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Optimization of cylindrical shells stiffened by rings under external pressure including their post-buckling behaviour

Paweł Foryś *

Institute of Applied Mechanics, Cracow University of Technology, al. Jana Pawła II 17, 31-864 Kraków, Poland

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ABSTRACT

Optimization of a simply supported cylindrical shell stiffened by inner rings is considered in this paper. The shell is loaded by external pressure. The first critical buckling load is maximized. A material volume and a slope of a post-critical path are assumed as optimization constraints. The inner rings are made from the material obtained from the shell by decreasing its thickness. This way the volume of the material remain constant. The structure is modelled and solved by the finite element method (FEM). The linear and nonlinear stability analyses are done in the ANSYS software. An effect of geometric imperfections on a shape of equilibrium path is discussed. The optimization was performed numerically using the modified particle swarm optimization method (MPSO). The results are compared with a reference cylindrical shell with no rings. The single ring placed in the middle of the shell is good enough for stabilization of a post-buckling path for a shorter shell, regardless of its thickness. It is necessary to use three rings optimally distributed along the shell length, for a longer shell. The additional optimization profit was obtained by varying internal diameters of the rings. The proposed concept of shell stiffening by inner rings eliminates a major disadvantage of smooth cylindrical shells, namely an unstable post-buckling path.

1. Introduction

The problems of optimization of shells against instability have received considerable attention for several decades and resulted in the numerous studies. The detailed surveys on the optimization of shells with respect to their stability are given, among others, by Krużelecki and Życzkowski [1], Życzkowski [2], Krużelecki [3]. The monographs by Gajewski and Życzkowski [4], Bochenek and Krużelecki [5] are devoted to structural optimization under stability constraints. Most of the papers concern the classical formulation of the optimization problems, which deals with maximization of the critical loading parameters under the appropriate constraints. It can be obtained either by an optimal modification of shape functions, namely by changing of a shape of a middle surface or a wall thickness or by application of the optimal reinforcements (inner or outer circular rings, longitudinal stringers, etc.).

Change of a shape of unstiffened shells with respect to a buckling load was investigated by Błachut and Wang [6]. The authors considered barreled shells subjected to hydrostatic external pressure. Błachut [7] presented results of maximization of the critical force of an externally pressurized shell. The optimal geometry has been sought within a class of generalised ellipses. Jasion and Magnucki [8] presented a procedure for designing a family of shells of revolution of a constant volume loaded by uniform external pressure. The problems of an optimal design of axially symmetrical shells against instability under hydrostatic pressure was considered by Krużelecki and Trzeciak [9], under elevated temperature induced load by Życzkowski et al. [10] and under combined loadings by Barski and Krużelecki [11] and Barski and Krużelecki [12]. The volume of a material and a capacity of a shell were considered as the equality constraints. The concept of a shell of uniform stability was applied.

The application of optimal reinforcements was the subject of research of Bushnell and Bushnell [13]. The authors presented the PANDA2 computer program for minimum-weight design of ring and stringer stiffened cylindrical shells. Tian and Wang [14] presented the Ritz method for the elastic buckling analysis of shells with ring stiffeners under general pressure loading. The cross-section of ring stiffeners can be of any shape and the rings can be arbitrarily distributed along a shell length. Graham [15] described the application of the finite element analysis to prediction of nonlinear elastic–plastic collapse of ring-stiffened cylinders under hydrostatic loading. Salehghaffari et al. [16] investigated quasi-static axial collapse response of cylindrical tubes externally stiffened by multiple identical rings.

* Fax: +48 12 628 33 70.
E-mail address: Pawel.Forys@pk.edu.pl

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Maximization of the critical load can often results in an unstable equilibrium path of a structure. That behaviour of a structure is unsafe during and after its critical working. The post-buckling behaviour of shells without stiffening was a subject of interest by Jasion [17]. The author considered a family of elastic shells of revolution, with the positive and negative Gaussian curvatures subjected to external pressure. The influence of a meridional radius of curvature on the critical load and the shape of the post-buckling path are presented. An unstable post-buckling path can be avoided by adding additional constraints into an optimization task. The concept, classification and formulation of non-standard optimization including constraints imposed on stability of a post-buckling path have been proposed by Bochenek [18], Bochenek [19] and Bochenek [20]. The numerical results for design of frame and shell structures are presented by Bochenek and Krużelecki [21] and Bochenek and Foryś [22]. In this later paper the particle swarm optimization method (PSO) was successfully applied. The evaluated version of the PSO named the modified particle swarm optimization (MPSO) was applied to optimal design of rotationally symmetrical shells of uniform stability stiffened by ribs by Foryś [23].

The stabilization of a post-buckling path for simply supported cylindrical shells of different length and thickness by the additional loadings acting on the structure without changing the shape or sizes of the optimized element was a subject of the following series of papers. Król et al., [24] presented results for shells loaded by radial compressive pressure. Krużelecki and Trybuła [25] presented results for shells loaded by torsion. Krużelecki and Trybuła [26] presented results for shells under combined state of loadings. Trybuła and Krużelecki [27] presented results for elastic–plastic cylindrical shells under external pressure and twisting moment. Three types of additional loadings were considered: active force applied to the structure, passive ones (the reactions of the additional supports) and both acting simultaneously. The additional load improves resistance against buckling and can stabilize an unstable post-buckling path.

The optimal design of a geometrically nonlinear elastic stiffened panel and an idealized fuselage section is presented by Ringertz [28]. Some form of homogenization e.g. the smeared stiffener technique is usually applied for more advanced structures. The post-buckling analysis of imperfect stiffened laminated cylindrical shells under combined loadings is presented by Shen [29]. Van Dung and Hoa [30] analyzed cylindrical shells stiffened by functionally graded rings and stringers under external pressure. Bisagni and Cordisco [31] described experimental data obtained from buckling and post-buckling tests on three stiffened composite cylindrical shells under combined loadings performed until collapse occurred. The framework of surrogate-based optimization including load-carrying capacity and imperfection sensitivity for stiffened shells is proposed by Hao et al. [32].

In this paper the stability of a post-buckling path for a cylindrical shell stiffened by inner rings loaded by uniform external pressure is included in the optimization process. The main goal is to raise the first critical buckling load and obtain the stable equilibrium path, simultaneously. It is assumed that the number of rings equals one or three. The rings are made from the material of the shell by decreasing its thickness. The volume of the material of the shell is constrained by the volume of the material of the reference cylindrical shell. The issue is important and it is lack of such solutions in the literature, so far.

2. Model of shell and method of solution

2.1. Model of stiffened shell

The non-stiffened reference and stiffened cylindrical shells are presented in Fig. 1. The geometry is described by the following symbols: R_0 stands for the radius of the shell, L_0 means its length and H_0 is the thickness of its wall. These values are constant. The shell is simply supported. It means that the shell edges cannot move in the radial direction but they can move in the axial and circumferential directions. Additionally, the two opposite nodes, placed in the middle of the shell length are constrained in the axial and circumferential directions to prevent the shell from possible rigid body motion. The shell is loaded by uniform external pressure p.

The shell – which parameters are looked for in the optimization task – is stiffened by one or three rings. The rings are distributed symmetrically with respect to the middle vertical symmetry plane. The following symbols are introduced: H is the wall thickness, H_0 is the rings width (constant and equals the thickness of the reference shell), r_2 and $r_{1,3}$ are the radii of the middle and the two outer rings, respectively, $z_{1,3}$ is the distance between the middle and the outer ring.

The finite element method (FEM) is used to solve the analysis task. The parametric model of the shell is created and written in the ANSYS Parametric Design Language (APDL). The finite element named SHELL181 is used. It has four nodes. Each node has six degrees of freedom: translations in the x, y and z directions and rotations about the x, y and z axes. It is well suited for large strain

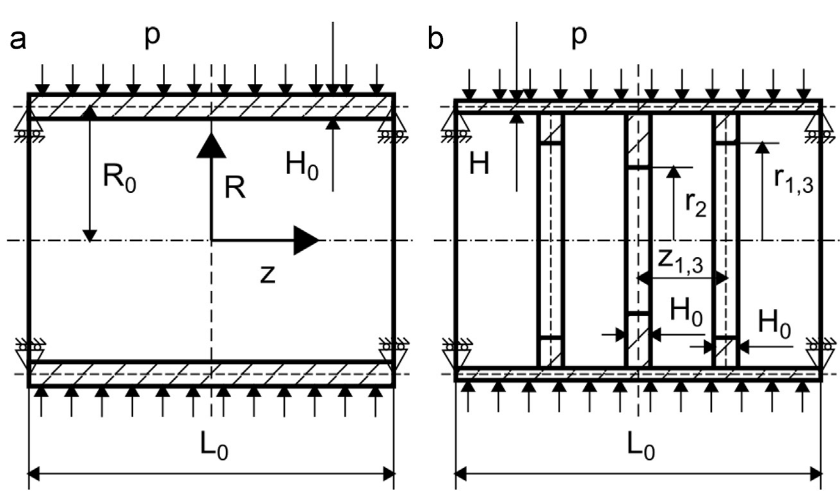

Fig. 1. Geometry, support and load conditions for (a) reference cylindrical shell and (b) stiffened cylindrical shell.