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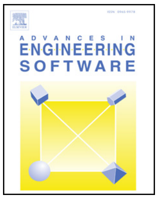

Research paper

Performance based discrete topology optimization of steel braced frames by a new metaheuristic

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A R T I C L E I N F O

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A B S T R A C T

Seismic topology optimization of structures is a challenging field of structural engineering. So far, a little number of studies has been conducted on this regard and all of them have presented conceptual designs which are of limited practical applicability. The main aim of the present study is to find the practical optimal placement of X- and diagonal bracing systems in steel braced frames subject to seismic loading. To achieve this purpose, a discrete topology optimization formulation is proposed in the framework of seismic performance-based design. A new metaheuristic algorithm, center of mass optimization (CMO), is proposed to deal with the performance-based discrete topology optimization (PBDTO) problem based on the physical concept of center of mass for mass distribution in space. Two challenging benchmark structural optimization problems are presented in order to demonstrate the computational merit of the proposed CMO algorithm compared to a number of algorithms in literature. Furthermore, PBDTO process is implemented for four multi-story steel braced frames by CMO. Performance of the proposed CMO-based discrete topology optimization framework in finding practical topology of bracing members for SBFs is demonstrated on PBDTO examples.

1. Introduction

In design and construction of steel structures, bracing system is one of the most suitable lateral load-resisting systems. The most important issue in designing a steel braced frame (SBF) is how to determine the style and arrangement of bracing members. In practice, this task is fulfilled to some extent based on designers' engineering experience and accordingly the best results may not be achieved in this manner. Obviously, optimization techniques can be effectively utilized to optimize the style and placement of bracings for SBFs. During the recent years, significant progresses have been made in the field of structural optimization and nowadays it is emerged as a practical design methodology. Generally, the structural optimization problems can be categorized in three categories: size, layout, and topology. Topology optimization is the most effective tool for designing of discrete and continuous structural systems but in comparison to the size and layout optimization its computational difficulties and numerical efforts drastically increase.

It is clear that topology optimization is the best tool for finding the optimal style and placement of bracings in SBFs. There are a few works in this area and the majority of them have used continuous topology optimization approaches. Stromberg et al. [1] proposed a methodology to determine the optimal angles of the diagonal members along the height of high-rise buildings in the framework of continuous topology optimization. In another study, Stromberg et al. [2] included beam-column elements in the continuous topology optimization process of braced frames to find the better optimal topology for high-rise buildings as compared to their previous work. Allahdadian and Boroomand [3] presented a topology optimization formulation for finding optimal layouts for planar frames under earthquake loading. Bobby et al. [4] proposed a methodology for the probabilistic topology optimization of tall buildings subject to wind loading. All of these works present conceptual designs which are of limited practical applicability. Different from the continuous topology optimization formulation, a discrete approach removes the bracing members with the lowest effect on the seismic performance of the structure from an originally fully braced frame and the obtained results will be of immediate applicability in practice. He and Wang [5] utilized a discrete topology optimization formulation for determining location of bracing members in a steel frame. Tantely and He [6] proposed a methodology for finding the best symmetric placements of bracings to retrofit the SBFs using collapse margin ratio (CMR). Their obtained results demonstrated that the optimum retrofit scheme has the best mix between structural safety and retrofitting cost.

Design optimization of structures subject to seismic loading is one of the most computationally intensive problems in structural engineering.

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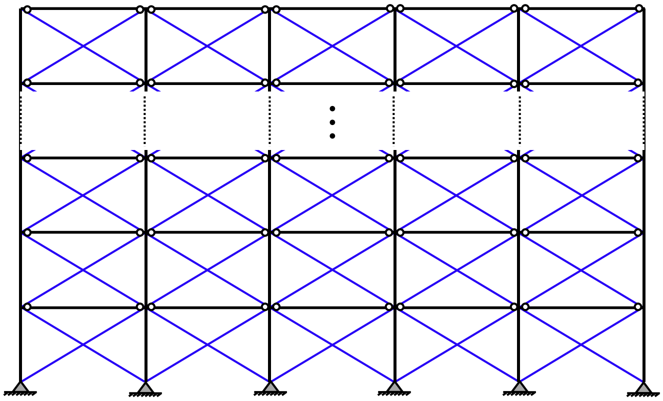

Fig. 1. A typical five-bay, multi-story fully braced frame.

Performance-based design (PBD) [7] is a modern approach for the design of structures to meet specified performance objectives for probable earthquakes. In the framework of PBD, structural performance is divided into several levels each corresponding to a level of seismic hazard and seismic structural responses should be calculated at performance levels by performing nonlinear structural analysis. Consequently, the computational complexity and intensity will be very demanding when the topology optimization is used for the design of structural systems in the framework of PBD and this implies that an efficient algorithm should be employed for searching the design space. During the last years, a considerable progress has been achieved in the development of nature-inspired optimization algorithms and numerous metaheuristics have been proposed by researchers in various disciplines of science and engineering. Popularity of these derivative-free algorithms lies in their flexibility and simplicity [8]. A comprehensive review on gradient-based and metaheuristic optimization algorithms has been conducted in [9].

The methodology proposed by Gholizadeh and Poorhosseini [10] is the first attempt to determine the optimal placement of X-bracing for SBFs in the framework of PBD using layout optimization. However, the main limitation of their methodology is that the style of bracing is taken to be fixed during the optimization process and in this case a limited number of layout design variables can be involved and consequently the global optimal topology of bracings cannot be determined. In order to address this important issue, in this study a performance-based discrete topology optimization (PBDTO) formulation is presented in which the unnecessary bracing members regardless of their style can be removed from an originally fully braced steel frame. As another novelty of this study, a new metaheuristic termed as center of mass optimization (CMO), is proposed to tackle the PBDTO problem of SBFs. The CMO is developed based on this physical principle that the distribution of mass in space is balanced around their center of mass. In this study, the efficiency of the CMO algorithm is illustrated by presenting two benchmark optimization problems and comparing its performance with that of some popular metaheuristics in literature. Afterward, four numerical examples of 3, 5, 10, and 15 story SBFs in the framework of PBDTO are solved by CMO to illustrate the advantages of the proposed methodology.

2. Performance-based discrete topology optimization

2.1. Structural model

Topology optimization of SBFs can be implemented using both continuous and discrete approaches. The output of a continuous topology optimization process is a conceptual design which requires serious regulations and post-processing in order to be applicable as a practical design. In contrast, a discrete topology optimization formulation leads to a design in which, besides determining optimal placement of bracing members, the optimal sections of beams, columns and bracing members are selected from a list of available standard profiles and consequently, post-processing is not required for the attained optimal designs. In fact, the discrete topology optimization of SBFs is the process of deletion of unnecessary bracing members from an originally fully braced frame and preserving the necessary ones in order to satisfy engineering requirements. Fig. 1 depicts a typical five-bay, multi-story fully braced frame in which all beam to column connections are considered to be ideally pinned and also the bracing members bypass each other.

As shown in Fig. 2a, for each bay of each story, X_{Ti} and X_{Tj} are defined as the topology design variables of bracing members. The value of these design variables can be either 0 or 1 indicating non-existence or existence of the bracing members, respectively. In addition, Fig. 2b–e depict four possible topologies of bracing members that can be applied in the optimization process.

For ith story of the five-bay, multi-story SBF the groups of topology and sizing design variables are illustrated in Fig. 3a and b, respectively. Worth mentioning that due to practical demands a symmetrical pattern is employed for grouping the design variables as depicted in Fig. 3.

According to Fig. 3, the design variables' vector for the ith story can be defined as follows

$$\text{Design variables}\begin{cases}\text{Topology} & \boldsymbol{X}_T=\{X_{T1}\quad X_{T2}\quad X_{T3}\quad X_{T4}\quad X_{T5}\}\\ \text{Sizing}\begin{cases}\text{Bracing} & \boldsymbol{X}_{Br}=\{X_{Br1}\quad X_{Br2}\quad X_{Br3}\quad X_{Br4}\quad X_{Br5}\}\\ \text{Column} & \boldsymbol{X}_C=\{X_{C1}\quad X_{C2}\quad X_{C3}\}\\ \text{Beam} & X_{Bm}\end{cases}\end{cases} \tag{1}$$

$$\boldsymbol{X}_i=\{\boldsymbol{X}_T\quad \boldsymbol{X}_{Br}\quad \boldsymbol{X}_C\quad X_{Bm}\}^{\mathrm{T}} \tag{2}$$

$$\boldsymbol{X}_{Br}\in\boldsymbol{\Delta}_{Br},\ \boldsymbol{X}_C\in\boldsymbol{\Delta}_C,\ X_{Br}\in\boldsymbol{\Delta}_{Br} \tag{3}$$

where $\boldsymbol{X}_T$ is a vector of topology design variables; $\boldsymbol{X}_{Br}$ and $\boldsymbol{X}_C$ are sizing design variables' vectors of bracing members and columns, respectively; X_{Bm} is a sizing design variable of beams; Sizing design variables are sequence number of steel profiles in a given list of sections; $\boldsymbol{\Delta}_{Br}$, $\boldsymbol{\Delta}_C$, and $\boldsymbol{\Delta}_{Bm}$ are available list of profiles for bracings, columns and beam, respectively; and $\boldsymbol{X}_i$ stands for ith story design variables' vector.

Vector of design variables for a five-bay SBF with ns stories is represented as follows

$$\boldsymbol{X}=\{\boldsymbol{X}_1\quad \boldsymbol{X}_2\quad \ldots\quad \boldsymbol{X}_{ns}\}^{\mathrm{T}} \tag{4}$$

where $\boldsymbol{X}_1$, $\boldsymbol{X}_2$, and $\boldsymbol{X}_{ns}$ are design variables' vectors of stories 1, 2, and ns, respectively.

2.2. Performance-based design

PBD is the most efficient methodology for the seismic design of safe

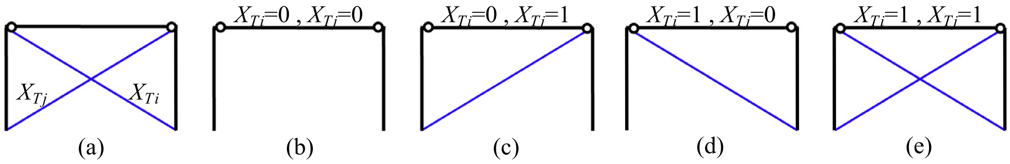

Fig. 2. (a) Topology design variables for each bay of each story, and possible topologies (b) without bracing; (c) only second bracing; (d) only first bracing; and (e) both bracing members.