Marine Structures 22 (2009) 836–854

Contents lists available at ScienceDirect

Marine Structures

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

Influence of residual stresses and geometric imperfections on the elastoplastic collapse of cylindrical tubes under external pressure

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ARTICLE INFO

Article history:
Received 23 January 2009
Received in revised form 24 July 2009
Accepted 5 September 2009

Keywords:
Buckling
Elastoplasticity
Imperfection sensitivity
Residual stresses
Cylindrical containers under external pressure

ABSTRACT

The buckling problem of a circular cylindrical shell has long been widely investigated due to its great importance in the design of aerospace and marine structures. Geometric imperfections and residual stresses are inevitable in practice and have been so far frequently considered in analytical and numerical predictions. But little attention has been paid until now on the combined influence of such initial defects on the critical and often unstable response of such elastoplastic structures. In this paper, a shell finite element is designed within the total Lagrangian formulation framework to deal with the elastoplastic buckling and post-buckling of thin cylindrical tubes under external pressure and axial compression. A specific experimental process will be introduced in order to measure residual stresses in the shell very accurately, so as to include them in the numerical calculations. The present formulation will enable us to describe the complete non-linear solutions, namely the critical pressures (bifurcation and limit (collapse) loads), the bifurcation modes and the bifurcated equilibrium branches up to advanced post-critical states. Comparisons will be

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doi:10.1016/j.marstruc.2009.09.003

made between numerical results and the experimental critical value and deformation patterns of a new generation profiler. Furthermore, the combined effects of geometric imperfections, residual stresses and plasticity will be analyzed.

1. Introduction

Failure of thin structures submitted to compressive loadings is mainly due to the buckling phenomenon. Their mechanical design implies thus the analysis of their buckling and post-buckling behaviors, namely the calculation of the critical loads, the bifurcation modes and possibly the post-critical equilibrium branches.

In elasticity, the bifurcation is related to the structural instability as shown in Koiter's theory. The problem is much more difficult with thicker structures where plasticity may occur before buckling. From a theoretical point of view, Shanley [1] was the first to give the tangent modulus critical load for a discrete model. Then, Hill [2] extended these results to a three-dimensional continuum by using the concept of "comparison elastic solid". He examined the uniqueness and stability criteria, and pointed out the difference between bifurcation and stability.

A comprehensive work on the buckling of structures was presented by Brush and Almroth [3]. They examined the effect of initial imperfections, inherent in many real structures, on the critical loads. When dealing with the buckling phenomenon, cylindrical shells are certainly among the most sensitive structures to all imperfection types (in comparison with beams and plates) and, as a matter of fact, very useful in industrial applications. For example, the bifurcation of a cylinder under axial compression, like a spherical shell under external pressure, corresponds to a sub-critical point (a load limit point on the bifurcated branch), namely an upper bound for the strength of the shell in the post-critical behavior. For that reason, the critical problem of a cylinder under axial compression was the subject of a lot of experimental and numerical investigations [4,5]. A wide variety of experimental results were obtained in terms of the boundary conditions, the geometries and the material parameters. Furthermore, different numerical models were devised in order to predict the critical loads as well as the advanced post-buckling behavior. Among others, Tvergaard [6] analyzed the effect of geometric and material parameters on the buckling behavior of a cylinder under axial compression. It was also shown that the boundary conditions are a deciding factor for obtaining various types of buckling modes. From a material point of view, different critical values are obtained in the literature, depending on the plasticity theory considered. In the case of a cylinder under axial compression, the critical stresses obtained by the deformation theory are fairly far from the ones corresponding to the flow theory. As a matter of fact, the solutions derived from the deformation theory turn out to compare best with the experimental results, although such a theory does not take into account the elastic unloading possibility. On the contrary, the flow theory overpredicts the critical loads. Comparisons between the predictions of both flow and deformation theories and experimental results were recently performed in Bardi and Kyriakides [7] and Bardi, Kyriakides and Yun [8], in the case of axially loaded cylindrical shells, including the effect of anisotropy with the use of Hill's yield criterion. The flow theory is shown to significantly overpredict both the critical stresses and strains, whereas the deformation theory gives rise to predictions much closer to the experimental values.

For this loading case, large discrepancies have always been observed between numerical and experimental results. The most significant feature is that the experimental critical loads sometimes fall down to less than half of the numerical values, see for instance Singer [9] for a review on the importance of shell buckling experiments. These differences, due to unavoidable imperfections in experiments, were explained by many authors. If the major influence of geometric imperfections on the buckling behavior of cylindrical shells is universally recognized, the importance of residual stresses has also been enhanced in the case of axial compressive stresses. Just let us mention Mandal and Calladine [10] and Lancaster, Calladine and Palmer [11], who investigated the buckling under self-weight of cylinders with free ends by means of an adequate experimental set-up. Since the ends were able to