Soil Dynamics and Earthquake Engineering 84 (2016) 224–237

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Period elongation-based framework for operative assessment of the variation of seismic vulnerability of reinforced concrete buildings during aftershock sequences

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ARTICLE INFO

Article history:
Received 11 February 2016
Accepted 13 February 2016

Keywords:
Reinforced concrete
Structural degradation
Seismic vulnerability
Time variation
Cascading events
Aftershock sequence

ABSTRACT

Safety assessment of structures and/or critical infrastructures is a key factor in post-seismic decision-making. In this context we present a performance-based framework for modeling time-variant vulnerability of reinforced concrete buildings during aftershock sequences. Structural damage is associated with first eigenperiod elongation, a performance metric whose measurement can complement visual inspection and assessment of structural health as a post-seismic operative tool. The proposed framework is applied for a series of reinforced concrete building models and two aftershock sequences. Damage states are defined using thresholds of period elongation. Numerical models of the buildings in each damage state are considered and their fragility curves are computed. The time-variant vulnerability is modeled with Markov chain as a function of the characteristics of the aftershocks sequence. Finally, the probabilities of the damage states are computed as a function of time during two real aftershock sequences.

1. Introduction

Earthquakes are the principal cause of degradation of the properties of structural elements in reinforced concrete (RC) buildings. Stiffness degradation is one of the reasons that modern seismic codes, such as Eurocode 8 [1], demand the stiffness of structural elements to be taken into account with its effective value, which equals a portion of the stiffness of the geometric section of each member. Apart from stiffness degradation, an increase of the damping ratio of the building may accompany seismic damage and affect its response. Another source of structural degradation is the aging effect and the natural deterioration of the structural materials. Pitilakis et al. [2] estimated the detrimental effect of the corrosion of steel reinforcement with time-dependent fragility curves of multistory buildings. Sanchez-Silva et al. [3] proposed a stochastic model that takes into account the effect of gradual non-seismic deterioration of structural materials along with the structural deterioration due to sudden events such as earthquakes and highlighted the importance of both modes of deterioration.

For the case of earthquake clusters such as aftershock sequences, Iervolino et al. [4] developed a probabilistic damage accumulation model for elastic–perfectly plastic single-degree-of-freedom (SDOF) structures and estimated the failure probability as an increasing function of time. Repeated earthquakes and the subsequent damage accumulation may lead to an increase of the inelastic displacement demand of SDOF systems and an increased ratio of the inelastic displacement to the maximum displacement of the elastic system [5]. According to Miranda and Ruiz-Garcia [6], degrading SDOF structures have higher strength and ductility demands than non-degrading structures, when excited by seismic input with a predominant period which is higher than their natural period. Mouyiannou et al. [7] assessed damage accumulation in masonry buildings due to the 2010–2012 Canterbury earthquake sequence and proposed state-dependent fragility curves for masonry buildings with pre-existing damage.

One way of quantifying the structural degradation of a building is through the elongation of its fundamental period. Cracking of reinforced concrete elements due to static loads, in addition to the presence of infill walls, is considered to affect significantly the elongation of the natural period of buildings [8]. Katsanos et al. [9] estimated that period elongation does not exceed 1.2 and 1.7 for the design earthquake and twice the design earthquake, respectively, in the case of moment resisting frames and dual structural

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http://dx.doi.org/10.1016/j.soildyn.2016.02.009
0267-7261/

system multi-story buildings designed with Eurocode 8. Only in extreme cases of severely degrading buildings a ratio of 2.0 was estimated. Katsanos and Sextos [10] proposed an empirical function for period elongation based on the structural period and the force-reduction factor. Moreover, they showed that Peak Ground Acceleration (PGA) has a low correlation with the predominant inelastic period in contrast to spectral acceleration. Based on measurements in damaged buildings after the 2011 Lorca earthquake Vidal et al. [11] proposed relationships for the period of the damaged buildings as a function of the number of stories. According to these relationships the period elongation is independent of the number of stories and equals 20%, 43% and 65% for EMS [12] damage grades 1, 2 and 3–4. These results are approximately equal to observations by Dunand et al. [13] for equivalent damage levels, who were certainly the first who associated the classical in-situ red-orange-green traffic light classification of damaged buildings with period elongation after the 2003 Boumerdes, Algeria earthquake. The period elongation ratio has been observed to be proportional to the stiffness and the force-reduction factor (ratio of the maximum seismic force to yield force) of SDOF oscillators [9], while the effect of earthquake magnitude, distance and soil conditions has been estimated to be of minor significance.

Jeon et al. [14] have developed aftershock fragility curves for reinforced concrete buildings in California. These aftershock fragility curves give the probability to exceed damage thresholds given the intensity measure and an existing damage state caused by the mainshock. Their most interesting finding is that buildings with damage caused by the mainshock, which is less than or equal to moderate, have less than 4% additional probability to develop severe damage in the aftershock sequence. Ebrahimian et al. [15] developed a performance-based framework in order to make operative forecasts for the first day after the mainshock. They computed event-dependent fragility curves and estimated the daily risk of exceeding of damage thresholds using synthetic aftershock sequences, which were generated with the Epidemic Type Aftershock Sequence model. Yeo and Cornell [16] introduced Aftershock Probabilistic Hazard Analysis and assessed the vulnerability of a building in a series of damage states in order to assess the time-variant probability of collapse. They also employed Markov chain analysis to estimate financial losses due to structural damage. The probability of collapse and financial loses constitute the input of their decision tree analysis framework for earthquake risk management.

The variation of the vulnerability immediately after the mainshock is a key factor in post-seismic decision-making. Given that reinforced concrete buildings may accumulate damage during aftershock sequences and become more vulnerable, it is necessary to employ procedures, which estimate the variation of seismic vulnerability during aftershock time-periods. The presentation of such a procedure is the aim of this article. This article, in contrast to previous work on this topic, focuses mainly on an efficient operative method proposed for assessing time-variant vulnerability during aftershock sequences. This method is based on the assessment of resonance frequency shift, which can be related to damage states [11,13] and the associated variation of fragility curves. Period elongation assessment can be used complementary and in support of visual inspection of buildings and expert judgment after a damaging earthquake. Furthermore, the proposed framework could be used to update vulnerability functions in an early-warning protocol (e.g. [17]). The building models considered herein are representative of critical infrastructures such as the Port of Thessaloniki, which is the site of one of the case studies. The structural health of such buildings is often monitored with proper instrumentation. Since structural degradation can be observed and localized through eigenfrequency variation [18–20], we have defined damage-state thresholds in terms of the relative increase of the period, as measured before an earthquake in the undamaged building and afterwards in the damaged building. The reduced stiffness of the structural elements of the degraded building models and period elongation is expressed as a function of total and maximum inter-story drift computed by non-linear time-history analyses. Once the relationships between maximum inter-story drift and period elongation have been estimated, the thresholds of the damage states are defined using period elongation values and the fragility curves of the original and degraded models are computed. The fragility curves are subsequently used to compute state transition probabilities in the Markov chain used to model the time-variation of vulnerability. The probabilities of the considered damage states are finally computed in the cases of two real aftershock sequences as application examples of the proposed framework, a detailed risk analysis with the proposed framework or a sensitivity analysis of its results are out of the scope of this article.

2. Building models

A series of low-rise and mid-rise reinforced concrete building models (Fig. 1) is selected as representative of typological categories in Greece [21]. The models are being referred to as C1L, C1M, etc. using the naming convention in HAZUS [22] according to building type. The characteristics of the selected models are summarized in Table 1 and include low-code and low-rise models of buildings with a structural system of bare (C1L) and regularly infilled (C3L) moment resisting frames, shear walls equivalent system (C2L) of frames coupled with shear walls carrying more than 65% of the base seismic shear force [23]; a mid-rise C1M type building models with low, moderate and high seismic code design; and a mid-rise low-code C2M building model. The rationale behind including bare frames in the analyses is that although the presence of infill walls is generally regarded as beneficial for the structure, when their layout is regular [21], it has been shown that their presence may be detrimental and their modeling can be challenging [24]. As far as the period of the C1M high-code building model is concerned (Table 1), it is higher than the periods of the C1M low- and moderate-code building models because of smaller dimensions of the seismic load-bearing structural members contrary to what would be expected. Low-code design level refers to seismic design according to the first seismic code that came into effect in Greece in 1959, while moderate design level is according to the Supplementary Clauses of 1985 and high-code level corresponds to design with the Greek seismic code of 2001 [25]. The provisions of the 2001 code bear similarities to EN 1998-1 [23] and demand capacity design with structural member detailing for ductile behavior aiming for energy dissipation in the seismic resisting system and plastic building collapse mechanisms. According to a 2001 survey, 32% of the building stock of Greece predated the 1959 code, 46% was constructed between 1959 and 1985, when a new seismic code was introduced, under which 22% of the stock was built [26]. Based on more recent data in the city of Grevena in Greece, the reinforced concrete buildings built after 1959, 1985 and 2001 consist 49%, 11%, and 19% of the building stock, respectively [27].

Three types of analyses are performed with OpenSees [28]: fiber, modal and non-linear time-history analyses. All building models are two-dimensional and *p–delta* effects are not included in the analyses. Although simplified 2D models are unable to account for effects related to irregularities such as torsion, it has been shown that they can be used to make an effective estimation of losses of real 3D structures [21]. The fiber analyses are employed to compute the yield moment and curvature of each structural element through a bilinear approximation of the numerical results. This data is then used in non-linear analyses to model the inelastic response of the elements with a distributed plasticity model of hysteretic response with stiffness