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Reliability-based optimal load factors for seismic design of buildings

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ABSTRACT

A reliability-based development of load factors for the combination of seismic and gravity loads is presented. The procedure aims at minimizing the total expected life-cycle cost of buildings, having as a constraint a maximum value of the mean annual failure rate. The loads considered are dead, live and earthquake loads. The methodology is applied to a large inventory of reinforced concrete frames and steel frames buildings located at a soft soil region of Mexico City. Artificial Neural Networks are used to efficiently obtain the designs and the reliabilities of the buildings in the inventory. For the range of load combinations studied, the optimal load factors were found to be insensitive to the value of life, but sensitive to the fundamental vibration period of the structures.

1. Introduction

The structural design process has evolved during the past three decades from working stress methods to limit states design, and during the next decade, performance-based seismic design will become increasingly prevalent. In order to achieve more predictable structural behavior and uniform reliability and to manage damage and costs within acceptable levels, the vast majority of building codes in the world have recognized the need of establishing reliability-based criteria for designing structures [1–4]. Gayton et al. [5] describe some commonly used methods for establishing such reliability-based codes. This paper focuses on design methods that are aimed at minimizing the total expected cost of buildings over their service lives. Such methods have been extensively studied (e.g., [6–13]); however, these studies generally focused on a limited number of relatively simple structures.

This paper proposes a method for establishing optimal seismic load factors for limit states design of buildings that are aimed at achieving minimum total expected life-cycle cost and, at the same time, to ensure that the annual structural failure (or limit state) probability does not exceed an acceptable threshold value. A distinguishing feature of the method is that the load criteria is applicable to the seismic design and performance evaluation of building inventories consisting of hundreds or even thousands of buildings, as might be found in a large urban area, and thus it would be useful to a Municipal Building Department in determining whether special seismic design requirements should be instituted within portions of its jurisdiction. The building inventory is assumed to consist of reinforced concrete (R/C) and steel buildings from 4 to 20 stories that are typical constructions in a high-seismic zone of Mexico City. The building inventory, which is representative of current building practices, is identified efficiently using Artificial Neural Networks (ANN), as described below. The occurrence of earthquakes is described by a Poisson process [14], and the structural performance of each building is identified through probabilistic analyses. The total building cost includes the initial cost plus the expected cost of the damage caused by future earthquakes, including repair cost, cost of damage to the contents, costs associated with the loss of life and injuries, and direct economic losses. All costs are discounted to present value. The loads considered are gravity (dead and occupancy live) and earthquake loads. In this study the focus is on the life safety performance requirement, which is the main concern of the Mexico City Building Code (MCBC); however, the total cost takes into account a range of damage states that might occur in the lifetime of the buildings.

2. General methodology

The general approach adopted in this study is summarized below. From steps 1 to 7, a building is designed with different trial

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load combinations; subsequently (step 8), the same methodology is applied to the inventory of buildings of the same type located in a high-seismic zone of Mexico City (soft soils denoted as Zone IIIb). Due to the large amount of data involved in the numerical process, two ANN models were used to manage the seismic analysis, design and reliability assessment of the building inventory; this process is further explained in Section 6. Details of the methodology follow in the remainder of Section 2. The steps are the following:1. A building is designed according to the Mexico City Building Code [15] (Section 4). In addition, the building is designed using ten alternative trial load combinations, which influence its structural reliability and total cost.2. The maximum structural capacity of the building is obtained by means of an incremental dynamic analysis (IDA) [16], using a set of seismic ground motions identified in Section 3, which are assumed to be suitable for representing seismic demands on buildings in Zone IIIb.3. For each load combination considered in step 1, the structural reliability is estimated by means of the annual rate of exceeding a certain maximum interstory drift (MID) (defined subsequently); the structural demand hazard curve is calculated as [17,18]:

$$\nu_D(d) = \int \left|\frac{d\nu(s_a)}{d(s_a)}\right| P(D > d|s_a)d(s_a) \tag{1}$$

where

ν_D *(d)* = the mean number of times per year that the MID exceeds a given value of *d*;

d = a given value of the maximum interstory drift index;

D = structural demand, represented by the MID;

S_a = pseudo-acceleration at the fundamental period of the building;

$\nu(S_a)$ = mean number of times per year that a seismic ground motion occurs with an intensity equal to or greater than S_a. It represents the seismic hazard curve for the site of interest; and

$$P(D > d|S_a) = 1 - \phi\left(\ln\left(\frac{d}{D}\right)/\sigma_{\ln D}\right) \text{ represents the fragility curve.} \tag{2}$$

4. The expected mean annual failure rate, ν_f, is calculated for each load combination using Eq. (3a) [19,20]:

$$\nu_f = \int \left|\frac{d\nu_D(d)}{d(d)}\right| p(C > d)d(d) \tag{3a}$$

where

ν_D *(d)* is the mean number of times per year that *d* is exceeded; and

P (C < d) represents the probability that the structural capacity *C* be smaller than the *d* associated with the collapse limit state.

The following constraint is imposed:

$$\nu_f(\gamma) \leqslant \nu_f(\gamma_o, MCBC-04) \tag{3b}$$

This constraint leads to a condition in which the expected annual failure rate are limited to values in such a way that the designs are at least as safe as those conforming to the MCBC 2004.5. Seismic demands are simulated from the seismic structural demand hazard curves (Eq. (1)) [21]. Earthquake occurrences are modeled by a Poisson process, and therefore, the intervals between earthquakes follow an exponential distribution.6. From the simulated seismic demand and the capacity of the structure, the damage index of the structure is calculated. Then, the total expected cost is estimated as function of the damage index. The expected cost is transformed to present value (*PV*) using the expression:

$$PV = \frac{FV}{(1+i)^n} \tag{4}$$

where *FV* is the value at future year *n* and *i* is the discount rate equal to 5%.7. A life-cycle analysis of building performance over 50 years is performed by Monte Carlo simulation. The total cost associated with the life of the structure is estimated for each combination as follows:

$$C_T(\gamma) = C_I(\gamma) + C_d(\gamma) \tag{5}$$

where C_T represents the total cost, C_I is the initial cost, C_d is the cost associated with damage; and γ represents the specific load factor combination used in the design (explained in detail in Section 5). Then, considering all the trial design load combinations, the minimum of the total expected cost of the building is obtained as:

$$\min(C_T(\gamma)) \tag{6}$$

8. The procedure mentioned in steps 1 to 7 is applied to all the buildings of the same type (both RC and steel buildings) within the seismic zone of interest (see Section 3). Here the total expected cost is considered equal to the sum of the total costs over the useful life of each building (*Mi*), designed for different load combinations. The expression to estimate the minimum value of total cost is:

$$\min CTDS(\gamma) = \min \sum_i CM_i(\gamma) \tag{7}$$

where *CTDS (γ)* represents the total cost of the buildings of the same type in Seismic Zone IIIb and, $CM_i(\gamma)$. ithe total cost over the life of building M_i designed for the combination γ. The optimum load combination is obtained from Eq. (7).

3. Seismic demand on buildings in seismic zone IIIb in Mexico City

3.1. Seismic demand modeling

The buildings in this study are assumed to be located in Seismic Zone IIIb in Mexico City. Zone IIIb is a region within a former lakebed, consisting of soft soils characterized by peats or highly organic or high-plasticity soft clays with undrained shear strengths less than 50 kPa and shear wave velocities less than 100 m/s [22]. The dominant period of the soil (T_s) is between approximately 1.5 and 2 s, which may lead to resonance in buildings with approximately the same fundamental periods. All buildings considered in this study were subjected to 31 narrow-band soft-soil ground motions recorded in Zone IIIb. These ground motions were recorded during subduction earthquakes with moment magnitudes of 6.9 or larger, and similar epicentral distances. Table 1 summarizes the main characteristics of the seismic records used in the analysis. The records were scaled by an amplification factor such that all of them have the same pseudo-acceleration (*Sa*) ordinate corresponding to the fundamental periods of vibration (T_0) of each building analyzed [23]. The response spectra of the records scaled for similar values of $Sa = 100\ cm/s^2$ for $T_0 = 0.90\ s$ are illustrated in Fig. 1.

3.2. Building inventory in Seismic Zone IIIb

The reliability-based load combinations for earthquake-resistant design were developed for a building inventory that is representative of the buildings commonly built in Seismic Zone IIIb of Mexico City. The number of buildings located in Zone IIIb is approximately 136,800, this information was gathered between 2015 and 2016 [24], it was necessary to simplify the analysis. Thus, it was assumed that the buildings were built of either R/C or steel (masonry or other types of building materials were ignored). It was also assumed that buildings with more than 18 stories belong to a single group (denoted lower frequency buildings). Fig. 2 shows all buildings located in Zone IIIb of Mexico City [24]. The buildings were grouped according to the number of stories because buildings