Probabilistic seismic vulnerability assessment of reinforced concrete moment frames exposed to corrosion

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ABSTRACT

Earthquakes and damages caused by corrosive environmental conditions are two important factors that threaten the desirable performance of structures in the coastal cities of the Persian Gulf in southern Iran. Taking into account both of these risks in the analysis and design of structures can reduce the loss of life and can lead to significant economic savings. In recent years, studies on the probabilistic seismic vulnerability assessment of structures have been developed. In this paper, a risk-based approach is used for seismic evaluation of reinforced concrete moment frames with medium ductility that are exposed to damage due to chloride-based corrosion of rebars in 4 important port cities of southern Iran (including Bushehr, Assaluyeh, Bandarabbas and Chabahar). A total of 18 reinforced concrete moment frames with different number of stories and in increments of 10 years after the initiation of corrosion, were subjected to incremental dynamic analysis (IDA). Then, using the risk integral, the annual probability of collapse for frames in the studied cities was obtained and evaluated. The results of this study show that over time after the initiation of corrosion, the probability of collapse of structures increases sharply, which indicates the high need for risk-based approach to evaluate and seismic design of structures that are exposed to damages due to aggressive environments.

KEYWORDS

Probability of collapse, Risk-based seismic evaluation, reinforced concrete moment frame, chloride-based Corrosion of reinforcement rebars, important port cities of southern Iran.

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Introduction

The concept of risk-based approach has been used in recent years to develop seismic risk maps of the United States, France, Europe, Romania and Spain [1-5]. In Iran, Taherian and Kalantari (2019) recently used this approach to develop risk-based seismic design maps [6].

In this article, 3 reinforced concrete (RC) moment frames of 3, 5, and 7 floors in 4 important port cities of southern Iran (including Bushehr, Asaluyeh, Banderabbas, and Chabahar) are considered. These frames are designed with the latest edition of our country's seismic regulations (standard 2800, fourth edition) and have already been evaluated by this research team in a non-corrosive state [7]. Then, the effect of corrosion in time periods of 10, 20, 30, 40 and 50 years on the results without corrosion is evaluated. A total of 18 models are built and the Incremental Dynamic Analyses (IDA) is performed on them. Finally, by using integral risk, the probability of modeled frames collapsing in the studied cities is determined and evaluated. The studied port cities are located in the area with high relative risk (zone II) based on the earthquake relative risk mapping in Iran Seismic Code (Standard 2800).

Risk-based analysis

The classical product presented in the following equation can be used to determine the seismic risk, $y(a_0)$, [8]:

$$y\left(a_0\right) = \int_0^{\infty} H\left(a\right) . \frac{dP_{a_0}\left(a\right)}{da} da \tag{1}$$

In this equation, $Pa_0(a)$ is the fragility curve, i.e., the conditional probability of fragility in terms of ground motion a for a design level a_0 and H(a) is the hazard curve, i.e., the probability of exceedance related to ground motion a. It is common to use lognormal distribution with mean μ and standard deviation β to determine fragility curves ($P(a)=\Phi([\ln(a)-\ln(\mu)]/\beta)$). In the process of risk-based analysis, μ is an acceleration that is considered equivalent to the annual probability of the structure collapsing (P_c) at the design code-based ground motion ($P_{c/gm}$). Therefore, P_c can be calculated by using equation 1, having a hazard curve and estimating the values of μ and β.

In this study, it was necessary to use the same probabilistic hazard model to derive seismic hazard curves so as to cover all the studied cities. Therefore, the hazard results obtained from the website of the European Facility for Earthquake Hazard and Risk (EFEHR - www.hazard.efehr.org) were used.

The effects of chloride-based corrosion on the studied structures

The RC buildings located on the coastal areas of Persian Gulf are usually experiencing corrosion in the steel bars. The average temperature above 30 degrees and relative humidity of about 70-90%, has made the Persian Gulf region one of the most corrosive environments in the world. In this research, the effect of corrosion on the studied structures has been considered in the form of 4 parameters, which will be discussed in the following.

Based on an experimental investigation, Du et al. (2005) proposed a time-dependent model to account for the effects of corrosion in the diameter and yield strength of steel bars subjected to chloride attack [9]:

$$d_s\left(t_i\right) = \sqrt{1-Q_{corr}\left(t_i\right)}\, d_{s0} \tag{2}$$

$$f_y\left(t_i\right) = \left(1.0-\beta_y Q_{corr}\left(t_i\right)\right) f_{y0} \tag{3}$$

$$Q_{corr}\left(t_i\right) = \frac{2.10(1-w/c)^{-1.64}}{d_c d_{s0}} t_i^{0.71} - \frac{1.10(1-w/c)^{-3.28}}{d_c^2 d_{s0}^2} t_i^{1.42} \tag{4}$$

in which $d_s(t_i)$ and $f_y(t_i)$ are time- dependent diameter and yield strength of the longitudinal reinforcement, respectively. ds_0 and fy_0 are initial diameter and yield strength of the bars, respectively. βy is the strength reduction factor which ranges from 0.16 to 0.45 for the ribbed bars. $Q_{corr}(t_i)$ is the percentage of the corroded mass with respect to the initial mass of the longitudinal bars.

The third parameter considered to apply the effect of corrosion on the studied structures is the ratio of the strength of the core concrete to the strength of the cover concrete, K_c, which is expressed by the following equation [10]:

$$K_c = 1 + \frac{\rho_s \sigma_{yh}}{\sigma_c} \tag{5}$$

$$\rho_s\left(t\right) = \left[1-Q_{corr}\left(t\right)\right]\rho_s \tag{6}$$

$$\sigma_{yh}\left(t\right) = \left[1-0.5Q_{corr}\left(t\right)\right]\sigma_{yh} \tag{7}$$

In which σ_c and σ_{yh} are the compressive strength of concrete cover and yield strength of stirrups, respectively; ρ_s is the ratio of the stirrups with respect to the concrete core area.

In this paper, to consider the effects of bond-slip of steel bars at members connection, zero-length elements were used at the beam-column connections and at the column's base (Figure 1). To determine the stiffness of these springs, the recommendations as per NIST GCR 17-917-46v3, were used [11]:

$$K_{SE} = \frac{M_y}{\theta_{BS}} \tag{8}$$

In which M_y is the yield moment and θ_{BS} is the spring rotation because of bars slip at the members connection.

Derivation of fragility curves of the RC frames

In this paper, the nonlinear fiber beam-column elements were employed according to NIST GCR 17-917-46v3 [11]. OpenSees platform was utilized for simulation of the considered RC frames. This modelling technique had already been used for simulation of the seismic behavior of RC frames without corrosion [8]. Finite element model of RC frame is shown in Figure 1. 22 pairs of far-field ground motions in soil type C and D included in FEMA P695 is used for IDA analyses.

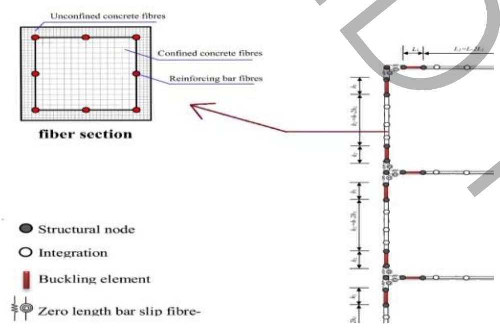

Figure 1. Finite element model of the RC frame [7]

Results and Discussion

The annual collapse exceedance probability of models at the design code-based ground motion ($P_{c/gm}$) for the studied models in the considered port cities after exposure to corrosive environment versus time is calculated by using risk integral (Equation 1). The mean value of $P_{c/gm}$ were determined 1.9E-5 to 2.97E-3 (Figure 2).

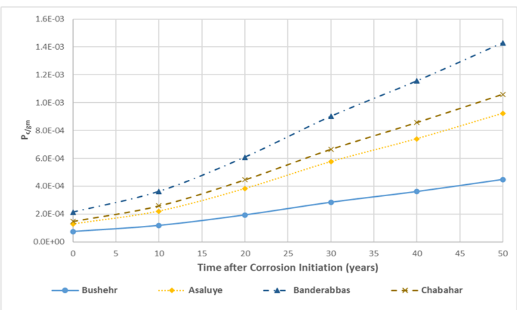

Figure 2. $P_{c/gm}$ with respect to the time after corrosion initiation for the port cities under study

Conclusions

The $P_{c/gm}$ for the studied RC frames increases substantially by increasing the time intervals after corrosion initiation (Figure 2). The obtained results show that $P_{c/gm}$ is different for the same structures in different cities and increases strongly with the passage of time after the beginning of corrosion, which is a strong reason for the necessity of using the "risk-based" approach for analysis and design of structures that are subject to corrosion.

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