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Damage prediction for regular reinforced concrete buildings using the decision tree algorithm

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ABSTRACT

To overcome the problem of outlier data in the regression analysis for numerical-based damage spectra, the C4.5 decision tree learning algorithm is used to predict damage in reinforced concrete buildings in future earthquake scenarios. Reinforced concrete buildings are modelled as single-degree-of-freedom systems and various time-history nonlinear analyses are performed to create a dataset of damage indices. Subsequently, two decision trees are trained using the qualitative interpretations of those indices. The first decision tree determines whether damage occurs in an RC building. Consequently, the second decision tree predicts the severity of damage as repairable, beyond repair, or collapse.

1. Introduction

Predicting damage in structures as a result of future earthquakes can be a very useful tool for seismic risk mitigation plans. A reliable estimation of damage has wide ranges of application in the seismic vulnerability evaluation of buildings that have not been designed to withstand earthquake loads. Such damage prediction can be used in scenario studies where effects of a single earthquake, often historically significant, on present-day portfolios in a region are evaluated [1].

Equivalent single-degree-of-freedom (SDOF) systems have significant contribution in many research in the field of earthquake and structural engineering [2–4]. The response of the multi-degree-of-freedom (MDF) structure including regular RC buildings can be related to the response of an equivalent SDOF system, if the response is controlled by a single mode, determined from a high enough modal participation factor. Different methods also make use of equivalent SDOF systems to predict damage in structures [5]. One useful way to predict damage in scenario studies is to calculate a *damage index* (DI) which normally has a value close to zero if the structure remains elastic and close to 1.0 when the structure reaches complete damage or collapse. The available methodologies in the literature to calculate the damage index can be classified according to the number of parameters used (e.g., single-parameter [6–8] or double-parameter [9,10]), type of the concept used (e.g., fatigue-based [11–13], energy-based [14,15], or drift-based [16,17]) or according to the assessment level (local [18,19] or global [20–22]). The main problem with most of those methodologies, however, is the use of quantitative (numerical) representations of damage to replace the qualitative (nominal) meaning of different damage levels.

A very frequently-used damage index in the literature is the one proposed by Park and Ang [23] shown in Eq. (1):

$$DI_{\text{Park and Ang}} = \frac{u_{\max}}{u_{\text{mon}}} + \frac{\beta . E_H}{F_y . u_{\text{mon}}} \quad (1)$$

The term $u_{\max}$ in this equation is the maximum deformations under earthquake loads (dynamic analysis), and the terms u_{mon} and F_y, also shown in Fig. 1, are ultimate deformation and the maximum base shear force from pushover analysis, respectively. Moreover, E_H is the non-recoverable dissipated hysteretic energy (Eq. (2)), and β is a positive constant between about −0.3 and +1.2 (obtains from 250 experimental tests), which depends on structural characteristics and history of inelastic response [24]:

$$E_H = F_y(u_{\text{mon}} - u_y) \quad (2)$$

An advantage of Park and Ang's equation is that it has been calibrated with experimental data. However, in some cases, when the system remains in the elastic mode ($E_H = 0$), the equation gives DI values way bigger than zero which can be misleading towards the damage evaluation of the building. To overcome this problem, a modified version of Eq. (1) is proposed [25] as shown in Eq. (3):

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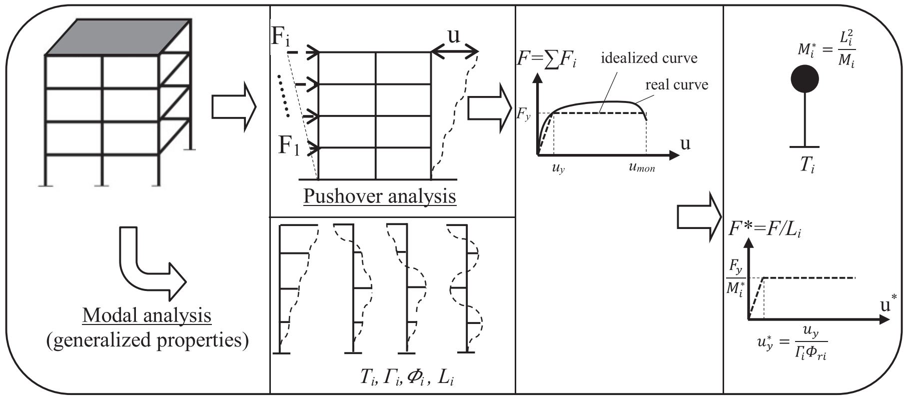

Fig. 1. Equivalent SDOF for the RC frame building.

$$DI_{\text{Kunnath etal.}} = \frac{u_{\max} - u_y^*}{u_{\text{mon}} - u_y^*} + \frac{\beta.E_H}{F_y.u_{\text{mon}}} \tag{3}$$

The added term u_y^* in this equation is the displacement at yield of the equivalent SDOF system (Fig. 1) used to calculate the damage index.

The variation of damage index values for a series of single-degree-of-freedom (SDOF) systems with different structural properties subjected to multiple earthquakes with different characteristics forms *damage spectra* [26]. To accomplish that, a regression analyses is performed to express the damage index as a function of structural properties and earthquake characteristics [27]. The main problem in developing damage spectra, however, is the damage index *outlier* values. According to the definition of the damage index, once the DI exceeds 1.0, the building is assumed to be in complete damage state. In other words, values higher than 1.0 would not physically make sense as higher DI values do not indicate heavier collapse. However, as the calculation of the damage index from any equation presented in the literature including Eq. (3) is mathematical, the result can be theoretically any value bigger than 1.0. Such values would become outliers in the regression analysis to develop damage spectra. To overcome this problem, as the main novelty in this research, we have replaced the numerical damage spectra concept by a damage predictor algorithm (DPA) that uses the qualitative (nominal) meaning of the damage indices instead of the quantitative (numerical) representation. Consequently, the damage index values are translated into the corresponding damage description and grouped into 4 damage classes from no damage to collapse.

The main objective of this paper is to present a damage predictor algorithm in the form of decision trees for reinforce concrete buildings based on the qualitative meaning of the damage index, considering the soil class of the building's site. The proposed decision trees can be used as the first step of a seismic vulnerability assessment for a group of buildings to determine buildings in dangerous condition, for a more elaborated investigation. A machine learning procedure is applied to train two algorithms for each soil class using multiple nonlinear dynamic analyses performed on SDOF systems with different structural properties, using 612 ground motion records. To keep the calculations simple, the damage predictor algorithms are calculated as functions of the parameters shown in Eq. (4):

$$DIA = f\left(M, R, PGA, \mu, T, \frac{F_y}{W}\right) \tag{4}$$

M, *R*, and *PGA* in this equation are the magnitude, site-to-source distance, and the peak ground acceleration at the structure's site in *g*, respectively. The symbol μ denotes the global displacement ductility of the structure, *T* is the period of the mode of vibration with the highest modal participation factor (normally the first mode), and $\frac{F_y}{W}$ is the normalized yield strength of the structure. The accuracy of the damage predictor algorithms are later evaluated using results obtained from the nonlinear dynamic analyses done on a 3-D model of a seven-storey building. Finally, it is shown that the algorithms identify similar damage levels for reinforce concrete buildings damaged in two earthquake in Athens (1999) and in L'Aquila (2009).

2. Damage index for RC frame buildings

2.1. Structural properties of representing SDOF

The damage predictor algorithms in this article are developed for existing RC frame buildings with no significant vertical or horizontal irregularities. For this reason, equivalent SDOF systems (Fig. 1) with the structural properties shown in Table 1 are used in the non-linear dynamic analyses to calculate the damage indices. The Takeda hysteresis model [28] is used for the numerical analyses that are performed with the computer program IDARC [29].

2.2. Ground motion characteristics

The proposed algorithm here is not supposed to take into account near-fault effects such as directivity and fling-step effects. Moreover, the number of data of ground motion records with a magnitude bigger than 7 is limited in a way that is difficult to properly develop an algorithm in that range. Consequently, earthquakes with a magnitude (M_s) between 5 and 6.9 that occurred in Europe since 1970 with a site-to-source distance between 10 and 100 km are selected from the European Strong-Motion Data [30]. For that purpose, 412 ground motion records at various stations, located on rock or stiff soil (Fig. 2), and another 200 recorded on soft and very soft soil (Fig. 3) are chosen to perform the nonlinear dynamic analyses using the structural properties shown in Table 1.

2.3. Calculation of damage indices

Using the structural properties shown in Table 1, Eq. (3) is applied to calculate the damage indices through conducting

Table 1
Structural properties of the RC frame buildings used to develop the damage predictor algorithms.

Period	$\frac{F_y}{W}$	Ductility
0.1–1.0	0.05–0.2	2–6