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Topology optimization of planar frames under seismic loads induced by actual and artificial earthquake records

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ABSTRACT

In this paper, layout optimization of structures under seismic loads is investigated. The difficulties faced in using actual earthquake records in the optimization process are addressed and some methods are proposed to deal with them. The objective is to minimize a suitable norm of displacements of the structure. Since the procedure is extremely time-consuming, along with using the actual record, an artificial record, created by employing basic concepts in earthquake engineering, is used for the optimization process. A series of Gaussian wave packet functions are used to fit the frequency content of the new artificial record to that of the actual one. The parameters obtained are reported for further studies. The well-known Solid Isotropic Material with Penalization (SIMP) method is employed and it is demonstrated that clear layouts may be found through an approach recently proposed by the authors based on the use of a nodal based interpolation of the design variables followed by a sequence of design mesh refining. The results of some numerical experiments are presented for a number of sample problems to show the effectiveness of the procedure proposed.

1. Introduction

Optimization of structures under transient loadings, especially earthquake induced loads, is one of the most important and challenging problems in structural engineering [1,2]. It is about two decades that research on design optimization of structures under earthquake loads is carried out. Generally, the structures are designed with the common knowledge of structural vibration principles and optimized by trial and error. Considering the need of a robust optimization method in this area, the layout of structure can be optimized using a topology optimization approach [3,4]. This however may be considered as a step toward a realistic engineering design. To the best knowledge of the authors, no research can be found in literature dealing with topology optimization of structures under actual earthquake records.

Topology optimization, referred to as generalized shape optimization, was introduced in the papers by Bendsøe and Kikuchi [5] and Bendsøe [6]. In numerous subsequent studies, the efficiency and effectiveness of this approach has been investigated [7]. The readers are referred to the review papers by Eschenauer and Olhoff [8], Rozvany [9] and a survey book by Bendsøe and Sigmund [10]. Most of the studies are in the realm of static problems.

Topology optimization of dynamic problems can be categorized into two groups: (I) eigen-frequency optimization and (II) transient response optimization. Procedures associated to the first category deal with the optimization of either fundamental frequency [11–14] or a series of natural frequencies [14] (or even the gaps between them [13,15]). Acoustic, phononic and photonic optimization problems may be categorized in this group [16,17]. Worthwhile to mention that optimization of the eigen-frequencies of a structure can only affect its general response. Hence the optimized topology of the structure is not necessarily the best one for a specific transient load. Among the methods in this category, topology optimization of planar structures considering their functionality under seismic loads was investigated in [18].

The second group includes the most general and also time-consuming optimization problems. In this category, topology can be optimized for any specific transient loading. There are few researches available in the literature dealing with problems associated to this category. Being time-consuming, transient optimization problems are mostly considered for one-dimensional problems [19–21]. In two-dimensional problems, Min and Kikuchi [22] optimized structures subjected to impulsive dynamic loads. In their work, the optimality criteria method was used as the optimization algorithm and the mean compliance of the structure in time was chosen as the objective function. Turteltaub [23] optimized the design of non-homogenous two-phase composites subjected to dynamic transient loads. The objective function was

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assumed to be time-averaged stress energy. In a successful attempt, the authors recently proposed an optimization algorithm for structures under transient harmonic base excitation [24].

The optimization problems in the second category are usually ill-posed and thus regularization schemes play a critical role in designing the algorithm. There is no research available on topology optimization of structures under actual earthquake loads addressing this issue. In [24] the authors addressed the problem under a short and smooth (harmonic) base excitation with a frequency equivalent to the dominant frequency in the actual earthquake. In this paper, the objective is to use a full period of earthquake record to obtain optimal layout of the resisting structures. To the best knowledge of the authors, this is the first study in this kind. We also attempt to employ an effective penalization technique to obtain clear black and white layouts. To this end, the Solid Isotropic Material with Penalization (SIMP) method is employed. The rationale underlying the current research may be found useful for the design of mechanical systems under similar severely time-varying excitations.

Apart from the issue of using topology optimization in static or dynamic regimes, numerical instabilities may be seen in topologies obtained by SIMP without using regularization schemes. Therefore, numerous regularization methods have so far been developed to overcome the effects known as checkerboards and mesh dependency. The details of the methods and procedures were extensively investigated in the review papers by Sigmund and Petersson [25] and Zhou et al. [26].

As in our previous study [24], two approaches will be followed in this paper; one is known as filtering technique using the average of sensitivities (see [27]) and the other is a technique using a node-based design with enhancive resolution (NDER) employed for a class of non-linear problems in [28]. It is expected to obtain clear black and white topologies without post-processing, since the existence of intermediate densities leads to unrealistic dynamic characteristics. To this end, small filter radii, or fine design mesh in case of NDER, should be used during the optimization process. Considering the fact that the analysis of the structure is to be performed over a full earthquake record, the whole optimization process becomes extremely time-consuming specially noting that the sensitivity analysis is another time consuming part of the solution. To decrease the computational cost, we propose a strategy to replace the actual earthquake record with an artificial one found via a fitting process based on frequency content. Using such a strategy, for example, we are able to replace the 27 s El-Centro earthquake record with a 1.6 s pulse-like record. Through some examples it is illustrated that the use of the replaced record leads to topologies similar to those obtained by the actual record. The essence of our experiences may be found useful for those who wish to employ time-consuming optimization techniques in problems with long period transient excitation.

The layout of the paper is as follows. In Section 2, the model used for the structure and the numerical solution method is described. Section 3 contains general features of the optimization algorithm including the description of the objective functions and the penalization technique. In Sections 4 and 5 we shall give an overview of the methods used for preventing instabilities and the method used for evaluating the sensitivities, respectively. The procedure for creating the artificial record is explained in Section 6. The numerical results of the optimization algorithm are presented in Section 7. Finally in Section 8 we summarize the conclusions made throughout the paper.

2. The model problems

Multi-story structures with concentrated mass at the story levels are considered. For the numerical simulation and the optimization procedure, to be explained later, it is assumed that (see also [24]):

- The structural elements are mass-less though we attribute a density to the material as the design variable.
- The spaces between the story levels are filled with a homogeneous material with small viscosity (material damping).
- The material remains elastic while experiencing the earthquake induced loads.

The first assumption states that the density used later does not directly contribute to the dynamic behavior of the system except through defining the material elasticity constants (i.e. no wave propagation effect is expected in the optimization domain). The second and third assumptions indicate that although no plastic deformation is expected in our simulations, small damping is considered to obtain more realistic behavior. Moreover, the two assumptions inherently convey that at the beginning of the optimization process a bracing system as a shear wall (e.g. steel plate shear wall) is considered by the user and then the final configuration of the bracings is found by the optimizer.

2.1. Numerical simulation

The dynamic response of structures may be simulated by using the finite element method. The numerical solution is to be found by a time integration scheme with the following generic relation

$$\mathbf{M}\ddot{\bar{\mathbf{u}}}_j + \mathbf{C}\dot{\bar{\mathbf{u}}}_j + \mathbf{K}\bar{\mathbf{u}}_j = \mathbf{R}_j, \qquad \text{at } t = t_j, \quad j = 1, \ldots, n, \tag{1}$$

where $\bar{\mathbf{u}}$ is an array containing the nodal displacements, $\dot{\bar{\mathbf{u}}}$ and $\ddot{\bar{\mathbf{u}}}$ represent the nodal velocities and the nodal accelerations, $\mathbf{K}$ and $\mathbf{C}$ are the stiffness and the damping matrices respectively, $\mathbf{M}$ is the mass matrix of the structures which has non-zero values at the degrees of freedom (DOFs) associated with the story levels. $\mathbf{R}$ is an array representing the loads acting on the structure (induced by excitation of the foundation). The subscript "j" is used to denote that the relation is written for the "jth" step of load at $t = t_j$. Also n represents the total number of load steps.

The well-known Newmark time integration is used in this research. Constant acceleration is assumed in each time step. The formulation may be found in many texts and thus it is not repeated here for the sake of brevity and conciseness (see [29] for further details). The final relation is written in a residual form as

$$\begin{aligned}\boldsymbol{\Psi}_j = {} & \left(\mathbf{K} + \frac{2}{\Delta t}\mathbf{C} + \frac{4}{\Delta t^2}\mathbf{M}\right)(\bar{\mathbf{u}}_{j+1} - \bar{\mathbf{u}}_j) - (\mathbf{R}_{j+1} - \mathbf{R}_j) \\ & - \left(\frac{4}{\Delta t}\mathbf{M} + 2\mathbf{C}\right)\dot{\bar{\mathbf{u}}}_j - 2\mathbf{M}\ddot{\bar{\mathbf{u}}}_j = \mathbf{0},\end{aligned} \tag{2}$$

which is to be solved for $\bar{\mathbf{u}}_{j+1}$. Noteworthy is that $\boldsymbol{\Psi}_j$ is to be used in the sensitivity analysis. In the above relation $\Delta t = t_{j+1} - t_j$.

2.2. Damping matrix construction

In this paper the damping matrix is constructed based on Rayleigh damping (see [29]),

$$\mathbf{C} = a_k\mathbf{K} + a_m\mathbf{M}, \tag{3}$$

where a_k and a_m are two specific constant coefficients. These coefficients are assumed to be independent of the design variables. Although they should be obtained by experimental tests, nearly realistic values are used in this paper. Here a_m is assumed to be zero since no wave propagation effect is considered in the domain of optimization.