



Stress constraints sensitivity analysis in structural topology optimization

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ABSTRACT

Sensitivity Analysis is an essential issue in the structural optimization field. The calculation of the derivatives of the most relevant quantities (displacements, stresses, strains) in optimum design of structures allows to estimate the structural response when changes in the design variables are introduced. This essential information is used by the most frequent conventional optimization algorithms (SLP, MMA, Feasible directions) in order to reach the optimal solution. According to this idea, the Sensitivity Analysis of the stress constraints in Topology Optimization problems is a crucial aspect to obtain the optimal solution when stress constraints are considered.

Maximum stiffness approaches usually involve one linear constraint and one non-linear objective function. Thus, the computation of the required sensitivity analysis does not mean a crucial limitation. However, in the topology optimization problem with stress constraints, efficient and accurate computation of the derivatives is needed in order to reach appropriate optimal solutions. In this paper, a complete analytic and efficient procedure to obtain the Sensitivity Analysis of the stress constraints in topology optimization of continuum structures is analyzed. First order derivatives and second order directional derivatives of the stress constraints are analyzed and included in the optimization procedure. In addition, topology optimization problems usually involve thousands of design variables and constraints. Thus, an efficient implementation of the algorithms used in the computation of the Sensitivity Analysis is developed in order to reduce the computational cost required. Finally, the sensitivity analysis techniques presented in this paper are tested by solving some application examples.

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1. Introduction

Since topology optimization of continuum structures problems was studied by Bendsoe and Kikuchi in 1988 [1,2], important tasks have been extensively analyzed (e.g. the Sensitivity Analysis and the Optimization Algorithms used to obtain the optimal solution). Although there are optimization algorithms that do not require the Sensitivity Analysis (e.g. GA, Optimality criteria [28,34]), most of the conventional optimization algorithms require specific information about the derivatives of the objective function and the constraints [8,10,18,21,22,31]. In fact, when the problem involves a large number of design variables and constraints, high order derivatives are more appropriate to reach the optimal solution [16–18].

Structural Topology Optimization problems with stress constraints usually introduce a large number of design variables (usually one design variable per element of the mesh of finite elements: the relative density [1–3,8,19,22,26,33]) and a large number of non-linear constraints (usually one stress constraint in the central node of each element [4,8,9,11,21,22,26,33]). In addition, if several load cases are considered, the number of stress constraints increases considerably.

In this paper, three different formulations of the stress constraints have been analyzed: the local approach [4,8,22,26,33], the global approach [14,22,24,25,27] and the block aggregation approach of the stress constraints [24,25].

According to that, the resulting optimization problems require efficient and specific optimization algorithms [16,22,30,31]. These algorithms usually require first order derivatives of the objective function and the constraints. In some cases, higher order derivatives need to be considered in the optimization process in order to avoid unexpected effects (e.g. zig-zag) [16].

In this paper we have used a Sequential Linear Programming with Quadratic Line Search optimization algorithm. This procedure requires first order derivatives of the stress constraints and the objective function, and first and second order directional derivatives of the stress constraints and the objective function [16,21].

The computation of these derivatives can be carried out by using different numerical algorithms (finite differences, analytical derivation). When it is possible and suitable, the most usual technique to obtain the sensitivity analysis is the theoretical analysis. Thus, the derivation algorithm consists in the implementation of the theoretical functions previously obtained by applying analytical differentiation techniques [17].

The analytical computation of the derivatives requires an important and rigorous mathematical study in order to obtain the expressions to

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be implemented in the optimization source code. In this paper we develop the whole derivation process of the stress constraints in topology optimization of structures. This theoretical analysis allows to obtain exact mathematical expressions of the derivatives of the stress constraints and good numerical approximations.

This paper is divided into 10 sections where this introduction is the first one. The second section is dedicated to present and briefly explain the optimization procedure used to solve the topology optimization problem. Section 3 is devoted to state the structural analysis methodology by means of a FEM model. Section 4 corresponds to the study of the sensitivity analysis of constraints that depend on the structural displacements and the design variables. Section 5 presents the sensitivity analysis of constraints that depend on a reference stress and on the design variables by using the algorithms proposed in Section 4. Sections 6, 7 and 8 are devoted to obtain the sensitivity analysis of three different formulations of stress constraints studied by the authors: the local approach, the global approach and the block aggregation of stress constraints. Section 9 presents some numerical examples of the topology optimization problem by using the techniques proposed in the previous sections. Finally, some conclusions are stated in Section 10.

2. Topology optimization methodology

The optimization methodology developed to solve the minimum weight structural topology optimization problem with stress constraints is based on an iterative process. The sensitivity analysis is an essential issue in this methodology to obtain adequate results.

The entire methodology is represented schematically in Fig. 1. Each iteration of the method is developed in a number of stages that need to be analyzed individually.

The first stage is the structural analysis, by means of the FEM, incorporating the effect of the relative density.

The second stage is the computation of the objective function, which is based on the weight of the structure. This objective function may optionally include a perimeter penalization. Then, stress constraints are computed and checked to verify the active constraints. Three different formulations can be used to deal with stress constraints. These formulations have been previously studied by the authors in [21,22].

The next stage is the computation of the first order derivatives of the active constraints. This stage is extensively analyzed in this paper in Sections 4.2.1, 6.1, 7.1 and 8.1.

The sensitivity analysis obtained is used in the next stage of the method to obtain the search direction. This direction is obtained with three different algorithms (see Fig. 1) depending on the number of active constraints (steepest descent method or SLP) and the existence of violated constraints (back to the feasible region algorithm).

Thus, first and second order sensitivity analysis can be obtained by using directional derivatives of the objective function and the constraints in the search direction previously obtained. Note that, the search direction has been already obtained by using one of the algorithms presented before. The analysis and computation of these directional derivatives is extensively studied in this paper in Sections 4.2.2, 6.2, 7.2 and 8.2.

These directional derivatives are included in the second order Taylor expansions of the objective function and the constraints to obtain the most adequate advance step in the search direction.

Finally, the design variables are modified according to the search direction and the advance step, and convergence is checked. If convergence is achieved, the optimal solution has been obtained. Otherwise, the process begins again in the first stage with the modified values of the design variables.

3. Structural analysis of the topology optimization problem

The structural analysis of the minimum weight topology optimization problem proposed in this paper is developed by using a

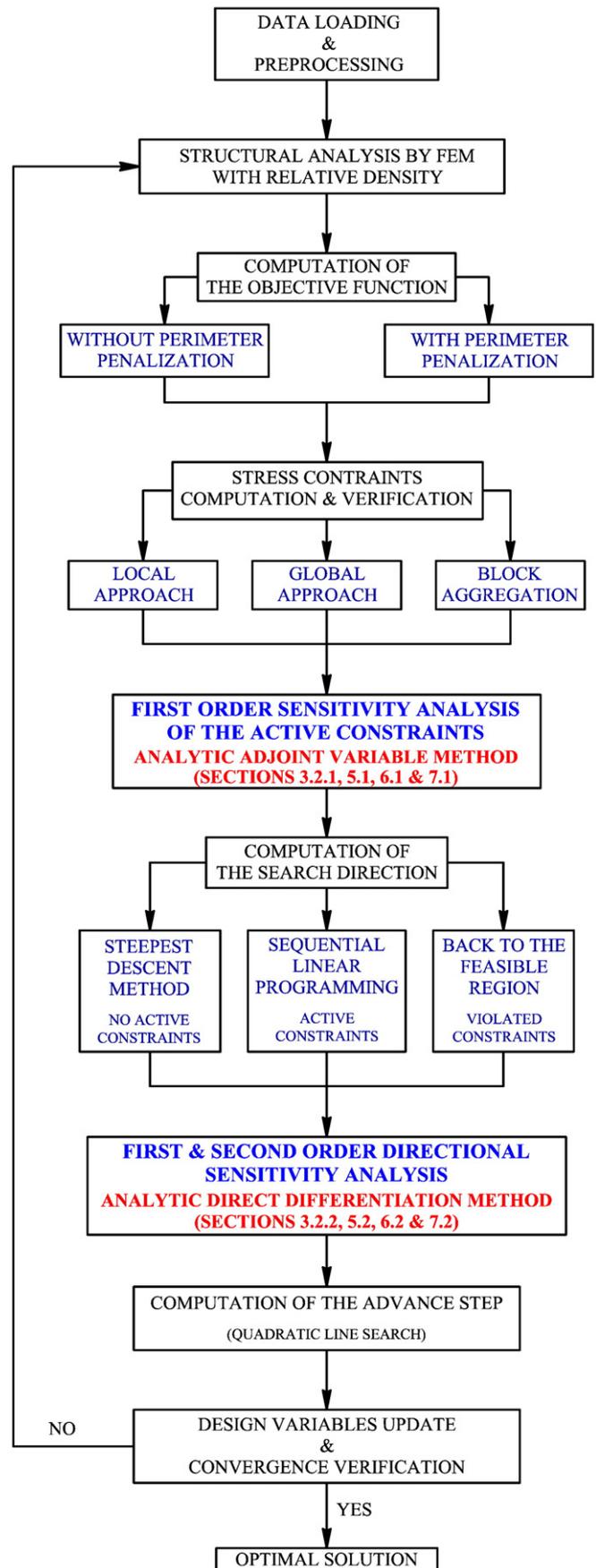


Fig. 1. Scheme of the topology optimization methodology.

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