Expert Systems with Applications 39 (2012) 2919–2926

Contents lists available at SciVerse ScienceDirect

Expert Systems with Applications

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

Performance based earthquake evaluation of reinforced concrete buildings using design of experiments

Mahdi Modirzadeh, Solomon Tesfamariam *, Abbas S. Milani

Okanagan School of Engineering, The University of British Columbia, Canada

ARTICLE INFO

Keywords:
Building vulnerability
Performance based earthquake engineering
Design of experiments
Decision making
Pushover analysis

ABSTRACT

Seismic resiliency of new buildings has improved over the years due to enhancements in seismic codes and design practices. However, existing buildings designed and built under earlier codes are vulnerable and require a performance-based screening and retrofit prioritization. The performance modifiers considered are soft story, weak story, and the quality of construction, which are collated through a walk down survey. The building evaluation is performed through a pushover analysis, and performance objective are obtained through initial stiffness of the pushover curve. Using a design of experiments technique, a reliable system input–output relation has been identified and used to evaluate the performance criteria at untried design points (i.e., buildings with different modifier values). The proposed method of performance based evaluation is illustrated through consideration of the different structural deficiencies on a typical six-storey reinforced concrete building in Vancouver. Through the designed experiments, the main and interaction effects of the performance modifiers have also been studied.

1. Introduction

The traditional seismic design practice entails specifying the desired performance objective, and subsequently the structure is designed to meet specific performance levels. Performance-based design is a more general approach in which the criteria are expressed in terms of achieving a set of performance objectives while the structure is under levels of seismic hazard (Ghobarah, 2001). The 1994 Northridge Earthquake, for example, highlighted the importance of considering performance-based seismic screening criteria (Elms, 2004).

For the performance-based seismic screening, there is a need for reliable building evaluation techniques (Ghobarah, 2001). The current states of practice for building performance evaluation are capacity-demand method (ATC, 1996) and linear or nonlinear time history analysis (THA) (FEMA, 1996). The nonlinear THA method provides the damage initiation and propagation, and also the collapse mechanism. The environment under which a building has been constructed (e.g., where there is a potential for lack of expertise and quality of construction, often coupled with numerous uncertainties in demand and capacity) should be incorporated in the performance based evaluation approach. The concept of performance based design and evaluation is widely used in structural engineering applications (e.g., Fajfar, 2000; Ghobarah, 2001; Kim & D'Amore, 1999; Porter, 2003). Tesfamariam and Saatcioglu (2008) summarized prevalence of several building performance modifiers from various earthquake field reconnaissance reports. Following that work, in this paper three main performance modifiers have been selected: soft story index (SSI), weak story index (WSI) and construction quality. The pushover analysis is used for evaluating buildings performance.

Given a structure, for design optimization purposes, often analysts are interested in studying individual and combined effects of performance modifiers on overall performance of the structure. This, in turn, can help them concentrate on main aspects of the design and also attain some mathematical models for predicting and optimizing the structure response. Design of experiments (DOE) is a technique that helps analysts choose and perform studies of this kind. Different types of objectives can be realized during a course of DOE (Robinson, 2000). For the first type of objective, one may be interested in a screening procedure in which a small number of factors (called 'main effects') are extracted from a larger pool of factors. The second type of objective aims at finding a functional description of how factors affect the response (i.e., the input–output relation). Eventually, using such a relation the goal can be to optimize the response surface functions. The third objective is when the experiments are tuned to give an estimation of testing errors (i.e., the robustness of the solution is of interest rather than its optimality). The fourth objective relies on obtaining a mathematical model for the input–output relation and also estimating the typical size and structure of errors.

In this study, a full factorial DOE method with a type-II objective as defined above has been aimed at. More specifically, the interest is in exploring the main and possible interaction effects

---

* Corresponding author. Tel.: +1 250 807 8185.
E-mail address: Solomon.tesfamariam@ubc.ca (S. Tesfamariam).

0957-4174/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.eswa.2011.08.153

of the performance modifiers (also referred to as design factors) on a main performance indicator (response) of a reinforced concrete building under earthquake loads. In doing so, a finite element model of the structure (a typical six-storey RC building in Vancouver) under prescribed load and boundary conditions is employed. Results of the computer experiments are then used to complete the DOE study. It is believed that similar applications of the DOE methods, especially once combined with computer experiments, can be beneficial for performance-based earthquake engineering problems given the high cost of physical experimentations and complexity involved in reinforced concrete structures. The concept of DOE has been previously used in other structural engineering applications (e.g., Liel, Haselton, Deierlein, & Baker, 2009; Möller, Foschi, Rubinstein, & Quiroz, 2009; Schotanus, Franchin, Lupoi, & Pinto, 2004; Zhang & Roschi, 2004).

2. Building performance modifiers

The *soft story index* (SSI) and *weak story index* (WSI) are encapsulated under vertical irregularity, and each are quantified through the relative storey stiffness and strength, respectively. The problem of soft story was first identified after the San Fernando earthquake (Scarlat, 2000). The softy story is defined by the stiffness of the lateral force resisting system in any story being less than 70% of the stiffness in an adjacent story (above or below) or less than 80% of the average stiffness of the three stories (above or below) FEMA 310 (ASCE, 1998). The relative length between two adjacent floors is used as a surrogate measure of SSI. The SSI can be quantified as:

$$\mathrm{SSI} = \frac{k_2}{k_1} = \left(\frac{L_1}{L_2}\right)^3, \tag{1}$$

where k_1 and k_2 are stiffnesses of two adjacent stories; and L_1 and L_2 are column heights of two adjacent floors.

The *weak story index* is defined by lateral force resisting system strength of any story being less than 80% of the adjacent story strength (above or below) (ASCE, 1998). The relative strength can be defined by considering areas of columns, structural walls and partition walls (Yücemen, Ozcebe, & Pay 2004). For the moment resisting frame building, in this study, only the column areas are considered. The WSI is defined as the ration of area of all column sections of the ground storey to the area of all column sections of the first storey:

$$\mathrm{WSI} = \frac{\sum(A_{col})_1}{\sum(A_{col})_2}, \tag{2}$$

where $\sum(A_{col})_1$ is the area of the ground storey columns and $\sum(A_{col})_2$ is the area of the first storey columns. In our case there are no shear walls so we deal only with columns.

The *quality of construction and material* used are critical factors to ensure the intended design protection is in fact in place. Examples of poor construction qualities may be: construction error; improper construction procedures; lack of anchorage of beam and column reinforcement; poor concrete quality. In this study, the compressive concrete strength $f_c^/$ is used as a surrogate measure of construction quality.

3. Pushover analysis

Pushover analysis is an evaluation technique used to quantify seismic induced non-linear response of structures. It is a static analysis as an approximation of dynamic response of structures, which has extensively been used for seismic performance evaluation of buildings (Ghobarah, 2000; Krawinkler & Seneviratna, 1998; Kim & D'Amore, 1999). The pushover analysis works on the premise that response of the structure can be related to the response of an equivalent single degree-of-freedom (SDOF) system, so the response is controlled by a single mode, and the shape of this mode remains constant throughout the time history response. When the dynamic behavior of a structure is dominated by the fundamental mode of vibration, the result of the pushover analysis with the load pattern proportional to the shape of the fundamental mode is accurate. Basically, the pushover analysis is based on a very restrictive assumption that the displacement is time independent. This makes this method inaccurate when higher mode effects are significant, i.e., in tall/moderately tall buildings (Fajfar, 2000; Kim & D'Amore, 1999; Mwafy & Elnashai, 2001). In the pushover method, there is a considerable correlation between the loading pattern and observed response. The load pattern can be either "fixed" or "variable" (Tso & Moghadam, 1998). In order to overcome some of the limitations of the method, it has been suggested to assume two different load patterns and then to envelope the results at the end (Fajfar, 2000). Fig. 1 shows result of a typical

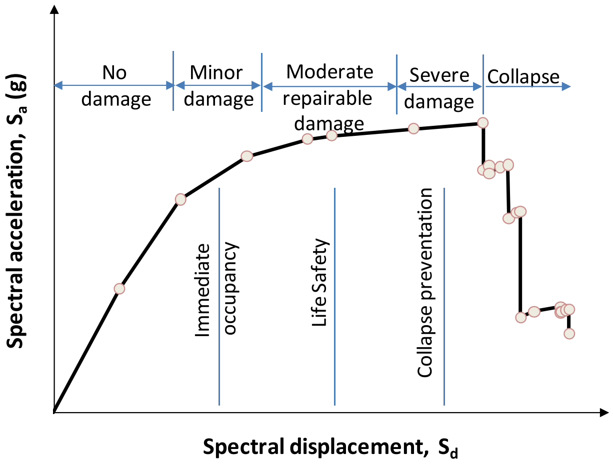

Fig. 1. A typical performance curve from pushover analysis.

Table 1
Comparing various seismic performance ratings (obtained from M Comerio, University of California, Berkeley 2000).

FEMA273		SEAOC vision 2000 rating			ATC post-earthquake assessment designation
Rating	Performance levels	Rating	Preformance expection	Anticipated damage	Green
S-l	Immediate occupancy	10	Fully operational	Negligable	
	Damage control	9			
S-2		8	Operational	Light	
		7			
S-3	Life safety	6	Life safe	Moderat	Yellow
		5			
S-4	Limited safety	4	Near collpase	Severe	
S-5	Collapse prevention	3			
		2	Partial collapse	Complete	Red
		2	Partial collapse-assembly areas		
		1	Total collapse		