shells under axial compression. Thornburgh [37] investigated the effects of the 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. Nevertheless, the influence of imperfection distributions on structural performances for cylindrical shells with weld lands is still far from being satisfactorily understood or solved, and such knowledge is particularly crucial for the fields of safety assessment and manufacturing.

In this study, the influence of imperfection distributions for stiffened shells with three types of weld lands was thoroughly investigated. Nonlinear explicit dynamic analysis method was utilized to predict the buckling and post-buckling behavior of stiffened shells under axial compression. As a concept of equivalent imperfection, dimple-shape imperfections produced by perturbation loads were adopted to substitute the measured imperfections, in order to reduce both the experimental and computational costs. Firstly, a 3-m-diameter orthogrid stiffened shell with axial weld lands was established according to Ref. [38]. Dimple-shape imperfections were compared and validated by the available experimental results and measured imperfections. The influences of imperfection positions and distributions on the collapse load were then examined based on single and multiple perturbation loads, respectively. Several critical understandings were gained by full exploration of the probability density function (PDF) of collapse loads based on Monte Carlo Simulation (MCS). Then, a 5-m-diamter orthogrid stiffened shell with circumferential and sequential axial weld lands was built, aiming to investigate the effects of imperfection distributions when circumferential weld lands are considered. Furthermore, a 5-m-diameter orthogrid stiffened shell with circumferential and staggered axial weld lands was developed to discuss the effects of distributions of axial weld lands. Finally, detailed comparison of three types of weld lands was made from the point-of-view of load-carrying capacity and imperfection sensitivity. Numerical results can provide general instructions about imperfection-critical areas for axially compressed stiffened shells with different types of weld lands, which require special attention in the manufacturing process.

2. Methodology

2.1. Nonlinear post-buckling analysis

In this study, nonlinear post-buckling analysis of stiffened shells was performed by using the explicit dynamic method. For an explicit dynamic analysis, by utilization of the explicit time integration with central difference method, the equation of motion can be written as

$$\left(\frac{\mathbf{M}}{\Delta t^2}+\frac{\mathbf{C}}{2\Delta t}\right)\mathbf{U}_{t+\Delta t}=\mathbf{F}_t^{\mathbf{ext}}-\mathbf{F}_t^{\mathbf{int}}+\left(\frac{2\mathbf{M}}{\Delta t^2}-\mathbf{K}\right)\mathbf{U}_t-\left(\frac{\mathbf{M}}{\Delta t^2}-\frac{\mathbf{C}}{2\Delta t}\right)\mathbf{U}_{t-\Delta t} \tag{1}$$

where, $\mathbf{M}$ is the mass matrix, $\mathbf{C}$ is the damping matrix, $\mathbf{K}$ is the stiffness matrix, $\mathbf{a}$ is the vector of nodal acceleration, $\mathbf{V}$ is the vector of nodal velocity, $\mathbf{U}$ is the vector of nodal displacement, t is the time, Δt is the time increment, $\mathbf{F}_t^{\mathbf{ext}}$ is the vector of applied external force, $\mathbf{F}_t^{\mathbf{int}}$ is the vector of internal force.

As is evident from Eq. (1), $\mathbf{U}_{t+\Delta t}$ depends only upon the time-dependent variables $\mathbf{U}_t$ and $\mathbf{U}_{t-\Delta t}$, thus it can be concluded that no convergence checks are needed when solving these equations. As such, nonlinear explicit dynamic analysis enables the prediction of load-displacement path for stiffened shells, from pre-buckling to post-buckling field, until collapse occurs [39–42]. However, since a very small element size can result in a huge increase of computational effort, the selection of an appropriate element size is usually a trade-off between accuracy and efficiency.

Moreover, various forms of geometric imperfections can be caused by manufacturing, transport, installation and even serving processes of stiffened shells, which increase the nonlinearity of buckling and collapse behavior under axial compression, and thus enhance the significance of performing the explicit dynamic analysis. In the implemented numerical analysis procedure, geometric imperfections can be taken into account by shifting the radial coordinate of each node according to nodal displacement vector. Geometry of an imperfect stiffened shell can be expressed