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Topology optimization considering fatigue life in the frequency domain

Jong Wook Lee [a], Gil Ho Yoon [b,*], Seung Hyun Jeong [a]

[a] Graduate School of Mechanical Engineering, Hanyang University, Republic of Korea

[b] School of Mechanical Engineering, Hanyang University, Seoul, Republic of Korea

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ABSTRACT

This research develops a new topological optimization (TO) method to assess dynamic fatigue failure in the frequency domain for random excitation forces. Besides static failure, fatigue life (or fatigue failure) is an important design criterion for the safety of mechanical and building structures. Therefore, many assessment theories and computational approaches have been proposed, and they can be divided into two categories: time domain and frequency domain. Although both approaches have been successfully applied for engineering purposes, they are rarely considered in structural TO. To consider fatigue failure caused by stochastic mechanical loads in structural TO, this research adopts fatigue assessment approaches in the frequency domain, such as narrow band solution, the Wirsching and Light method, the Ortiz and Chen method, and Dirlik method. For TO, we perform an adjoint sensitivity analysis with those fatigue assessment methods. We consider some two-dimensional benchmark problems and show that the present design method successfully constrains fatigue.

1. Introduction

This research presents a new topology optimization (TO) method that can consider fatigue life in the frequency domain. In addition to static failure, fatigue life or fatigue failure is an important design criterion for the safety of mechanical and building structures, as shown in Fig. 1. When a mechanical structure is excited by an arbitrary dynamic load, some cracks arise inside the structure, and those cracks can eventually cause the fracture of the structure. Thus many assessment theories and computational approaches have been proposed, and they can be divided into two categories: time domain and frequency domain. Although they have been successfully applied for engineering purposes, they are rarely considered in structural TO. Thus, this study contributes to this research area by developing an optimization formulation and modifying these theories and approaches to make them suitable for structural optimization.

Fatigue life, which is the time before a sudden fracture, can be assessed in the time or frequency domain [1–9]. The rain flow counting method is generally accepted as the standard approach in the time domain. However, its application is limited to a relatively simple load profile and a short time period. To consider complex load profiles for a long time span, applied loads should be analyzed in the frequency domain with the S–N curve. Some assessment methods have already been developed [3–9]. These methods calculate the PSD (power spectrum density) function and PDF (probability density function) of applied loads; their features are briefly explained in the subsequent sections, or see [3,4,8,9] for more details. Using PSD and PDF, the

* Corresponding author.
E-mail addresses: ghy@hanyang.ac.kr, gilho.yoon@gmail.com (G.H. Yoon).

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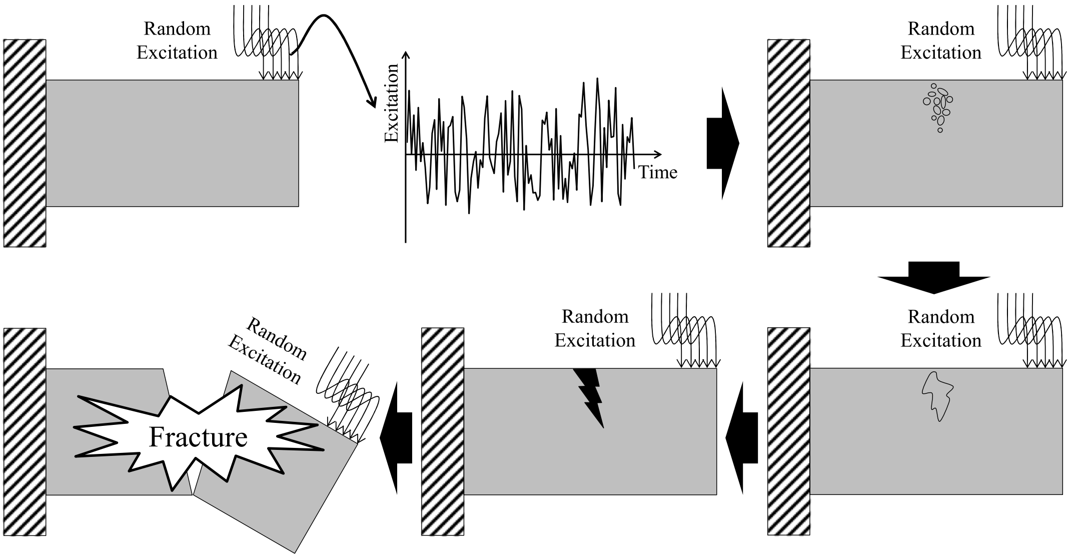

Fig. 1. General fatigue progress process.

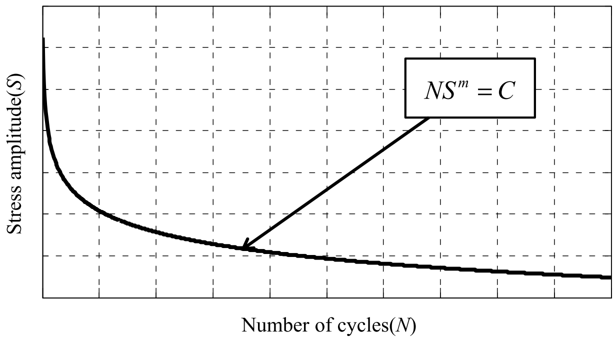

Fig. 2. *S*–*N* curve for fatigue analysis.

time history information of applied loads can be analyzed in the frequency domain, making it easy to analyze a complex load over a long time. The load profiles in the frequency domain are further divided into the narrow band frequency region and the wide band frequency region, depending on the frequencies of the focused applied load. The assessment in the narrow band frequency region was first proposed in [3,4,8,9], and it is called the *narrow band solution* [3,4,8,9]. Although this narrow band solution is efficient and conceptually easy to understand, it neglects information from the wide band frequency region, and its assessment is conservative. To overcome those limitations, many new approaches, such as the Wirsching and Light method, the Ortiz and Chen method, and Dirlik method, have been proposed [5–7].

From a structural optimization point of view, it is important to consider both fatigue failure and static failure. Much research has already been done to address structural failures [10–28]. The consideration of local failures in TO is especially difficult, and much research has been conducted. However, researchers rarely consider the fatigue constraint in structural TO, which allows free-material distribution [27,29–31].

TO was proposed in [32,33], and it has been applied to various application areas [34–38]. Because it allows free-material distribution, it can provide much better initial designs than the size or shape optimization methods. Despite its dissemination in various multiphysics systems, its application to the failure constraint is still a difficult problem because of stress singularity, the local constraint issue, and nonlinear behavior. Thus, many innovative ideas such as *qp*-relaxation, the *p*-norm approach, and regional constraints have been proposed to resolve these issues [10–12,14–18,21,22,26,39]. Recently, static failure for ductile and brittle materials and the dynamic fatigue constraint for harmonic load (one-frequency load) have been considered in TO [26,27]. But it remains difficult to consider complicated dynamic loads. To contribute to these research fields and consider complex load profiles over a long time period, this research applies fatigue life assessments in the frequency domain to TO. Similar to structural TO for static failure, many theoretical difficulties, such as the local constraint, stress singularity, and nonlinear constraint issues, occur in the fatigue constraint in the frequency domain of interest. To resolve them, the *qp*-relaxation approach and the *p*-norm approach have been applied, which permits the structural TO problem to be solved with consideration of fatigue failure in the frequency domain.