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Buckling of Shells—Pitfall for Designers

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1. Introduction

Purpose

IN order to produce efficient, reliable designs and to avoid unexpected catastrophic failure of structures of which thin shells are important components, the engineer must understand the physics of shell buckling. The objective of this survey is to convey to the reader a "feel" for shell buckling, whether it be due to nonlinear collapse, bifurcation buckling, or a combination of these modes. This intuitive understanding of instability is communicated by a large number of examples involving practical shell structures which may be stiffened, segmented, or branched and which have complex wall constructions. With such intuitive knowledge the engineer will have an improved ability to foresee situations in which buckling might occur and to modify a design to avoid it. He will be able to set up more appropriate models for tests and analytical predictions. The emphasis here is not on the development of equations for the prediction of instability. For such material the reader is referred to the book by Brush and Almroth.[11]

Emphasis is given here to nonlinear behavior caused by a combination of large deflections and plasticity. Also illustrated are stress redistribution effects, stiffener and load-path eccentricity effects, local vs general instability, imperfection sensitivity, and modal interaction in optimized structures. Scattered throughout the text are tips on modeling for computerized analysis. The survey is divided into nine major sections describing: 1) several examples of catastrophic failure of expensive shell structures; 2) the basics of buckling behavior; 3) "classical" buckling and imperfection sensitivity; 4) nonlinear collapse and the appropriateness of linear bifurcation buckling analyses for general shells; 5) bifurcation buckling with significant nonlinear prebuckling behavior; 6) effects of boundary conditions, load eccentricity, transverse shear deformation, and stable postbuckling behavior; 7) optimization of buckling-critical structures with consequent modal interaction; 8) a suggested design method for axially compressed cylinders with stiffeners, internal pressure, or other special characteristics; and 9) two examples in which sophisticated buckling analyses are required in order to derive improved designs. The paper focuses on static buckling problems.

Some Catastrophic Failures

To the layman buckling is a mysterious, perhaps even awe-inspiring, phenomenon that transforms objects originally imbued with symmetrical beauty into junk (Fig. 1.1). Occasionally unaware of the possibility of buckling, engineers have designed structures with inadequate safety margins (Fig. 1.2). The large cylindrical tower on the left in Fig. 1.3 failed in 1956[1] because of buckling under internal hydrostatic pressure of a torispherical end closure at its lower end. A 38 m tall steel water tower, the tank portion of which is sketched in Fig. 1.4, collapsed in 1972[2,3] when it was being filled for the first time. The collapse of the entire tower was triggered by local instability in the conical portion of the tank at the deepest water level in a mode similar to that displayed for the Mylar laboratory model photographed in Fig. 1.5.[4] According to the prediction given in Fig. 1.6,[5] nonsymmetric bifurcation buckling occurs at a load factor $p_{nb} = 0.943$, slightly below that corresponding to axisymmmetric collapse,

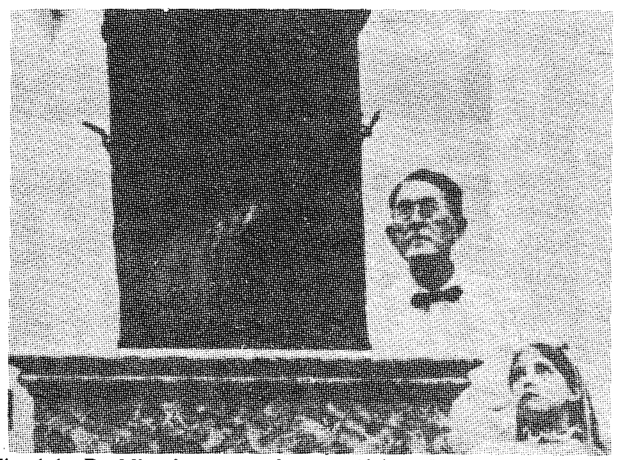

Fig. 1.1 Buckling is a somewhat mystifying phenomenon (courtesy of St. Regis Paper Co.).

David Bushnell joined Lockheed Missiles & Space Company, after receiving his B.S. and M.S. degrees in aerospace engineering from the Massachusetts Institute of Technology in 1961. In 1965, while at Lockheed, he earned his Ph.D. in Aeronautics and Astronautics at Stanford University. He then began extensive investigations of the stress, buckling, and vibration behavior of thin shell structures. That work has resulted in over 40 papers and ultimately in the development of the BOSOR4 and BOSOR5 computer programs, widely used codes for the stress, buckling, and vibration analysis of shells of revolution. Many of the examples in this survey article are based on applications of these computer programs to practical problems involving complex shell structures. In 1975 Dr. Bushnell received the ONR/AIAA Structural Mechanics Research Award, the topic of his investigation being "Stress, Buckling, and Vibration of Hybrid Bodies of Revolution." He served as Associate Editor of the *AIAA Journal* from 1977 to 1979 and was a member of the AIAA Structures Technical Committee 1978 to 1979. Dr. Bushnell was elected the Outstanding Engineer of the AIAA San Francisco Chapter for the year 1978, and is an Associate Fellow.

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