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Worst Multiple Perturbation Load Approach of stiffened shells with and without cutouts for improved knockdown factors

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ABSTRACT

An optimization framework of determining the worst realistic imperfection was proposed by the present authors to study the reduction of the load-carrying capacity of unstiffened cylindrical shells. However, with regard to stiffened shells, especially when cutouts are included, the dimple combination pattern should be judged in a more rational manner. In this study, node coordinates are utilized to describe the position of each dimple-shape imperfection for Worst Multiple Perturbation Load Approach (WMPLA), which is an improvement of the MPLA using an optimization algorithm to find the application positions that will reduce the buckling load. Further, a novel method to determine the density of possible positions of dimple-shape imperfections is proposed based on eigenmode shape for stiffened shells without cutout. In addition, the effects of cutouts on the proposed method are investigated in detail. The effectiveness of the proposed method is demonstrated by comparison of several conventional methods to obtain improved knockdown factors (KDFs).

1. Introduction

1.1. Background

Prediction of load-carrying capacities of axially compressed thin-walled cylinders is a classical structural analysis problem. In general, the large discrepancies between experimental and theoretical predictions of thin-walled cylinders are primarily attributed to initial geometric and loading imperfections, i.e., small deviations from perfect geometry [1–3] and perfect loading distributions [4–7], respectively. For a perfect cylinder, the maximum load P_0 occurs at a bifurcation point, where unstable equilibrium states that are adjacent to the primary equilibrium path exist. Once initial imperfections are included, the cylinder would extend part way into the cusp and then exhibit a limit-point load, which is significantly lower than P_0 [8]. For this case, the theoretical buckling load is inadequate to represent the load-carrying capacity of the as-built structure. Moreover, different structural constructions have different sensitivities to imperfections [9], and thus a design must be evaluated by imperfection sensitivity analysis before it can be used with full confidence.

1.2. Imperfection sensitivity

When investigating the effect of initial imperfections, theoretical buckling load is usually calculated using linear buckling analysis, and the design load is obtained by multiplying this theoretical buckling load with a knockdown factor (KDF) [10–12]. Based on a large collection of testing data in 1960s, KDFs of cylindrical shells were proposed by NASA SP-8007 [13], which are still extensively used in the preliminary design of shell structures prone to buckling. However, according to recent experimental studies [10,14,15], these KDFs turned out to be very conservative, and the shell structures designed by this guideline are extremely redundant and heavy, thus affecting the payload capacity of launch vehicles and aircrafts. Compared to the traditional experimental approach, analysis-based approaches are more promising to obtain improved KDFs from the point-of-view of economy [16].

The topic on the imperfection sensitivity of thin-walled cylinders has been extensively conducted. Winterstetter and Schmidt [17] classified three approaches for the numerical simulation of imperfect shell structures: realistic, worst and stimulating geometric imperfections. Specifically, realistic imperfections can be determined by a non-contact optical measurement method [10]. Unfortunately, one major problem is that measured imperfections are usually not available within the context of a design process, before real structures have been built; worst imperfections can be determined mathematically by optimization methods [18,19]. However, it is still doubtful whether these approaches can provide imperfection shapes and amplitudes

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which are close enough to real imperfections occurring in practical structures; stimulating imperfections are a type of artificial imperfection, which can result in the characteristic physical shell buckling behavior. The incorporation of geometric imperfections using eigenmode shapes is a commonly applied technique [20,21]. The European standard for steel shell structures [22] 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, the corresponding results are considered to be conservative, because eigenmode-shape imperfections represent deformation shapes with a high bias towards buckling [23], which may cause a high decrease of the axial stiffness even for small imperfection amplitudes [21]. Moreover, eigenmode-shape imperfections are also mode-dependent for many cases, especially when some eigenmodes are axially oriented and others are circumferentially oriented.

Hühne et al. [14] suggested the single perturbation load approach (SPLA) for creating a single dimple-shape imperfection. It is considered as a type of realistic, worst and stimulating imperfection, because: 1) it can be observed in measured imperfection patterns and verified in real test conditions [24]; 2) it can find the geometric imperfection that gives the minimum buckling load [18]; and 3) the single dimple-shape imperfection can produce physically meaningful response characteristics, which are typically similar to the initial phase of a real buckling process [15]. Then, the SPLA was compared with four other methods commonly used to create geometric imperfections: eigenmode-shape, geometric dimple-shape, axisymmetric and measured imperfections, respectively [21]. Results indicated that further studies should focus on large stochastic studies with measured imperfections to identify if there are real cases where the initial geometric imperfection produces a reduction in the axial stiffness. Further, a combined methodology of the SPLA with a stochastic approach was proposed by Degenhardt et al. [25]. Specifically, the SPLA deals with the traditional imperfections, e.g. geometric and loading imperfections, and the stochastic approach considers the non-traditional ones, e.g. variations of wall thickness and stiffness [26–28]. 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, thus leading to large scattered KDFs. Moreover, because the determination of KDFs relies on the distribution of probability density, the value of KDF needs to be validated by large number of experiments before it can be used with full confidence. To cope with this problem, based on a finite number of dimple-shape imperfections, an optimization framework of determining the worst realistic imperfection was proposed by the present authors to study the reduction of the buckling load of cylindrical unstiffened shells [29,30], aiming to provide a reference for improving KDFs of thin-walled cylinders.

With regard to stiffened shells, the density of possible positions of dimple-shape imperfections should be judged in a more rational manner, since the combined dimple shape proposed by the previous study [29] may no longer be suitable. It is because the essence of geometric imperfections is the superposition of a small/large number of local out-of-plane deformations with various forms, which may accelerate the evolutions of local deformations to global deformations with the increase of axial compression, and thus results in a remarkable reduction of load-carrying capacity [31, 32]. The local anisotropic stiffness caused by stiffeners can restrict the developments of initial deformations, consequently, the imperfection sensitivity of stiffened shell may be significantly different from the one of the corresponding unstiffened shell using the Smeared Stiffener Method (SSM).

1.3. Stability of stiffened shells with cutouts

Cutouts with various shapes are often used in aerospace and aircraft structures for easy access, inspection, electric lines and so on [33]. Inevitably, the existence of cutouts interrupts the continuous distributions of stress and strain and results in a significant reduction of load-carrying capacity. Many studies [34-36] have been conducted on the stress, deformation and buckling characteristics of thin-walled structures with cutouts (square, circular, elliptic and triangular shapes).

For stiffened shells with cutouts, the possible positions of dimple-shape imperfections become more complicated due to the global anisotropic stiffness caused by cutouts. In practice, cutouts are unavoidable in aerospace thin-walled structures for various reasons [37], thus leading to geometric discontinuities, which may cause substantial stress concentrations and subsequently influence the stability of the structures [33]. Kumar and Singh [38] investigated the effects of various cutout shapes and sizes on the post-buckling responses of composite plates. The influences of different reinforcing grid configurations on the collapse loads of composite stiffened shells were examined and compared in detail by Shi et al. [39]. On this basis, the effects of random geometric imperfections on the buckling loads of axially compressed cylinders with rectangular cutouts were also investigated [40]. In general, the effects of imperfections with various forms on the load-carrying capacities of stiffened shells with cutouts are not quite well studied until now.

1.4. Paper synopsis

Based on a finite number of dimple-shape imperfections, an optimization framework of determining the worst realistic imperfection was proposed by the present authors for unstiffened cylindrical shells. With regard to stiffened shells, the position of dimple-shape imperfection is described for WMPLA based on node coordinates in this study. Further, a novel method to determine the density of possible positions of dimple-shape imperfections is proposed based on eigenmode shape for stiffened shells without cutout. In addition, the effects of cutouts on the proposed method are investigated in detail. The effectiveness of the proposed method is demonstrated by comparison of several conventional methods to obtain improved KDFs.

2. Method of analysis

2.1. Post-buckling analysis of stiffened shells with dimple-shape imperfections

Nonlinear post-buckling analysis of stiffened shells with dimple-shape imperfections can be divided into three steps. First, a concentrated perturbation load is applied to the half-way of cylinder surface, and the deformation shape of the stiffened shell is obtained by nonlinear static analysis under a given perturbation load. Second, the deformation of the stiffened shell is introduced to the perfect geometry by modifying nodal coordinates. Third, an axial compression load is applied by enforcing a uniform end-shortening, and then the evolution of buckling phenomena, in terms of deformation, stress and strain, is traced by nonlinear explicit dynamic analysis, until structural collapse is observed. It should be noted that the dimple-shape imperfection considered herein is stress-free, slightly differing from the single dimple-shape imperfection developed by Hühne et al. [14], since it is likely that any real geometric imperfection might be relatively stress-free, actually, it has also been concluded that the associated stress only has little influence on the prediction of lower bound buckling load for dimple-shape imperfections [11].

2.2. Surrogate-based optimization for WMPLA

Post-buckling analysis of stiffened shells is extremely time-consuming in general, especially for a nonlinear explicit dynamic