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Numerically and experimentally predicted knockdown factors for stiffened shells under axial compression

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ABSTRACT

Stiffened shells in launch vehicles are very sensitive to various forms of imperfections. In this study, the imperfection sensitivity of a 4.5 m diam isogrid stiffened shell under axial compression is investigated. The measured imperfection, NASA SP-8007 and several types of assumed imperfections, including eigenmode-shape imperfection and dimple-shape imperfections (produced by the single perturbation load approach (SPLA) and worst multiple perturbation load approach (WMPLA)), are introduced into FE model to predict the knockdown factors (KDFs), respectively. Then, the buckling test of this full-scale stiffened shell under axial compression is carried out to validate the above numerical approaches. It can be found that the KDF predicted by the WMPLA is very close to the test results, while the ones predicted by eigenmode-shape imperfection and NASA SP-8007 are extremely conservative. Besides, the measured imperfection and other assumed imperfections are proven to be risky, because these methods overestimate the actual load-carrying capacity. Finally, it can be concluded that the WMPLA is a potential and efficient approach to predict KDFs in the design stages for future launch vehicles.

1. Introduction

Due to the high ratio of stiffness to weight, stiffened cylindrical shells are widely used in the aerospace and aircraft designs. Up to now, many studies have concerned about the prediction of collapse or buckling loads of stiffened shells under axial compression [1–10]. As is generally recognized, one of the most significant sources for the discrepancy between theoretical predictions and experimental results of collapse load is the presence of initial imperfections, mainly including geometric imperfections and loading imperfections, which can be defined as the deviations from perfect configuration and loading distributions [11,12]. Geometric imperfections can reduce the collapse load drastically compared to that of the perfect shell. Once initial geometric imperfections are introduced into the FE model of thin-walled shells, the load versus end-shortening curves would decline fast and then exhibit a limit-point load, which is significantly lower than the collapse load of the perfect shell. In this case, knockdown factors (KDFs) are usually employed to quantify this effect, which can be obtained by performing imperfection sensitivity analysis at the design stage.

In practice, the theoretical buckling load of axially compressed thin-walled shells is usually calculated by linear buckling analysis, and the design load is then obtained by multiplying this theoretical buckling load with a KDF [13,14]. Based on a large amount of experimental data, an empirical prediction approach of KDFs for cylindrical shells was developed by NASA SP-8007 [15], which is still extensively used in the preliminary design of cylindrical shell structures prone to buckling. However, according to the experimental study of unstiffened shells [16], this guideline was demonstrated to be very conservative, and the shell structures designed by this guideline would be extremely redundant and heavy, thus affecting the payload of launch vehicles and aircrafts.

Compared to the experimental approaches, analysis-based approaches are more promising to obtain improved KDFs from the point-of-view of economy [17]. In recent years, a large amount of researches were conducted by analysis-based approaches on the subject of imperfection sensitivity of thin-walled cylindrical shells. Three types of geometric imperfections were classified by Winterstetter and Schmidt [7]: realistic, worst and stimulating geometric imperfections. Specifically, realistic imperfections can be measured approximately by non-contact optical measurement methods [14], and then they can be used to determine KDFs. However, one important problem is that measured imperfections are usually not available within the context of design stage, before

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cylindrical shells have been manufactured. Therefore, the form of geometric imperfections should be assumed during the design stage. As a typical assumed imperfection, worst imperfections can be determined mathematically by optimization methods [18,19]. However, it is still doubtful whether these approaches can provide rational imperfection shapes and amplitudes that are close enough to measured imperfections. Stimulating imperfections are another type of assumed imperfections, which can result in characteristic physical buckling behavior. For example, the incorporation of geometric imperfections using eigenmode shapes is a commonly applied technique [1]. The European standard [20] for steel shell structures recommended that the imperfection should be specified in the form of eigenmode shapes, with its amplitude linked to fabrication quality, unless a different unfavorable pattern is justified. However, this approach has been proven to be overly conservative [14,21,22], because eigenmode-shape imperfections represent the deformation shapes with a high bias towards buckling, which may cause a large reduction of axial stiffness, even for small imperfection amplitudes [1].

As a promising basis shape, the single perturbation load approach (SPLA) for producing a single dimple-shape imperfection was proposed by Hühne et al. [14]. It can be considered as a realistic, worst and stimulating imperfection pattern, because: 1) It can be observed in the measured imperfections and verified in real experimental conditions [23]; 2) It represents a type of geometric imperfection leading to a relatively low collapse load [18]; 3) The single dimple-shape imperfection can produce physically meaningful buckling characteristics, which are typically similar to the initial phase of real buckling process in tests. Therefore, the SPLA has been widely utilized by many researchers to investigate the imperfection sensitivity of shell structures [24,25]. Castro et al. [1] performed the comparison of different methods commonly used to create geometric imperfections, including eigenmode-shape, dimple-shape, axisymmetric and measured imperfections. Results indicate that the SPLA can predict the KDFs in a straightforward way, also, it was suggested that further studies should focus on stochastic studies with measured imperfections, aiming to identify if there are real cases that the initial geometric imperfection produces a reduction of axial stiffness. Recently, a stochastic procedure that realistically describes the imperfection sensitivity of composite shells was developed [26]. In addition, reliability-based design optimization was investigated for stiffened shell considering various uncertain factors [27–29], such as the variations of manufacturing tolerance, material properties and environment aspects, etc.

Based on a finite number of single dimple-shape imperfections, a new method called Worst Multiple Perturbation Load Approach (WMPLA) was proposed by the authors [30] to improve the accuracy and reliability of KDFs of cylindrical shells, where multiple dimple-shape imperfections are applied on the shell surface, and then the most detrimental combination of these dimple-shape imperfections can be found by optimization methods. Subsequently, the WMPLA was extended to stiffened shells in terms of nodal coordinates. In order to improve the optimization efficiency, surrogate model was introduced in the optimization of stiffened shells [31–35], which can release the CPU burden of applying the WMPLA. Then, the imperfection-insensitive designs of stiffened conical shells [36] and stiffened cylindrical shells [37] with reinforced cutouts by curvilinear stiffeners were investigated later.

In addition, a large amount of experiments were investigated for the purpose of model validation [38–42]. The post-buckling behavior of three stiffened composite cylindrical shells was investigated by performing the buckling tests [43]. Results indicate that the collapse phenomenon was sudden and destructive due to the failure of stringers. With the development of measurement techniques [38,39], geometric imperfections of full-scale cylinders can be obtained before buckling tests. Degenhardt et al. [44] presented an exhaustive overview about the buckling tests, measurement setup and buckling simulations, and discussed how these observations could be used to obtain less conservative, laminate-dependent KDFs [45]. Also, NASA released the guideline about shell buckling design criteria based on measured imperfections [46]. After measuring the specimens, initial geometric imperfection data obtained from six composite shells were taken into account in the nonlinear finite element analysis to predict the KDFs. Results indicate that measured geometric imperfections have the potential to improve the accuracy of KDFs compared to NASA SP-8007. Moreover, the experiments of stiffened composite cylindrical shells were also investigated to verify the KDFs obtained by means of analysis-based imperfection approach [43].

Owing to the expensive computational cost of simulation, Smeared Stiffener Method (SSM) [47] and Numerical Implementation of Asymptotic Homogenization (NIAH) [37,48] were adopted into the optimization process of stiffened panels for improving the efficiency. Also, surrogated-based optimization considering load-carrying capacity and imperfection sensitivity was investigated by Hao et al. [21] to find the optimum design with low imperfection sensitivity. Doreille et al. [49] proposed a fast and accurate analysis tool for composite shells based on finite element method. The minimum weight optimization was carried out for T-stiffened and hat-stiffened panels based on equivalent model [50]. Moreover, a new robust design strategy for thin-walled composite structures was proposed by Wille et al. [51], which combines strength requirements in terms of the limit and ultimate load with robustness requirements evaluated by the structural energy until collapse. As a promising configuration for future launch vehicles, hierarchical stiffened shell was proposed by the authors for low imperfection sensitivity and high load-carrying capacity compared to traditional stiffened shells [52,53]. Also, stiffened shells with B-spline generatrix shapes were investigated for both the cases of elastic and plastic buckling [54], and an optimization framework was established to decrease the imperfection sensitivity. Additionally, Ning et al. [55] proposed a novel shell with cross-section formulated by NURBS interpolation on control points, and the positions of each control point can be optimized by evolutionary algorithms.

In this study, the imperfection sensitivity of a 4.5 m diam isogrid stiffened shell is investigated numerically and experimentally. The prediction methods of KDFs for stiffened shell under axial compression are introduced firstly. Then, various forms of imperfections are taken into account, such as eigenmode-shape imperfection, NASA SP-8007, SPLA, measured imperfection and WMPLA. By means of these numerical approaches, the KDFs of this isogrid stiffened cylindrical shell are obtained, respectively. After that, the buckling test is carried out to validate the above numerical approaches. Finally, the results of numerically and experimentally predicted KDFs are discussed in detail.

2. Numerical methods of imperfection sensitivity analysis

2.1. Eigenmode-shape imperfection approach

In practice, eigenmode-shape imperfections are still widely used in the assessment of actual load-carrying capacity of thin-walled structures. To be specific, the normalization of several eigenmode vectors is introduced into FE model by means of modifying the nodal coordinates. The geometry of imperfect structure is described by nodal coordinates of finite element model as:

$$X = X_P + X_I \tag{1}$$