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Influence of wall constructions on the load-carrying capability of light-weight structures

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Dedicated to Professor Choon Fong Shih, President of the National University of Singapore on the occasion of this 60th birthday.

Abstract

Results of systematic numerical studies are presented which suggest that suitable alternative wall constructions may lead to elastic load-carrying capacities of light-weight structures which significantly exceed those of conventional monocoque constructions, and that in certain cases this improvement may also be accompanied by a decrease in imperfection-sensitivity. Two kinds of wall modifications are considered: a hybrid wall construction where the skin of a light-weight structure is coated with a low-density material, and nonhomogeneous – in particular lattice and biaxially corrugated – wall constructions. The paper focuses on the elastic load-carrying behavior of shell- and plate-like structures, and structural efficiency is assessed on the basis of their bifurcation buckling resistance while other design criteria, such as e.g. stiffness and plasticity, are not taken into account.

Keywords: Auxetic lattices; Elastic buckling; Finite element method; Lattice structures; Light-weight structures; Load-carrying capability; Hybrid structures

1. Introduction

To ensure the economy, safety, and long-term reliability of lightweight structures, their load-carrying capability should be as high and their imperfection-sensitivity as low as possible. Unfortunately, numerous investigations on the buckling and postbuckling behavior of shells performed over the past decades seem to indicate that optimizing the weight-efficiency of thin-walled compression members inevitably leads to a catastrophic buckling behavior – and a correspondingly high imperfection-sensitivity – which in design practice is usually accounted for via empirical knock-down factors (Arbocz and Singer, 2000; Brush and Almroth, 1978; Budiansky, 1974, 1999; Hutchinson and Koiter, 1970; Koiter, 1945, 1963; NASA, 1965, 1968; Singer et al., 1997, 2002; Thompson, 1972; Thompson and Lewis, 1972; Thompson and Supple, 1973). Well-known classical

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examples of this are monocoque shells and, in particular, the circular cylindrical shell under axial compression as well as the spherical shell subjected to uniform external pressure. Perfect (elastic) configurations of these structures tend to fail suddenly, and their experimental buckling loads are merely a fraction of their respective theoretical values. Similar tendencies are typically also observed in the case of optimized structures such as, for example, stringer-stiffened and sandwich shells.

On the other hand, the results of the numerical studies presented below indicate that suitable alternative wall constructions can lead to elastic load-carrying capacities which significantly exceed those of conventional monocoque structures, and that in certain cases this improvement may also be accompanied by a decrease in imperfection-sensitivity. Both effects are of considerable practical importance because they may justify increased allowable design loads and/or a corresponding reduction in structural weight. This opens the way to interesting new types of lightweight construction.

Two kinds of wall modifications are considered here: In the first case – a hybrid wall construction – the skin of a light-weight structure is coated with a low-density material, while in the second nonhomogeneous wall constructions are considered. In both instances the effective biaxial bending stiffness is increased (with only a moderate or no increase in weight), which, in turn, leads to a significant improvement in the overall load-carrying capability.

The purpose of the present article is to explore the extent to which such alternative wall constructions may increase the load-carrying capability of thin-walled structures (with an emphasis on plates and shells) as well as to assess their potential usefulness as weight-saving alternatives to conventional kinds of light-weight construction. The treatment aims at baseline assessments of the efficiency of the structural configurations investigated and is not meant to be exhaustive. In particular, structural comparisons are made solely on the basis of elastic buckling resistance, and – as a first step – failure is equated with bifurcation buckling (see also Budiansky, 1999). More specifically, linear elastic bifurcation loads are used as the primary strength criterion, whereas the influence of other relevant design factors, such as e.g. stiffness and/or plastic deformations, on the load-carrying behavior have not been taken into account in this investigation. These aspects are the subject of ongoing research.

All quantitative evaluations are based on systematic numerical analyses using the finite element codes ABAQUS and ANSYS, and pertinent details concerning the computational models employed will be given in the later chapters.

2. Hybrid wall constructions

From experiments on silicon rubber cylinders filled with rubber foam, and analytical results based on judiciously simplified mechanical models (Karam and Gibson, 1995), as well as preliminary numerical studies reported in (Obrecht et al., 2006), one may conclude that substantial improvements in the elastic load-carrying capability and weight-efficiency of thin-walled compression members are possible when their skin is coated – on one or both sides – with layers of a low-density material whose thicknesses are small in comparison with the structure's overall dimensions and which therefore make only a limited contribution to the total weight. In addition, some of the results indicate that such compliant layers may also lead to a reduced degree of imperfection-sensitivity. As a result, coated shells of this type may have competitive weight- and strength-advantages over more established types of thin-walled construction – such as e.g. monocoque, stiffened, or even sandwich configurations.

Since for axially compressed elastic circular cylindrical shells both the theoretical load-carrying capacity – given by the classical bifurcation stress σ_{cl} (see Eq. (1)) – and the imperfection-sensitivity are particularly high, they are ideal candidates for testing the effectiveness of such hybrid wall constructions. Taking the classical buckling and imperfection-sensitivity analyses by Koiter (1963) and Budiansky and Hutchinson (1972) on axially compressed circular cylindrical shells as a starting point, the configuration shown in Fig. 1 was chosen as the basic mechanical model. Its geometrical and material parameters are the shell's thickness t, its radius R, length L, Young's modulus E_s, and Poisson's ratio ν_s, as well as the thicknesses t_c and t_o of the inner and outer layers, and their respective Young's moduli E_c and E_o, and Poisson's ratios ν_c and ν_o. To facilitate the interpretation of the results given below, various thickness levels of the inner and outer layers (t_c and t_o) are also plotted in the right-hand part of Fig. 1. Both hollow and coated, perfect and imperfect configurations are con-