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Probabilistic shape design optimization of structural components under fatigue

Manolis Georgioudakis *, Nikos D. Lagaros, Manolis Papadrakakis

Institute of Structural Analysis and Antiseismic Research, School of Civil Engineering, National Technical University of Athens (NTUA), Zografou Campus, 15780 Athens, Greece

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ABSTRACT

Many failures of structural components are attributed to fatigue due to repeated loading and unloading conditions. The crack growth due to fatigue, represents a critical issue for the integrity and capacity of structural components. Apart from the loading conditions, the shape of the structural components plays an important role in their service life. In this study, extended finite element and level set methods are integrated into a probabilistic shape design optimization framework aiming to improve the service life of structural components under fatigue. In this context, the relation between the geometry of the structural components and their service life is investigated. The effect of uncertain material properties as well as the crack tip initialization, described by random variables is also examined. Comparisons between optimized shapes obtained for various targeted fatigue life values are addressed, while the location of the initial imperfection along with its orientation are found to have a significant effect on the optimal shapes for the components studied.

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1. Introduction

Structural failure is considered among the most challenging phenomena in solid mechanics. Many failures of structures are attributed to fatigue due to cyclic loading. A key parameter that affects significantly the service life of the structural components is their shape. Despite the progress achieved over the past decades in developing numerical methods for fatigue analysis, there are issues still open to be addressed for accurately designing structures in order to maximize their service life, especially when such problems are treated in a probabilistic way.

In the present study, a reliability analysis based structural shape design optimization formulation is proposed where probabilistic constraints are incorporated into the formulation of the design optimization problem, aiming to investigate the relation between geometry and fatigue life in the design of structural components. The objective of this study in addressing the structural shape optimization problem considering uncertainties is twofold. Firstly, to demonstrate the importance as well as the necessity of considering uncertainty into the design of structural systems under fatigue. On the other hand, to investigate the feasibility of the proposed formulations of the optimization problem for realistic structures in terms of improving their service life.

In particular, structural shape design optimization problems are formulated, considering the influence of various sources of uncertainty, i.e. randomness on the crack initialization along with the uncertainty on the material properties. The extended finite element method (XFEM) is adopted to solve the nested crack propagation problem, as originally proposed by Moës et al. [23] with the introduction of adaptive enrichment technique and the consideration of asymptotic crack tip fields and Heaviside functions. XFEM formulation is suitable for this type of problems since mesh difficulties encountered into CAD-FEM shape optimization problems are avoided using fixed mesh approaches. In association to XFEM, the level set description [26] is used to describe the geometry providing also the ability to modify CAD model topology during the whole optimization procedure.

Furthermore, the shape design optimization problems are formulated in terms of minimization of the structural component volume subject to constraint functions related to targeted service life (i.e. minimum number of fatigue cycles allowed). Nature inspired optimization techniques are chosen for solving the structural shape optimization problems, since they were found to be robust and computationally efficient even for complex problems. The proposed computational framework was applied into structural components test examples. In particular, two characteristic structures are analyzed and comparisons between optimized shapes obtained

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* Corresponding author.

E-mail addresses: geoem@mail.ntua.gr (M. Georgioudakis), nlagaros@central.ntua.gr (N.D. Lagaros), mpapadra@central.ntua.gr (M. Papadrakakis).

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for various targeted service life values are provided. It is shown that with proper shape changes the service life of structural components subjected to fatigue loads can be enhanced. The location of the initial imperfection along with its orientation are found to have a significant effect on the optimal shapes for the components examined.

The rest of the paper is organized as follows: in Section 2 the structural shape optimization problem considering uncertainties is defined. The appropriate mathematical model and the corresponding description of the optimization process are explicitly stated. Subsequently, in Section 3 the basic ingredients for handling the fatigue problem in the context of the XFEM are given. In Section 4, the proper search algorithm for solving the structural optimization problem is highlighted as a result of a sensitivity analysis between four metaheuristic search algorithms in a benchmark multi-modal environment. Finally, in Section 5 numerical tests are provided to illustrate the capabilities of the proposed methodology.

2. Structural shape optimization under fatigue

The relation between shape design and fatigue of structural components dates back in 1962, when Heywood [15] published his book concerning the design against fatigue. In analyses he performed for Rolls Royce aircraft engines, he discovered that the formation of an optimal fillet in the region of stress concentrations is beneficial in order to reach a maximum lifetime of mechanical engineering components which verified also by photoelasticity experiments.

In the last decades, many methods have been proposed to handle the shape optimization problem under fracture process, incorporating also the extended finite element method. Indicatively, Edke and Chang [7] presented a shape sensitivity analysis method for calculating gradients of crack growth rate and crack growth direction for 2D structural components under mixed-mode loading, overcoming the issue of calculating accurate derivatives of both crack growth rate and direction. This work was further extended by Edke and Chang [8] to a shape optimization framework to support the design of 2D structural components under mixed-mode fracture for maximizing the service life and minimizing their weight. Furthermore, Li et al. [20] proposed some elegant XFEM schemes for performing LSM based structural optimization, aiming to improve the computational accuracy and efficiency of XFEM, while Su et al. [33] considered a reanalysis algorithm based on incremental Cholesky factorization which is implemented into an optimization algorithm in order to predict the angle of crack initiation from a hole in a plate with inclusion.

Moreover alternative approaches to XFEM and optimization methods have been proposed. In Zhou et al. [35] a procedure for handling fatigue requirements for size and shape structural optimization problems is presented where fatigue life was approximated through approximation of stresses to enhance the accuracy of the results. In [3], a simple and efficient algorithm for FEM-based computational fracture of plates and shells is proposed, for both brittle and ductile materials on the basis of edge rotation and load control. Nanthakumar et al. [24] proposed an iterative procedure to solve the inverse problem of detecting multiple voids in a piezoelectric structure. In each iteration the forward problem is solved for various void configurations, and at each iteration, the mechanical and electrical responses of a piezoelectric structure is minimized at known specific points along the boundary to match the measured data.

In the context of plane fracture problems, Dijk et al. [6] introduced an algorithm based on a rotation of edges including the injection of continuum softening elements directly in the process region. In the work by Nanthakumar et al. [25] a computational method for the optimization of nanostructures is presented, aiming to capture and elucidate surface stress and surface elastic effects on the optimal nanodesign. In this direction, the authors used XFEM in order to solve the nanomechanical boundary value problem, which involves a discontinuity in the strain field and the presence of surface effects along the interface. Finally, in Fang et al. [13], the problem of structural optimization problem for vehicle fatigue durability involving uncertainties is studied. In an effort to simultaneously improve performance and robustness of the fatigue life for a truck cab, a multiobjective optimization is formulated as a robust design optimization problem where the authors validated some surrogate models through a comparative study.

However, to the authors knowledge there is not an holistic framework for dealing with the problem of design optimization of structural components under fatigue considering uncertainties. This motivates us to propose a new computational framework demonstrating the importance as well as the necessity of considering uncertainty into the design of structural systems under fatigue. The proposed approach constitutes an efficient procedure, capable to take into account uncertainties related to various sources of uncertainty, both aleatory and epistemic uncertainties, as well as to investigate the influence on the shape of the crack propagation path and the structural capacity eventually.

2.1. Problem formulation

In this study, a deterministic (DET) and a probabilistic (PROB) shape optimization problem are proposed for the design of 2D structural components under fatigue. According to the deterministic formulation, the goal is to minimize the material volume expressed by an optimized geometry of the structural component subject to constraints related to the minimum service life allowed. The deterministic formulation of design problem is defined as follows:

$$\begin{aligned} \min: \quad & V(\boldsymbol{s}) \\ \text{subject to}: \quad & N_c(\boldsymbol{s}) \geqslant N_{min} \\ & s_i^{low} \leqslant s_i \leqslant s_i^{up}, \quad i = \{1, 2, \dots, n\} \end{aligned} \tag{1}$$

V is the volume of the structural component, $\boldsymbol{s} = [s_1, s_2, \dots, s_n]^T$ is the vector of the design variables, s_i are the i-th design variable, relative to the geometric characteristics of the structural component, with lower and upper limits s_i^{low} and s_i^{up}, respectively and N_c is the service life in terms of number of fatigue cycles with the target lower limit N_{min}.

On the other hand, the probabilistic formulation (PROB) of the design problem is defined as follows:

$$\begin{aligned} \min: \quad & V(\boldsymbol{s}) \\ \text{subject to}: \quad & \overline{N}_c(\boldsymbol{s}, \boldsymbol{x}) \geqslant N_{min} \\ & s_i^{low} \leqslant s_i \leqslant s_i^{up}, \quad i = \{1, 2, \dots, n\} \\ & x_j \sim f_j(\mu_j, \sigma_j), \quad j = \{1, 2, \dots, nr\} \end{aligned} \tag{2}$$

where $\overline{N}_c$ is the mean number of fatigue cycles and $\boldsymbol{x} = [x_1, x_2, \dots, x_{nr}]^T$ is the vector of the random variables, x_j is the j-th random variable, following the f_j distribution, relative to the stochastic variable characteristics, with mean value μ_j and standard deviation σ_j.

It is common in probabilistic analysis to distinguish between uncertainty that reflects the variability of the outcome of a repeatable experiment and uncertainty due to ignorance. The last one is sometimes referred as "randomness", commonly known as "aleatoric uncertainty", which cannot be reduced. However, both deterministic and probabilistic approaches rely on various model

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