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Optimization of the reinforced concrete structural systems under seismic load

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Abstract

In this paper a fully automated optimization procedure of reinforced concrete structures exposed to earthquakes by using genetic algorithm-GA optimization method is implemented. Given the highly stochastic nature of the earthquake, its extreme effects and possible catastrophic consequences, special attention must be paid to solving this problem. The behaviour of structural systems was assessed employing nonlinear dynamic analysis. Localized nonlinearities are taken into account by using finite elements that are able to realistically describe the hysteresis behaviour of reinforced concrete structures under cyclic loading. The problem of structural optimization comes down to achieving the optimal response under earthquake load with minimal material consumption. However, the main goal of optimization is to achieve a favourable response in the sense of performance-based design and the minimum consumption of materials is a criterion of lesser importance. Seismic load is modelled using an artificially generated accelerogram whose response spectrum closely approximates the design acceleration spectrum defined by relevant seismic code. The optimization procedure defines the target performance levels, with the imposed limits of the largest interstory drifts. The first target performance level refers to earthquakes of lower intensity and shorter return periods and must prevent excessive damages. The second target performance level represents earthquakes with the highest expected intensity in the observed area. Damage limitation is the primary goal of the optimization procedure, which is then followed by ultimate limit state verification. Numerical examples cover both simple, geometrically regular and uniform systems as well as irregular structures. For all analysed examples, optimization by using the GA method resulted in structures that fully meet the SLS and ULS constraints. Structures optimized in this manner easily achieve a desired response to earthquakes.

Key words: earthquake, reinforced concrete, optimization, genetic algorithm, nonlinear time history analysis

1 Introduction

As a natural phenomenon, earthquake belongs to the group of extreme loads that can cause excessive damage to the load-bearing structure. They can cause the collapse of buildings, infrastructure facilities etc. with catastrophic economic consequences with possible loss of human lives. Design of structural bearing systems to full (elastic) seismic load is uneconomical and often unable to meet the performance-based criteria prescribed by modern design codes. Catastrophic earthquakes in the recent past (Loma Prieta 1989, Kobe 1995) have shown that the proper design and construction of details can provide adequate safety of the building's load-bearing structure.

The load-bearing seismic system must maintain capacity and stability during the earthquake, with no loss of human lives for the most significant expected load. Nevertheless, there is a possibility of significant damage in predetermined places across the building. The calculation according to modern standards cannot include all the nonlinearities that the actual structure has. One must also consider the extremely stochastic nature of the earthquake load. Buildings that comply with modern codes result in relatively safe structures for protecting human lives during catastrophic earthquakes. However, the economic damage caused by these earthquakes, and more importantly, by the action of earthquakes of lower intensity, was unacceptably extensive, where many buildings suffered damage whose repair was economically unacceptable. When an earthquake occurs, the building should achieve a target performance level that includes load-bearing and non-load-bearing elements (for different seismic load levels). In the literature, [1], there are various levels of targeted behaviour: for example, "*immediate occupancy*" (IO), "*life safety*" (LS), and "*collapse prevention* (CP) ".

Structural optimization of seismically resistant structures aims to optimize the structural system's response under earthquake (performance-based earthquake design) with minimal material consumption (an optimal combination of cross-sections). To obtain the most realistic structural response under earthquake load, one must model a structural system with nonlinear finite elements (with the so-called plastic hinges located at the elements' ends). The plastic hinges represent localized hysteretic material behaviour under cyclic load.

The earthquake loading can be modelled as time series (accelerogram) of the real or artificially generated earthquake. This paper uses an artificially generated accelerogram (matched with specific target response spectra from [2]. The numerical model prepared in this way is subjected to a nonlinear time history analysis (nonlinear dynamic analysis). The primary goal of optimization is to achieve the building's excellent behaviour for the level of seismic load on the verge of damage (excessive cracking). This performance level corresponds to level: "*immediate occupancy*" (IO). Only minor damage is allowed, and the building is safe to reuse immediately after the earthquake ends.

The seismic load level corresponding to this target behaviour level is 50 % of the maximum (ULS) seismic load. As the primary indication of the building's performance, one

must control interstory drift. For the buildings where the non-structural elements (for example, drywalls) are directly connected to the main structural elements (beams and columns), interstory drift must be smaller than 0,5 % to prevent excessive damage of non-structural elements. If there is no automation in this design process, one must manually change the element's cross-sections, re-run nonlinear time history analysis, evaluate results, check the violation of the imposed interstory drift limitations and continue with iterations until the optimal combination of cross-sections is found.
Achieving the optimal combination of cross-sections is not an easy task, and it takes many iterative steps by trial and error to achieve an approximately optimal design. This paper presents the process of automation of the above steps to achieve the optimal structural system under earthquake loads. To solve the optimization problem under constraints provided by [2] it has been implemented Genetic Algorithm (GA). Software used for nonlinear dynamic analysis is SAP2000 [4] with an implementation of GA method in MATLAB [5].

2 Optimization

In our paper we have analysed a multi-story reinforced concrete frame with i=1, 2…,N members. As design variables are taken cross section dimensions: width bi and depth hi. Objective function is defined as total cost of all concrete elements:

$$\text{Minimize: Total Cost} = \sum_{i=1}^{N} w_i b_i h_i \tag{1}$$

Design procedure must result with the reinforced concrete frame that is sufficiently strong and ductile under strong earthquakes. On the other hand, building serviceability under moderate and minor earthquakes must be provided without significant damage to structural and non-structural parts of the building. Interstory drift is defined as follows:

$$\Delta u_i = u_i - u_{i-1} \le d_i h_i \left(i = 1,2,..,N \right) \tag{2}$$

Δu_i is the interstory drift of the i-th story, u_i and u_{i-1} are the displacement of two adjacent floors, h_i is the height of the i-th story and d_i is the drift limit ratio specified by code. The problem of optimal design (optimal response of the building under earthquake load) can be generally defined as:

- Minimize the objective function:

$$f = f\left(x_1, x_2, \ldots, x_N \right) \tag{3}$$

- Under prescribed constraints (interstory drift):

$$g\left(x_1, x_2, \ldots, x_N \right) = \frac{\Delta u_i}{d_i h_i} \le 1 \left(i = 1,2,..,N \right) \tag{4}$$

- The variables are also constrained; they have predefined range (lower and upper limit):

$$x_{i,L} \leq x_i \leq x_{i,U} \left(i = 1,2,..,N \right) \qquad (5)$$

Optimization analysis has been done using a genetic algorithm (GA). GA method [3] is a suitable tool for real engineering, highly nonlinear problems, while it is a robust method and not prone to get locked around local minimum point. The simulation starts with a population of random strings, and each of them is then evaluated to calculate the fitness value.
Thereafter, the population is operated by three operators: reproduction, crossover, and mutation. The new population of points is created and evaluated. If the termination criterion is not met, the population is operated by the above three operators with a new fitness evaluation. When the GA algorithm converges to the proximity of the global minimum point, then we can use the gradient method and quickly calculate the exact value of the global minimum.

3 Numerical examples

A six-story (6*3,5m), three-bay (3*6,0m) building is analysed to illustrate the inelastic optimal design method. Nonlinear time history analysis has been used to implement the genetic algorithm method. Assuming that non-structural brittle elements are attached to the structure (no special details with construction joints to allow for relative movements without damage) conservative value of 0,5 % interstory drift is chosen. Artificial accelerogram has response spectra, which is a good match to response spectra from [2] (type 1, soil type B, a_g=0,3g). For all members concrete with the compressive strength, f_c, of 50 MPa and steel reinforcement with the yield strength, f_y, of 500 MPa are used.
After initial calculation, see Fig1, we can see that building does not satisfy imposed limitations on maximal interstory drifts. At the end of the optimization process, it has been realized structure that fully satisfies the imposed restrictions and, in that sense, achieves the best behavior in the event of an earthquake, see Fig2.
Same effectiveness has been achieved at structural system with irregular geometry and unfavourable distribution of stiffness in elevation, see Fig 3 and Fig 4.

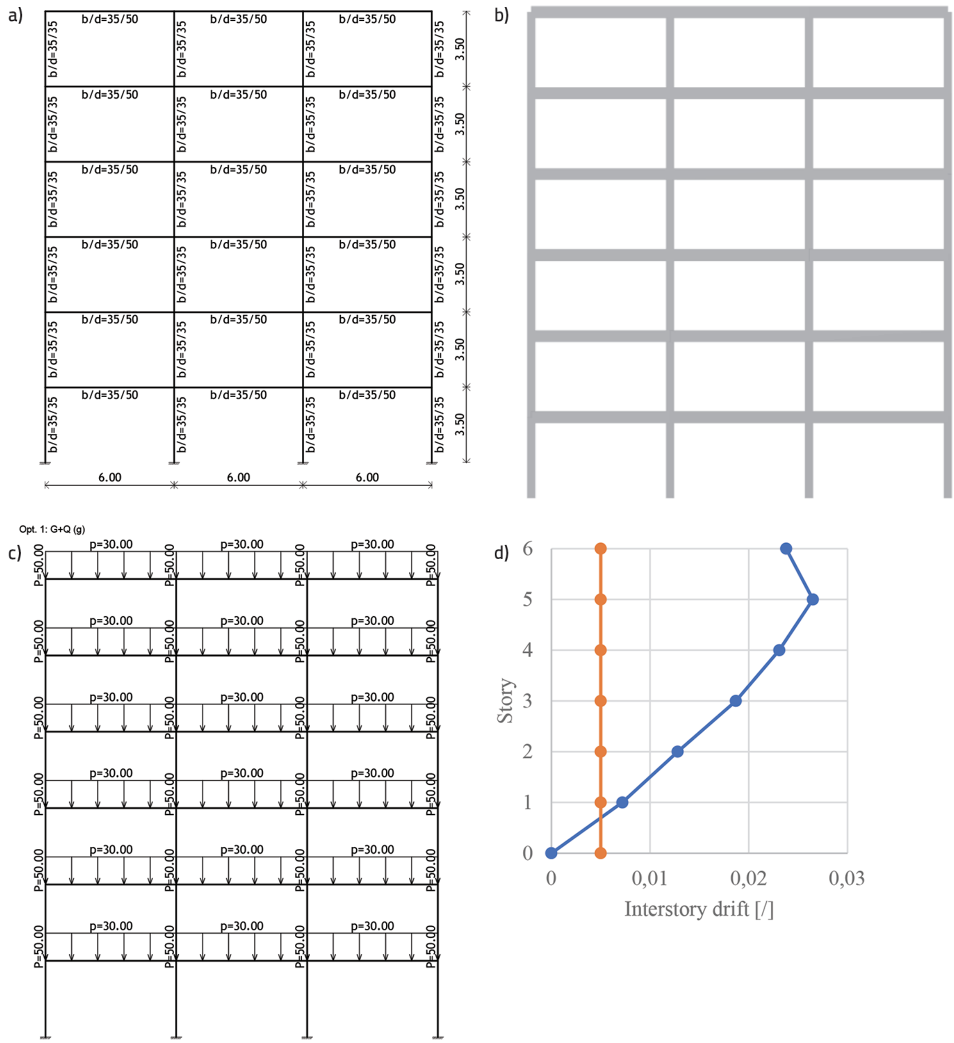

Figure 1. a) Initial geometry, b) Initial 2D view; c) Loads, d) Initial interstory drifts

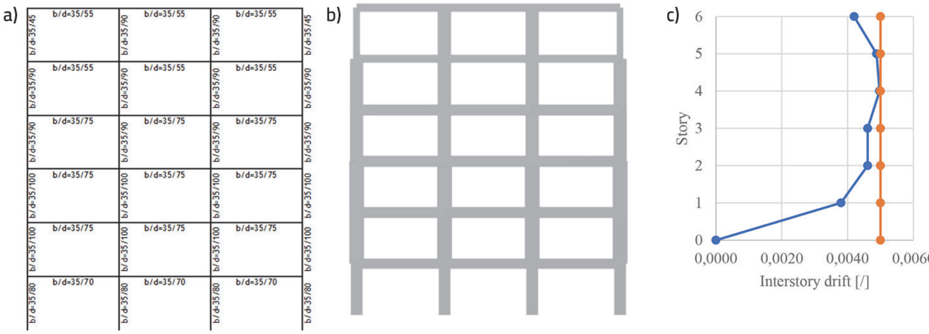

Figure 2. a) Final geometry, b) Final 2D view; c) Final interstory drifts

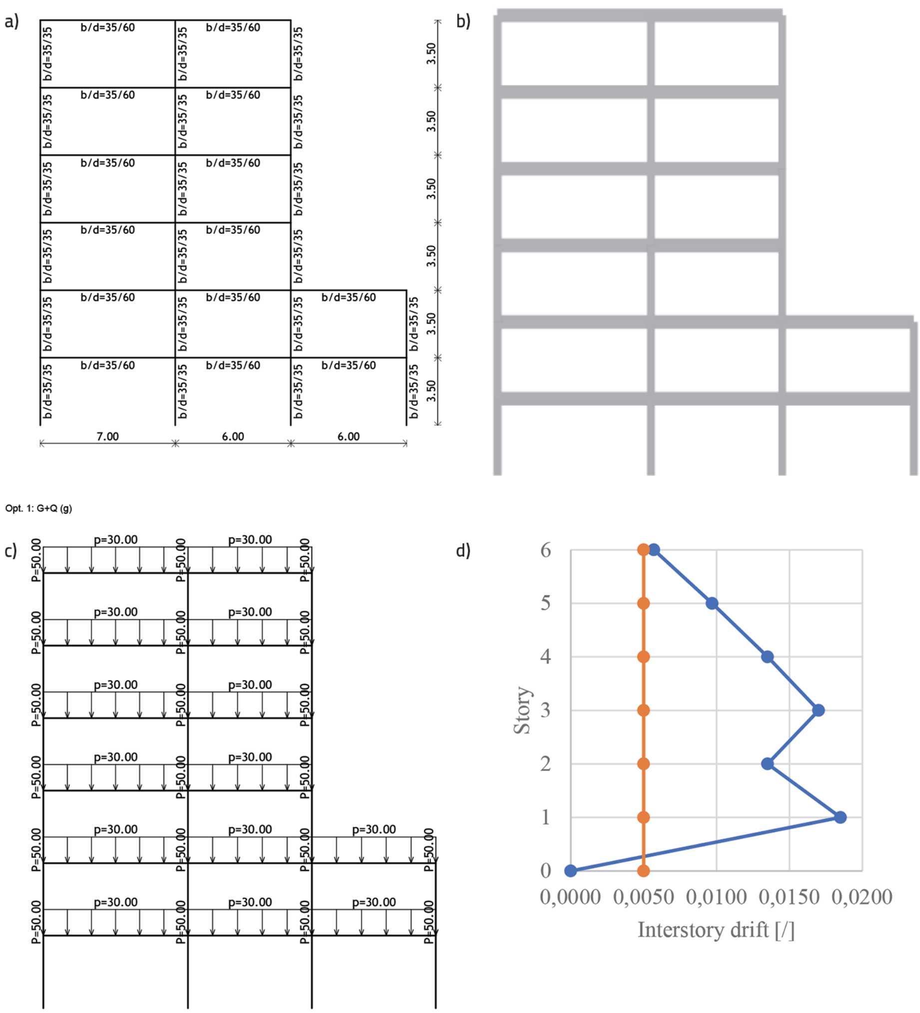

Figure 3. a) Initial geometry, b)Initial 2D view, c) Loads, d) Initial interstory drifts

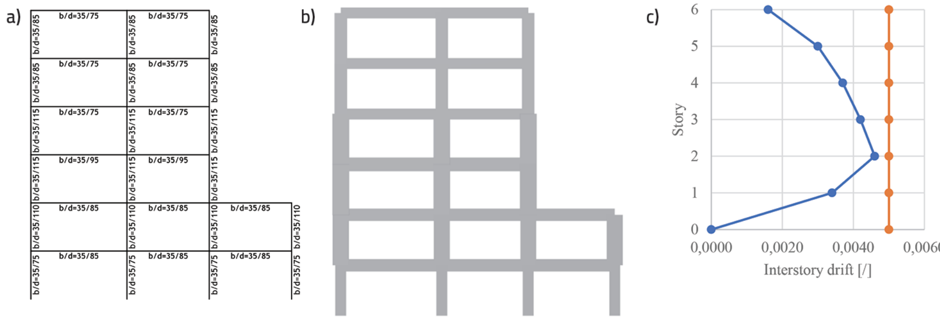

Figure 4. a) Final geometry , b) Final 2D view, c) Final interstory drifts

4 Concluding remarks

The optimization method can achieve a cost-effective design, with minimal use of concrete, and produce an optimal final design with a uniform distribution of ductility along the building. With the implementation of an effective optimization procedure, it is possible to gain a better insight into the behavior of the structure during earthquakes, detect weak points of the structure and achieve a more robust design.

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