Engineering Structures 150 (2017) 300–317

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Nondestructive method to predict the buckling load in elastic spherical shells

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ARTICLE INFO

Article history:
Received 6 January 2017
Revised 3 July 2017
Accepted 7 July 2017

Keywords:
Nondestructive method
Elastic buckling load
Spherical shells

ABSTRACT

This paper presents a general methodology for predicting the critical buckling loads of spherical shells using a nondestructive test. For this purpose, the well known graphical method of predicting buckling loads, i.e., the Southwell's nondestructive method for columns is analytically extended to spherical shells and a new formula is derived for the critical buckling load of uniformly compressed spherical shells. Subsequently, finite element simulation and experimental work proved that the theory is also applicable to spherical shells with an arbitrary axi-symmetrical loading as well. The results show that the technique provides a useful estimate of the elastic buckling load provided care is taken in interpreting of the results. The usefulness of the method lies in its generality, simplicity and in the fact that, it is non-destructive. Moreover, it does not make any assumption regarding the number of buckling waves or the exact localization of buckling.

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1. Introduction

Due to the increasing use of shell type structures in space vehicles, submarines, buildings and storage tanks, interest in the stability of shells has accordingly increased by researchers and practicing engineers. On the other hand, as the variety and the quantity of shells increase, the determination of shell behavior becomes more and more important. Because a hemispherical shell is able to resist higher pure internal pressure loading than any other geometrical vessel with the same wall thickness and radius, the hemispherical shell is one of the important structural elements in engineering applications (Fig. 1). It is also a major component of pressure vessel construction. A spherical vessel is a very strong structure and they have a smaller surface area per unit volume than any other shape of the vessel.

In spherical shell structures, one of the most important things is to determine the buckling load of these structures either experimentally or theoretically. The modern design technique goes into the model investigation, especially, for complicated structures as shells. Since in most cases, the true behavior of the shell has not been known or very difficult to know, the best thing is to make some assumptions and then to verify these assumptions by means of model tests. Accordingly, the determination of the buckling loads of hemispherical shells either experimentally or theoretically is very important.

Jones et al. [1] investigated the problem of a thin spherical linearly-elastic shell, perfectly bonded to an infinite linearly-elastic medium. A constant axisymmetric stress field is applied at infinity in the elastic medium, and the displacement and stress fields in the shell and elastic medium are evaluated by means of harmonic potential functions. Nie et al. [2] derived an asymptotic solution for nonlinear buckling of orthotropic shell on elastic foundation. They performed an extensive parametric study for deformation and buckling of such structures. Uchiyama and Yamada [3] studied nonlinear buckling of elastic imperfect shallow spherical shells by mixed finite elements. They used nine-node shell element and mixed formulation for stress resultant vectors then they compared finite element results with fifty-two experiments on the elastic buckling of clamped thin-walled shallow spherical shells under external pressure. Dumir et al. [4] investigated axisymmetric buckling of orthotropic shallow spherical cap with circular hole. Analysis has been carried out for uniformly distributed load and a ring load at the hole. Grünitz [5] examined the buckling strength of clamped and hinged spherical caps under uniform pressure with a circumferential weld depression by using the finite element method. The results obtained show a significant decrease in the buckling strength due to these imperfections depending on the location of the weld. Xu [6] developed a non-linear shear-deformation theory for the axisymmetric deformations of a shallow spherical cap comprising of laminated cylindrically-

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http://dx.doi.org/10.1016/j.engstruct.2017.07.020
0141-0296/Published by Elsevier Ltd.

Nomenclature

S	slope of w verses w/p line	ε_y	the unit elongation or strain in y-direction
u	displacement of the shell element in x direction	ε_1	the unit elongation of middle surface in x-direction
v	displacement of the shell element in y direction	ε_2	the unit elongation of middle surface in y-direction
w	displacement of the shell element in z direction	υ	Poisson's ratio
U_0	effect of initial imperfections	χ_x	change of curvature in x-direction
V	shearing force in straight members	χ_y	change of curvature in y-direction
y	deflection of straight member	t_0	thickness of shell
α	buckling coefficient to be determined experimentally	p_{cr}	classical buckling pressure
ε_x	the unit elongation or strain in x- direction	$H()$	a mathematical operator

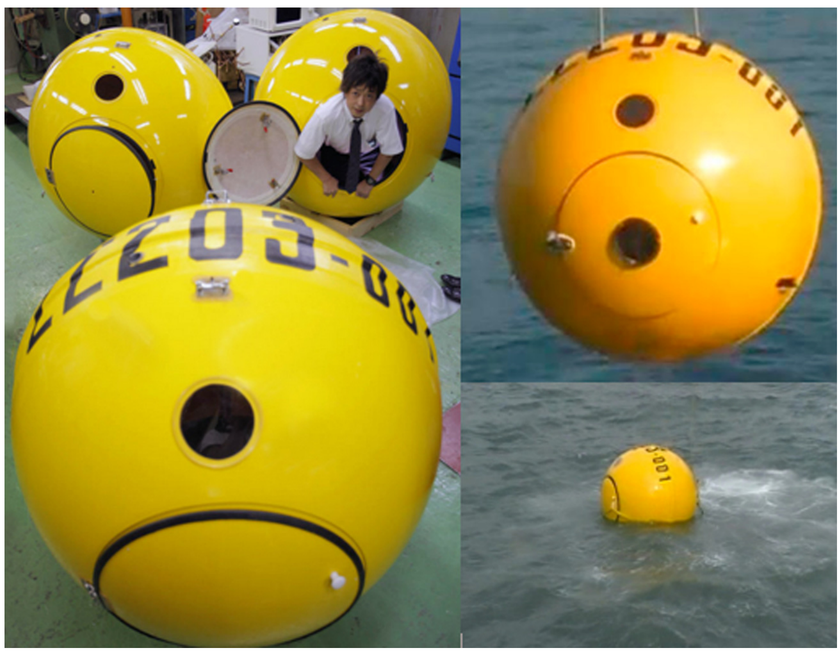

Fig. 1. A tsunami proof vessel, it holds up several people.

orthotropic layers. He expressed the governing equations in terms of the transverse displacement, stress function and rotation. Numerical results on the buckling and post-buckling behavior of spherical caps under uniformly-distributed loads were presented for various boundary conditions, cap rises, base radius-to-thickness ratios, numbers of layers and material properties. Dumir et al. [7] presented axisymmetric buckling analysis for moderately thick laminated shallow annular spherical cap under uniformly distributed transverse load. In their study, buckling is considered under quasi- static load. Annular spherical caps have been analyzed for clamped and simple supports with movable and immovable in-plane edge conditions and typical numerical solutions have been compared with the classical lamination theory.

Zhang et al. [8] investigated the buckling of spherical shells subjected to external pressure. They performed geometrically and materially nonlinear buckling analysis of thin-walled stainless steel spherical shells and compared the results with experimental data. All test samples buckled within an elastic- plastic range. According to their findings, the real load- carrying capacity of a spherical shell can be obtained numerically from measured geometric shape and average wall thickness, as well as from the assumption of elastic- perfectly plastic material properties.

Karagiozova et al. [9] studied the deformation and snap-through behavior of a thin-walled elastic spherical shell in the form of a table tennis ball subjected to axial compression under quasi-static and impact loading experimentally and numerically. In this study, the researchers evaluated the influence of dynamic effects on the compression process.

Gupta and Gupta [10] studied the different collapse modes of metallic hemispherical domes which are resting on a flat plate and are compressed with axial central point load and offset load. They developed a finite element computational model for the axisymmetric mode of collapse. In their proposed model the material of the deforming dome has been idealized as rigid viscoplastic. They used experimental results to validate the computational model. Then, the effects of the different process parameters on the deformation behavior of the shells have been presented and discussed.

Yang et al. [11] investigated peripheral deformation and buckling of stainless steel hemispherical shells compressed by a flat plate. They performed an experimental investigation on stainless steel hemispherical shells under axial compression. They used eight kinds of shells with radius-to-thickness ratios that range from 57.1 to 125 for their experimental study. They compressed shells by a solid flat plate. Based on their experimental observations and the slope of load-deformation curves, the deformation process of thin shells compressed between two plates can be divided into four different stages: local flattening, axi-symmetric inward dimpling, non-symmetric multiple lobes, and peripheral deformation and buckling stage.