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Reaction forces control design of shell structures in plastic range based on free-form optimization method

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ABSTRACT

In this study, we propose an optimization method for the reaction forces control problem of shell structures in plastic range. The sum of squared error norms between reaction forces in the plastic range and the target forces are minimized under a volume constraint. The total strain theory is employed for simplicity under the assumption that the considered force or enforced displacement increases monotonically, so that the final deformation is path-independent. The optimum shape design problem is formulated as a distributed-parameter system, and we assume that a shell is varied in the out-of-plane direction to the surface whereas the thickness is not varied during the shape change. The shape gradient function and the optimality conditions for this problem are derived theoretically using the material derivative method and the adjoint variable method. The shape gradient function calculated from a non-linear finite-element analysis is applied to the H^1 gradient method for shells proposed by one of the authors to determine optimum shape variation. The optimal shape of a shell structure can be obtained without shape parameterization while maintaining surface smoothness. Numerical examples are presented to demonstrate the validity and practical utility of the proposed free-form optimization method.

1. Introduction

Shell structures have been widely utilized in industrial structures such as automobiles, airplanes, and civil structures. They have excellent structural characteristics and eco-friendly features (e.g., they are resource-saving), but easily encounter insufficient strength, buckling, or vibration problems. Therefore, optimum designs for shell structures are strongly demanded not only in the elastic range but also in the plastic range. Automotive suspensions are generally required to have sufficient strength against nonlinear buckling under unanticipated loading. A crash box attached to the front end of an automotive body is also an example of plastic design, where nonlinear buckling behavior is used positively to absorb kinetic energy. It is important in these nonlinear buckling design problems to keep the material strength in the plastic range wherein material and geometrical nonlinearities need to be considered. In the present work, we try to develop a numerical shape optimization method for controlling the strength of a shell structure under plastic deformation considering material and geometrical nonlinearities.

From the perspective of the wide range of numerical structural optimization considering nonlinearities, many works have been reported. For instance, in size optimization, Kamyab and Salajegheh [1] carried out size optimization of nonlinear scallop domes using an enhanced particle swarm optimization (EPSO) algorithm in which the EPSO was constructed by hybridizing the particle swarm optimization algorithm and a cellular automata computational strategy. Yuge and Kikuchi [2] carried out topology optimization of a frame structure subjected to plastic deformation based on the generalized layout optimization method. Buhl et al. [3] dealt with topology optimization of structures undergoing large deformations. Bruns and Tortorelli [4] proposed a topology optimization method for compliant mechanism designs with large displacements and hyperelastic materials. The topology optimization problem with geometrical nonlinearity was also solved by Gea and Luo [5], where the optimization problem was formulated using a microstructure-based design domain and was solved by a sequential convex approximation method. Jung and Gea [6] presented topology optimization considering both material and geometrical nonlinearities. Stegmann and Lund [7] proposed a topology optimization method for layered shell structures with geometrical nonlinearity in which the topology optimization of shell structures was fulfilled using the SIMP approach together with a filtering scheme. Osaki and Nishiwaki [8] implemented topology optimization with

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geometrical nonlinearity for truss shapes. Gomes and Senne [9] developed an alternative algorithm named "sequential piecewise linear programming" for the design of structures under small displacements which was an extension of the sequential linear programming algorithm proposed by the same authors. Yoon et al. [10] investigated topology optimization of a continuum structure tracing a prescribed nonlinear load-displacement trajectory. In shape optimization, Ihara et al. [11] proposed a nonparametric design method for the compliance minimization problem of solid structures with material nonlinearity and the displacement control problem of solid structures with geometrical nonlinearity. Ha and Cho [12] developed a level-set-based topological shape optimization method for geometrically nonlinear structures with hyperelastic materials in a total Lagrangian framework by using an unstructured mesh. Based on the H^1 gradient method, Shintani et al. [13] proposed a solution for the mass minimization problem of solid structures subjected to a reaction force. Lee et al. [14] employed the equivalent static loads method for nonlinear static response structural optimization to determine a workpiece's shape.

Among the work concerning shape optimization of shell structures with nonlinearities, most of the proposed numerical optimization methods for shape design of shell structures are classified as parametric methods. In such methods, a shell is parameterized by using parametric surfaces, design elements, or CAD parameters and then the optimum parameters are searched in the vector space by combining mathematical programming with sensitivity analysis. Ringertz [15] describes a numerical method for the optimal design of nonlinear shell structures using finite element analysis and the Newton barrier method. Awruch and Almeida [16] studied multi-objective optimization of composite laminate plates considering the geometrically nonlinear behavior by using genetic algorithm (GA) and finite element method (FEM). Tanlak et al. [17] investigated optimal shape design of box-shaped bumper beams mounted on vehicles and served as shock absorbers. Khosravi et al. [18] proposed size and shape optimization of thin-walled structures with geometric nonlinearity, where the optimal shapes were obtained using the optimality criteria method without performing the sensitivity analysis. The response surface method was also employed in some studies. Yamazaki and Han [19] designed tubes owning the maximizing energy absorption capacity by using the response surface method and mathematical programming. Avalle et al. [20] proposed a multipoint optimization procedure based on the response surface methodology to solve problems concerning an impact load to tubular thin-walled structures. Kurtaran et al. [21] optimized the shapes of a cylindrical tube, a simplified vehicle and so on for crashworthiness design by using the response surface method and GA. A stochastic process based on the response surface method is utilized by Lee et al. [22] in order to maximize the crashworthiness characteristics of a cylindrical tube. This method is especially good at modelling the nonlinear, multi-modal functions that often bring about in design engineering. Zarei and Kroger [23] adopted a multi-objective crashworthiness optimization of tubes to maximize energy absorption and specific energy absorption of dynamic crash problem. The D-optimal design of experiments method has been applied in order to reduce the number of needed points for approximations in the response surface method. This method is effective for reducing the number of design variables and seldom causes a jagged boundary problem. However, it can't avoid the parameter dependency and the optimal shape is only determined in a small design vector space. In other words, the structural performances of the obtained shape and the optimal shape are limited.

In contrast, parameter-free methods can avoid the problems of parametric methods, but have seldom been studied. Firl and Bletzinger [24] proposed a node-based method with nonlinear kinematics in order to optimize the shape of thin shell structures.

With the above background concerning shape optimization of shell structures with nonlinearities, we propose a parameter-free, or free-form, shape optimization method for designing the optimum free-form shape of a shell structure with material and geometrical nonlinearities. Shimoda and his partners proposed the free-form optimization method for shells that originated from the traction method [25], and applied it to linear stiffness problems with isotropic material [26] and with orthotropic material [27]. This method consists of four main processes: (1) theoretical derivation of the shape sensitivity, also called the shape gradient function, in a function space based on the material derivative method and the adjoint variable method; (2) numerical calculation of the shape gradient function; (3) determination of the optimum shape variation by using the H^1 gradient method for shells; and (4) shape updating. In the present work, we extend this method to the free-form design problem of a shell structure considering material and geometrical nonlinearities with the aim of controlling the reaction forces within target values under a volume constraint. Using the free-form optimization method for shells, we obtain optimum free-form shells efficiently without any shape parameterization while maintaining surface smoothness.

However, computational cost becomes a large problem since nonlinear analyses with plastic deformation are repeatedly implemented for shape optimization. In order to avoid this problem, we employ the total strain theory with load path independence under the assumption that the loading increases monotonically. Although this assumption is not strictly true, it is often introduced in simulations for plastic forming to reduce computational cost [13]. For instance, the panel stiffness, oil-canning resistance, and dent resistance of shell structures are evaluated in the development of automotive doors or hood, where the monotonically increasing force or enforced displacement is applied [28,29]. Furthermore, in the plastic design of shell structures in various fields, the dynamic problems are often changed to the static problems for simplification, where the static deformation quantity or reaction force is evaluated according to the monotonically increased force or enforced displacement instead of the dynamic one. This simplification can be also applied in the strength design of suspension under abnormal loads, strength design of interior parts in terms of head-on collision, initial reaction force design of crash box under low-speed collision, and so on in the design of automotive structures. Note that shell structures under compressive loads often buckle before going to plastic range. The reaction force in such behavior can also be controlled with the proposal method, because we considered both of material nonlinearity and geometrical nonlinearity.

In the following sections, the domain variation for free-form shell design and the governing equation for the shell structure are described first. Next, we formulate the problem as a distributed-parameter system in which the sum of squared error norms between the reaction forces and the target values is minimized under a volume constraint. The shape gradient function and the optimal conditions of this problem are derived theoretically using the material derivative method and the Lagrange multiplier method. Next, we introduce the H^1 gradient method for shells to determine optimum shape variation in detail. Finally, the validity and practical utility of this method are verified through four design examples.

2. Shape variation and governing equation for a shell as a set of infinitesimal flat surfaces

2.1. Governing equation

As shown in Fig. 1 and Eq. (1), we consider a shell of initial bounded domain $\Omega \subset \mathbb{R}^3$ (boundary $\partial\Omega$), mid-surface A (boundary ∂A), side surface S, and plate thickness h. It is assumed for simplicity that a shell structure occupying a bounded domain is a set of infinitesimal flat surfaces as shown in Fig. 1, in which the notation dA expresses a small area.