Computers and Structures 170 (2016) 49–61

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Seismic design optimization of multi–storey steel–concrete composite buildings

Georgios S. Papavasileiou, Dimos C. Charmpis *

Department of Civil and Environmental Engineering, University of Cyprus, 75 Kallipoleos Str., P.O. Box 20537, 1678 Nicosia, Cyprus

ARTICLE INFO

Article history:
Received 5 December 2014
Accepted 28 March 2016
Available online 18 April 2016

Keywords:
Structural optimization
Discrete optimization
Evolution Strategies
Earthquake-resistant
Pushover analysis
Frequency constraints

ABSTRACT

This work presents a structural optimization framework for the seismic design of multi–storey composite buildings, which have steel HEB-columns fully encased in concrete, steel IPE-beams and steel L-bracings. The objective function minimized is the total cost of materials (steel, concrete) used in the structure. Based on Eurocodes 3 and 4, capacity checks are specified for individual members. Seismic system behavior is controlled through lateral deflection and fundamental period constraints, which are evaluated using nonlinear pushover and eigenvalue analyses. The optimization problem is solved with a discrete Evolution Strategies algorithm, which delivers cost-effective solutions and reveals attributes of optimal structural designs.

1. Introduction

Steel–concrete composite elements are intended to fill the gap between reinforced concrete elements and pure steel elements. The utilization of steel–concrete composite elements is not a new concept, since they have gradually gained popularity during the course of the 20th century mainly in North America, Japan and Europe, while early applications of such elements at the end of the 19th century have been recorded. Over the past few decades, numerous steel–concrete composite structures have been erected worldwide. This form of construction is seen as an alternative mainly to constructing pure steel structures. The increasing preference in composite elements can be primarily attributed to the fact that concrete, a significantly less expensive material compared to steel, is utilized in an effort to cost-effectively replace a percentage of the required steel sections area. This way, overall material cost in a structure can be reduced and, at the same time, better lateral support and fire protection of the steel elements can be achieved, since concrete (which usually covers steel elements) offers a much better performance at high temperatures than structural steel. However, although the incorporation of steel–concrete composite elements in a structure is nowadays regarded as established design and construction practice, the investigations conducted on how such practice can be exploited in the most cost-effective way are rather limited.

Structural optimization is widely recognized as a valuable computational tool that aids engineers in identifying cost-effective designs. Numerous seismic design optimization applications for steel structures (e.g. [1–12]) and reinforced concrete structures (e.g. [13–15]) are presented in the literature. For composite elements and structures, the available publications are much less and are mostly dealing with the design optimization of composite floors [16–18] and beams [19–22]. The publications on the design optimization of composite buildings are rather few [23–25] and do not fully and explicitly take into account the complete set of design requirements that should be normally specified for composite buildings. In fact, these works concentrate on achieving adequate system performance to lateral (wind or earthquake) loading and actually ignore member capacity checks. This way, however, requirements on withstanding vertical (gravitational) loads are neglected and especially the beams are most probably underdesigned. Moreover, in the aforementioned existing works, there is no control over the composite structures' eigenperiods, which means that designs with unrealistic vibration properties are not excluded from being selected as feasible optimal solutions. Thus, a more complete design optimization framework for composite buildings is needed.

The present paper is concerned with the design optimization of earthquake-resistant multi–storey composite buildings with steel–concrete columns. In these buildings, the composite columns consist of steel members with standard I-shaped sections fully encased in concrete; steel beams with standard I-shaped sections and (optional) steel bracings with standard L-shaped sections are

---

* Corresponding author. Tel.: +357 22 89 2202; fax: +357 22 89 5322.
E-mail address: charmpis@ucy.ac.cy (D.C. Charmpis).

http://dx.doi.org/10.1016/j.compstruc.2016.03.010

considered. The aim of the developed optimization procedure is to minimize the total materials cost in a composite building under explicit constraints imposed based on member capacity checks of formal design codes. In particular, individual composite and pure steel members of the building assessed are required to satisfy the provisions of respective Eurocodes. Overall seismic resistance is controlled through additional constraints on interstorey drifts and top-storey displacements, which are evaluated using nonlinear static pushover analyses. Moreover, an upper allowable limit for constraining the fundamental period of the building is specified. The optimization problem is solved with a discrete Evolution Strategies algorithm, which can effectively handle the standard options available in the market for steel members. The optimizer is linked with a powerful structural analysis software (OpenSees [26]) to automatically obtain the structural response results needed for the evaluation of constraints. Hence, the contribution of this work is that it comprehensively presents and assesses a complete and well-organized framework for seismic design optimization of composite buildings. In an effort to enrich the available knowledge on the behavior of composite structures and facilitate the cost-effective use of composite elements, the developed optimization procedure is exploited to identify attributes of optimally designed composite buildings.

The remainder of this paper is organized as follows. Section 2 describes the structural design requirements specified for composite buildings in this work. Details on the structural configuration of the analyzed buildings, as well as on their numerical modeling and analysis, are given in Section 3. The implemented design optimization procedure is explained in Section 4. Design optimization results for composite buildings are reported and discussed in Section 5. Section 6 concludes the paper with some final remarks.

2. Structural design requirements

In the framework of the optimization procedure implemented in the present work, each solution evaluated as a candidate optimum design of a composite building needs to be checked with respect to pre-specified feasibility constraints. These constraints represent the design requirements imposed by the adopted design codes, guidelines, etc. and include both individual member capacity checks and seismic system performance checks.

The design of the structural members of the buildings considered is performed according to the provisions of Eurocode 4 (EN 1994-1-1 [27]) for composite column members with concrete-encased steel HEB sections and Eurocode 3 (EN 1993-1-1 [28]) for pure steel beam members with IPE sections. The capacities of columns are checked with respect to axial force (EN 1994-1-1, Section 6.7.3.5), shear force (EN 1993-1-1, Section 6.2.6), bending moment (EN 1994-1-1, Section 6.7.3.3), combined axial force and biaxial bending moment (EN 1994-1-1, Sections 6.7.3.6 and 6.7.3.7) and the respective types of local and global buckling (EN 1994-1-1, Section 6.7.3). The capacities of beams are checked for shear force (EN 1993-1-1, Section 6.2.6), bending moment and interaction with shear force (EN 1993-1-1, Sections 6.2.5 and 6.2.8), as well as the respective types of local and global buckling (EN 1993-1-1, Section 6.3). The bracings are not considered to participate in the transference of the gravitational loads to the foundation, so their pure steel L-sections are determined based on the structural system performance.

The overall seismic resistance of a structure is controlled through lateral deflection constraints. Following the provisions of FEMA 440 [29] and ASCE/SEI 41-06 [30], the structure's seismic capacity for the collapse prevention performance level can be assessed by performing a displacement-controlled nonlinear pushover analysis up to a pre-specified displacement. More specifically, a node at the roof level of the structural model is required to be able to reach a target displacement Δ_{target}, which is estimated as:

$$\Delta_{target} = C_0 C_1 C_2 C_3 S_a \frac{T^2}{4\pi^2}. \tag{1}$$

In this equation, C_0, C_1, C_2 and C_3 are factors defined in [29] and S_a is the design pseudo-acceleration of the structure with fundamental period T. Moreover, the maximum interstorey drift is constrained to be less than 4% of the storey height. This drift-limit is suggested in [30] for concrete frames. As there is no provision specifically for steel–concrete composite frames, the 4% limit is preferred over the 5% limit suggested for pure steel frames. It is noted that the internal forces developed in structural elements during the pushover analysis due to the combination of horizontal and gravitational loads are not checked with respect to the above mentioned provisions of Eurocodes 3 and 4 for steel and composite members. Enforcing the satisfaction of such provisions under this load combination and analysis would reduce the cost-effectiveness of the optimized designs achieved, since their intended seismic performance does not preclude the failure of individual structural elements, provided that partial or full system collapse is not triggered.

Preliminary test runs using all aforementioned design requirements of this section revealed the tendency of the implemented optimizer to select structural designs with high fundamental periods (even over 2 s in some cases). Such structures generally attract relatively small earthquake-induced forces, but are also associated with increased potential for damage to non-structural components and building contents, as well as for discomfort of occupants, during seismic events. In order to avoid these undesirable long-period buildings, an additional design requirement is employed in this work, according to which the fundamental period of a structure is not allowed to exceed a threshold value $T_{\max}$. Period/frequency-information is incorporated also in a number of other optimization applications in structural mechanics (e.g. [31–34]). As no data on specifying $T_{\max}$ for composite buildings were found, the formula proposed in [35] for limiting the fundamental period of steel buildings is adopted herein:

$$T_{\max} = 0.045 H^{0.80}, \tag{2}$$

where H is the building height (in feet) above the base.

3. Structural configuration, modeling and analysis of composite buildings

3.1. Structural configuration

The steel–concrete columns of the composite buildings assessed in the present work are designed as fully encased I-shaped (HEB) sections (Fig. 1(a)). A concrete layer of 5 cm around the steel section's edges is assumed, in which longitudinal (bars of 10 mm diameter) and transversal (stirrups of 8 mm diameter) reinforcement is installed. For small steel section sizes (up to HE 180 B), 3 longitudinal bars per side are used; for larger steel section sizes, 5 longitudinal bars per side are installed. Stirrups are placed with 10 cm spacing around the longitudinal bars. The external concrete cover is fixed to 2.5 cm. Thus, a composite column section is fully defined just by specifying the encased HEB-section; once the HEB-dimensions are known, the amount and layout of concrete and its reinforcement in the composite section can be deduced based on the section description given in this paragraph. The steel HEB-sections have a common orientation across all columns of a building. Specifically, all HEB-members are placed with their cross-sections' major axes parallel to the global horizontal x-axis of the building.

The beams and bracings are designed as pure steel elements (Fig. 1(b) and (c)). For the building's floors, corrugated composite slabs and secondary beams are installed. The columns at the base of the building are assumed to be fixed, while all beam–column