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Life cycle cost optimization of earthquake-resistant steel framed tube tall buildings

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Abstract

Past earthquakes revealed that while fulfilling the requirements of the conventional design codes guarantees the life safety of the occupants, considerable economic losses may still be incurred. This highlights the importance of considering life cycle losses in the design procedure of structures. In this research, the significance of the life cycle seismic risk costs in the optimal design of steel framed tube tall buildings is investigated. Typical 20- and 40-story buildings are optimally designed based on three approaches: the code-based, the cost-based, and the fixed weight approach. The first approach only minimizes the initial cost of the building while in the second and third approaches the total cost of the building in its lifetime is considered. Endurance Time (ET) method is used as the tool for seismic life cycle cost analysis. The requirements of the building codes are treated as the optimization constraints and the resulting problem is solved using the gradient-based algorithms. The results indicate that the cost-based approach results in the best practical design with the minimum total cost in the lifetime. The design based on the fixed weight approach reveals that the code-based design of tall buildings will not necessarily lead to the most economical use of material. Using ET method as the analysis tool along with the gradient-based algorithms as the optimization tool provides an efficient framework for the optimal seismic design of high-rise buildings based on life cycle costs.

Introduction

In recent years, rapid population growth, as well as the scarcity of land and its high price have led to a growing tendency toward the construction of high-rise buildings in metropolitan areas. The resistance to lateral loads caused by either wind or earthquake is the main driving force in the development of efficient structural systems for these structures. Among various structural systems, tubular structures are very efficient and widely used in tall buildings around the world. In these systems, the structural efficiency is greatly promoted by positioning the primary lateral load resisting systems on the perimeter of the building. Tubular structures can be designed in different forms including framed tube, tube-in-tube, bundled tube, and braced tube [1]. Moreover, these structures can be classified as reinforce concrete, steel, or composite structures based on the primary material used in their structural system. This study is solely focused on the evaluation of the steel framed tube tall buildings. The framed tube system consists of closely spaced perimeter columns tied together by deep spandrel beams at the floor levels so that the building operates as a huge vertical cantilever to resist lateral loads effectively [2]. Inspired by this concept, many researchers have proposed simple approximate methods for the analysis of framed tube structures by modeling them as a huge cantilever box beam [3], [4], [5]. However, for design purposes, the precise analysis of the responses of the structure using a realistic structural model is necessary. Moreover, in order to take into account the shear lag effects in the analysis procedure accurately, a three dimensional (3D) structural model is required [6].

The reliable and economical design of high-rise buildings is usually a challenging task due to their complex nature, numerous structural members, and strict constraints imposed by building codes. In the traditional method, the design is performed based on an iterative and time-consuming trial and error procedure. Accordingly, the resulting design is not necessarily the most economical and may involve substantial waste of material in the construction stage. This sheds light on the importance of using optimization tools in the design procedure to attain savings in the construction cost [7], [8], [9]. In this respect, Spires and Arora presented the formulation of the optimal design for reinforced concrete (RC) framed tube tall buildings to achieve the minimum construction cost [10]. In addition, the analysis procedure was simplified with the help of Khan's equivalent plane frame model [11]. Baker proposed an energy-based technique for optimal sizing of the lateral bracing in high-rise buildings where drift controls the design [12]. Chan et al. developed a computer-based resizing technique for the minimum weight design of steel high-rise buildings subject to drift constraints [13]. Chan et al. proposed an automatic resizing technique to achieve the optimum design of steel high-rise buildings under the design constraints imposed by the design codes. The applicability of this strategy was demonstrated by determining the least-weight design for a 3D 50-story building under dead, live, and wind loads [14]. Moghaddam and Hajirasouliha presented an optimization technique to reach the uniform distribution of deformation in 2D tall shear buildings under seismic excitation [15]. Shin et al. conducted a parameter study into the effects of various design parameters on the tube action of an RC 55-story building to propose optimal design approaches for tubular systems [16]. Xu et al. presented an optimization procedure for the design of an actual supertall building acted by wind load under lateral drift constraints [17]. Li et al. proposed a procedure for the optimal structural design of tall buildings under wind loads. The proposed procedure employs an improved genetic algorithm to find the design with the least weight considering lateral drifts and top acceleration constraints [18]. Recently, Sarcheshmehpour et al. proposed a practical framework for optimum seismic design of steel high-rise buildings subject to all constraints prescribed by design codes. The framework was employed for the comparison of the seismic behavior of the tube-in-tube and the framed tube systems in typical 3D 20-,40-, and 60-story buildings [19].

The aforementioned studies, deal with the assignment of minimum resources while fulfilling the minimum requirements prescribed by the design codes. Such an approach does not necessarily lead to an economical design with the least total cost in the lifetime of the building [20]. In other words, past earthquakes and hurricanes demonstrated that although satisfying the requirements of the conventional design codes provides the life safety of the occupants, significant economic losses may still be imposed [21]. This sheds light on the need for an improved design procedure to reduce damage and economic losses to an acceptable level along with protecting human life. For this purpose, the life cycle cost (LCC)-based design approach was developed to incorporate directly the economic concerns into the design procedure [22]. In recent years, life cycle cost analysis (LCCA) has been in the spotlight of many researchers [23], [24], and has become a key concern of the design procedure employed for controlling the initial and future costs of the structures [25]. In the field of LCCA of high-rise buildings, the majority of the previous studies focused on quantifying the wind-induced damage and losses [26], [27], [28], [29]. Moreover, some researchers have devised the methodologies for LCCA of tall buildings under both seismic and wind loads. In this respect, Mahmoud and Cheng proposed a framework based on structural reliability and demonstrated its application through LCCA of typical 10-story and 30-story 2D moment-resisting frames [30]. Also, Venanzi et al. developed a strategy for the estimation of losses due to nonstructural damage under seismic and wind loads. They applied the proposed strategy to the simplified model of an RC 76-story building based on the Euler–Bernoulli beam theory [31].

Recently, the interesting topic of LCC optimization of structures has attracted the attention of many researchers [20], [32], [33], [34]. In this area, most of the previous works have followed the mentioned topic for low to mid-rise 2D frames. For high-rise buildings, despite abundant studies on the design optimization considering minimum construction cost, a limited number of studies have been conducted on the determination of the optimal design from an LCC-based perspective. This is due to the huge computational burden associated with such optimization problems. In this regard, Kleingesinds et al. [35] presented a strategy for multi-objective optimal LCC-based design of multiple tuned mass dampers (TMDs) installed in high-rise buildings. In this technique, the initial cost of the TMDs is taken as the first objective function and the LCC due to nonstructural damage under both wind and seismic loads is considered as the second objective function. They applied the proposed methodology to the simplified model of an RC 76-story building (equipped with four TMDs at the 76th floor) based on the Euler–Bernoulli beam theory. In another work, Venanzi et al. [36] proposed a framework for LCC-based design optimization of high-rise buildings equipped with TMDs under wind loads. In the presented framework, the unified optimal design of both the main structure and TMDs is carried out by minimizing the total cost of the building in its lifetime. The efficiency of the proposed technique was demonstrated by applying it to the simplified model of an RC tall building.

LCCA of structures is associated with the estimation of structural responses in multiple hazard levels. To achieve a reliable response estimation, employing a realistic model of the structure and a response history-based analysis method is almost inevitable. In this regard, conventional time history analysis using earthquake ground motions would lead the seismic loss assessment of high-rise buildings including thousands of members to be a time-consuming process. The situation worsens in the case of LCC-based optimal design of the structure requiring repetitive calculations. To cope with this difficulty, the endurance time (ET) method can be employed as a highly efficient analysis tool. In this method, the structure is subjected to predesigned intensifying excitation functions rather than a set of progressively