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Design of carbon fiber reinforcement of concrete slabs using topology optimization

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HIGHLIGHTS

- Topology optimization is used as a tool to locate the region of the reinforcement.
- Optimization technique is compared with the conventional technique for strengthening.
- The aim of optimization is to minimize the quantity of material, thereby reducing costs.
- Similarity of criteria for maximizing the stiffness and strength of the structure is discussed.
- Topology optimization can be an effective tool to support the reinforcement design.

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ABSTRACT

Topology optimization is used as a tool to aid the reinforcement design of concrete slabs with carbon fiber reinforced polymers (CFRP), based on increased load capacity. Topology optimization is used to locate the region of application of the reinforcement. The theoretical and practical aspects of reinforcement design are discussed. Numerical simulations are performed using the finite element method concomitantly with the automated optimization procedure. The Density Method, a simple, efficient and robust approach, is used in the optimization technique. A discussion is given about the similarity of topology optimization criteria for maximizing the stiffness and strength of the structure. The applications of this technique are compared with the conventional technique for strengthening concrete slabs. By optimizing the distribution of the reinforcement, the aim is to minimize the quantity of material, thereby reducing costs. The obtained results show that the topology optimization can be an effective tool to support the reinforcement design in concrete structures.

1. Introduction

Several structural reinforcement techniques have been developed in recent decades to increase the load-bearing capacity of reinforced concrete structures. These techniques consist basically of adding structural elements to the outer side of load-bearing parts. The reasons behind the need for reinforcement have to do with design and construction errors, and with design changes that alter the mode in which the building is used [1].

The structural reinforcement techniques developed in recent decades consist of basically adding structural elements to the external side of parts, according to the preferential load directions. Traditionally, reinforcements of concrete structures were usually made with steel plates [2]. More recently, carbon fiber reinforced polymers (CFRP) emerged as an efficient solution in view of their corrosion resistance, low weight, high strength and stiffness, good adaptation to complex shapes, and their ease of installation and maintenance.

One of the difficulties in designing a reinforced structure is to determine how best to distribute the sheets or strips of CFRP on the surface of the repaired parts. The usual practice is to resort to experience, construction method, and the structural behavior of the reinforced element. However, in the case of members with complex geometries, boundary conditions, and loads, the choice of the best distribution of the reinforcement may not be evident. The determination of an efficient reinforcement configuration in a structure is commonly done by "trial and error" which does not rigorously ensure that the optimum design has been achieved. In such cases, mathematical optimization can be a useful tool to find more efficient solutions. Structural optimization, in particular, is aimed at creating structures that perform better and consume less material, thus reducing costs.

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In a structural optimization problem, one or more objective functions must be defined, with or without constraints, to guide candidate designs in a search space that satisfies the conditions of the objective function(s) and constraint(s). Topology optimization emerged in response to the need to improve the optimization of shapes (including boundary conditions), allowing for better distribution of material within the design domain, i.e., within the structure whose geometry will be modified. Topology optimization has to do with how the material is distributed in the design domain, which is defined according to the space where the structure is to be located. This distribution is done iteratively and systematically.

The material's optimal topological distribution is tied to an objective, which may be, for instance, minimization of the structure's final volume in order to save material, or maximization of its stiffness, or even maximization of the strength of the part. Unlike shape optimization, in topology optimization, holes can be created in the domain during the optimization process. Thus, topology optimization enables one to obtain a new configuration of the structure.

The topology optimization of continuous structures is a relatively recent theme in the field of structural optimization. One of the most important works in this type of optimization is that of Bendsoe and Kikuchi [3]. Few works in the literature report on the use of topology optimization to generate optimal geometric configurations of concrete structures [4,5]. Works involving carbon fiber reinforced slabs are of an experimental and numerical nature, using the finite element method and analytical solutions developed in Fourier Series [6–9]. A recent study presents a topology optimization procedure to aid in the effective distribution of reinforcement on the sides of parts [10], however, in this work results are restricted to the theoretical cases. Some aspects, such as design in the ultimate limit state, are not considered in the reinforcement distribution.

The objective of this work is to use topology optimization as a tool for determining the area of application of CFRP in reinforced concrete slabs based on the increased load capacity of the structure. Reinforcement design is presented in its theoretical and practical aspects. The numerical simulations are performed by the finite element method concomitantly to the automatic topology optimization procedure. A discussion is given about the criteria for topology optimization aimed at maximizing the stiffness and strength of the structure. By optimizing the distribution of the reinforcement, our goal is to minimize the quantity of material, thereby reducing costs. The results are compared with the conventional technique for reinforcing concrete slabs.

2. Formulation of the topology optimization of slab reinforcement

The purpose of topology optimization is to remove or redistribute material iteratively and systematically, determining the optimal distribution in the design domain. The objective of optimum distribution may be, for example, minimization of the volume of the final structure or maximization of its stiffness in order to save material. It allows one to identify the optimal structural layout, i.e., the number, position and size of the members, as well as voids. Holes can be created in the domain during the optimization process. Thus, a new configuration of the structure can be obtained, starting from basic definitions: the design domain, the boundary and loading conditions, the objective function(s), and design constraint(s) imposed (Fig. 1).

The first step in topology optimization of continuous structures is to define the design domain, boundary conditions and applied loads. The second step involves discretizing the domain using finite elements. Other methods of numerical analysis can be used, provided that they are sufficiently generic to deal with complex shaped structures resulting from the optimization. The resulting information is then inserted into an optimization algorithm, which distributes the material iteratively in the design domain, in order to minimize or maximize the objective function, which may, for example, be maximization of stiffness, which is equivalent to minimization of compliance or minimization of strain energy of the structure for static loads. The result obtained is a structure with optimum topology (geometry). In the numerical implementation of topology optimization, the finite element model that discretizes the design domain is not altered during the iterative optimization process, only the distribution of the material in the elements is changed.

A material model must be created in the iterative step of distribution of the material. Among the existing models, the Homogenization Method is based on microstructures formed by mixing homogeneous materials. Each point in the structure's domain is defined as a composite material that is generated through the periodic repetition of a microstructure composed of solid and void material, according to two basic forms. The Homogenization Method is robust, but it has a computational cost and complex numerical implementation due to the large number of design variables. A relatively simple method of modeling and computational implementation for the material model is the Density Method. This method uses only one design variable, which is the relative density of the material in each element of the design domain [11].

In the Density Method, the design domain is discretized by finite elements, which are filled homogeneously by the material. The idea is to rearrange the material, changing its density (ρ) in each element. Thus, at the end of the optimization process, one obtains solid elements (density 1), which contain material, and void elements (density 0), which contain no material. The presence of intermediate colors (gray) between black (solid region) and white (void region) has no practical purpose and should be eliminated. Graphically, the results of the iterative optimization procedure indicate that white elements have highly compliance (void), black elements have low compliance (solid material) and gray elements have intermediate compliance (intermediate state of the material). The design variables are therefore the densities of the elements. In the last step, the regions of solid material should form the load pathways, while the other regions will be occupied by voids.

In the present formulation, we minimize the mean compliance of the structure, which is equivalent to its strain energy. This also corresponds to maximizing the global stiffness of the structure. Thus, the topology optimization problem can be equated as [11,12]:

$$Minimize: S(X) = U^T K\, U = \sum_{e=1}^{N} (x^e)^{\beta} \left[(u^e)^T k^0 u^e \right]$$

$$: \text{minimization of the mean compliance of the structure} \tag{1}$$

Subject to :

$$\frac{V(X)}{V_0} = f : \text{volume constraint of the material} \tag{2}$$

$$KU = F \Rightarrow KU = \sum_{e=1}^{N} (x^e)^{\beta} \left[k^0 u^e \right] = F$$

$$: \text{behavior constraint(equilibrium of the structure)} \tag{3}$$

$$x^e_{\min} \leqslant x^e \leqslant x^e_{\max}, e = 1, \ldots, N : \text{lateral constraint}$$