HIGHLIGHTS:

- Newly formulated intensity measure based on the modified acceleration spectral intensity for RC corroded buildings

- Robust seismic fragility analyses of existing RC buildings with smooth bars subjected to various levels of corrosion.

- Response of corroded RC buildings to sequential mainshock-aftershocks motions

SEISMIC FRAGILITY OF EXISTING RC BUILDINGS WITH CORRODED BARS UNDER EARTHQUAKE SEQUENCES

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Abstract: Earthquakes are not isolated events but, typically, dominated by a larger-magnitude excitation (Mainshock – MS) and many smaller-magnitude motions (Aftershock – AS). Most often, such destructive events bring more damage than a single strong motion. Nowadays, many existing non-seismic designed reinforced concrete (RC) structures are classified as either functional-obsolete or sub-standards. The seismic performance of these aged structures can be even more critical if some phenomena, such as corrosion, occur. The present study aimed at evaluating the seismic vulnerability of typical existing RC structures subjected to earthquake sequences and various levels of corrosion. A probabilistic approach based on fragility analysis and thus use of three different seismic intensity measures (IM), was employed. A four-story RC building was used as a testbed for Incremental Dynamic Analyses (IDA) with an advanced finite element (FE) modelling. Twenty as-recorded natural motions were selected from international databases and inserted into the three-dimensional FE model. A new seismic intensity measure was provided and compared to commonly accepted use of peak ground acceleration (PGA) and spectral acceleration at the first natural period of the structure ($Sa(T_1)$); the modified spectral acceleration intensity (MASI). The limit states of limited damage (LD) and severe damage (SD) are discussed as capacity thresholds. The outcomes of numerical investigations showed that multiple excitations and corrosion significantly affect the seismic vulnerability of the investigated building. Additionally, MASI appeared to be the most effective intensity measure to assess the seismic fragility of corroded RC buildings. It is concluded that modern seismic-based technical codes are no longer conservative for assessing RC structures with detrimental ageing phenomena, e.g. corrosion.

Author Keywords: Corrosion; Seismic Fragility Assessment; Earthquake Engineering; Structural Modelling; Probabilistic analysis.

1. Introduction

Modern seismic-based codes state that reinforced concrete (RC) structures should be designed to withstand a single strong ground motion. However, the complexity of fault systems and the dynamic stresses generated by single events can trigger multiple aftershocks (Ruiz Garcia et al. 2012). Typically, earthquake sequences produce large displacements for RC buildings and, therefore, detrimental effects, such as corrosion, can be critical for those structures. A large portfolio of existing RC structures are considered obsolete such that the effects of aggressive agents and sequential ground motions can rapidly reduce the mechanical properties of the concrete and steel reinforcements, and, therefore, the global seismic resistance of such structures (e.g. Di Sarno and Pugliese, 2019). Potentially, motion sequences may completely change the non-linear response of RC structures due to the short period of occurrence between mainshocks and aftershocks, which does not allow to take any actions aimed at retrofitting or repairing the building. Recently, there have been quite a few studies on the seismic assessment of structures subjected to earthquake swarms. Di Sarno (2013) conducted a numerical study on the effects of earthquake sequences on the inelastic response of RC framed structures. Results showed that an accurate hysteretic model should be used to reliably predict the non-linear response and, account for the stiffness and strength degradation of RC buildings.

Aldelnaby (2018) employed two-hundred forty sequences from the 2011 Tohoku earthquake in Japan on three different RC frames to generate the structural parameters for the fragility assessment. The results showed that aftershocks might have a more significant impact after the occurrence of mainshocks. The impact of mainshocks is relevant for subsequent aftershocks due to the damage accumulation; and, the seismic response of a seismic-designed building is almost the same when subjected to either sequence or mainshock. Panchireddi and Ghosh (2018) presented a novel study on aged RC bridge subjected to sequential ground motions. They considered four levels of corrosion over a time-span of 100 years and compared the damage index for the case of non-corroded and corroded RC bridges. Results showed that corrosion has a significant impact on the seismic vulnerability of RC bridges, which becomes critical when the structure is subjected to both ground motion sequences and harsh corrosion condition. The damage index increases when corrosion occurs, causing collapse or strongly inelastic behaviour.

The present study aimed at investigating the effects of ground motion sequences and different levels of corrosion on typical existing RC buildings. Corrosion was simulated through an external exposure with a one-sided and two-sided attack for the edged columns and beams. Incremental dynamic analyses (IDAs) were performed considering mainshock-aftershock seismic sequences. A probabilistic assessment via Fragility analysis, in terms of a global approach, was carried out. Inter-storey drifts and fragility curves were compared through the limit states of Limited Damage (LD) and Severe Damage (SD). Limit values were taken as an average of the response parameters obtained by non-linear static analyses using three different lateral loading patterns. Results of the comprehensive numerical simulations indicated that corrosion and multiple excitations have a relevant effect on the maximum inter-storey drift ratios and, thus, the seismic vulnerability of non-seismic designed existing RC structures, as shown for a typical multistorey building used a case-study.

2. Seismic Fragility Assessment

Modern seismic-based codes specify that at least seven earthquake ground motions should be considered to obtain an average non-linear response of RC structures (e.g. Eurocode 8 – Part 3, 2004, among others). However, guidelines do not provide any indications for RC structures under seismic sequences and corrosion effects. In the present study, a set of twenty natural as-recorded ground motions was selected from PEER NGA strong motion database (PEER, 2020). Each earthquake consisted of two horizontal components and used to simulate far-field conditions. A time gap equals thirty times the fundamental frequency was used between mainshocks and aftershocks to bring the structure to the rest and cease any movement caused by damping.

Three different IMs were considered, namely peak ground acceleration (PGA), spectral acceleration at the first natural period T1 of the building (Sa[T1]), and the modified acceleration spectral intensity (MASI). The former IMs, i.e. PGA and Sa(T1), have been extensively used in fragility studies, e.g. Elnashai and Di Sarno (2015). MASI is defined herein as the modified acceleration spectral intensity and requires the characterization of two periods of vibration, namely the fundamental period and the elongated (inelastic) period. Typically, strong ground motions force the structures to elongate their natural periods and experience large damage. Although laborious to estimate, Eurocode 8 (EN 1998 – Part-3, 2004) states that the maximum elongation period due to the non-linear behaviour is twice the fundamental period of the structure, which is reasonable for existing non-seismic designed structures. MASI can be expressed as follows:

$$\text{MASI} = \int_{T_1}^{2T_1} S_a(T)\,dT \quad (2)$$

where T is the period of vibration of the structural systems and T1 is the natural period.

To represent the seismic performance levels of the structural system and build the fragility curves, the inelastic response of the existing RC building was evaluated via the IDA procedure (Vamvatsikos and Cornell, 2002). The structure was subjected to multiple earthquake excitations, and various corrosion rates. The IDA procedure involved ground motions that were adequately scaled through the use of coefficients to simulate the linear and nonlinear response of the RC building. The hunt-fill algorithm (Vamvatsikos and Cornell, 2004) was used to pick an initial elastic step (e.g. PGA = 0.005g) and five more steps to hunt the first non-convergence in terms of the infinite value of the inter-storey displacement; two additional steps were specified to reach up to the inelastic response ("flatline"). The coefficients to scale the natural motions were related to either the structure collapse or large inter-storey drift ratios. A typical relationship between a damage measure quantity (EDP) and an intensity measure (IM) was then obtained by interpolating these two parameters. As a result, the maximum inter-storey drift ratio (MIDR) was adopted as an engineering demand parameter (EDP).

The probabilistic approach to derive the fragility curves is commonly used for the evaluation of the global and local response of RC structures, and it is here defined as follows (1):

$$P\left(\mathrm{EDP_i} \geq \mathrm{EDP_{LS}} \middle| \mathrm{IM} = x\right) = \Phi\left[\frac{1}{\beta_i}\ln\left(\frac{\mathrm{IM}}{\mathrm{LS_i}}\right)\right] \quad (1)$$

where P is the probability of exceedance of the specified limit state based on the ground motion intensity, Φ is the probability density function of a normal distribution, β_i is the lognormal standard deviation, and LS_i is the median value that represented a ground motion intensity that has 50% probability for the occurrence of the limit state from the nonlinear static analyses. In addition to a probabilistic model, a fragility assessment requires the evaluation of the structural capabilities of all components (e.g. columns and beams), so two different limit states, including limited damage (LD) and significant damage (SD) were adopted as capacity thresholds. The aforesaid limit states were defined by performing non-linear static analyses (NSA) on the testbed RC building considering three different lateral loading patterns and three levels of corrosion. Table 2 shows the maximum inter-storey drift ratio (MIDR) threshold values from the NSAs (Table2).

Table 1. Limit States expressed as inter-storey drift ratio, IDR [%]

Corrosion Rate, CR [%]	SD [%]	LD [%]
0	1.87	1.06
10	1.44	0.93
20	1.17	0.90

(*Keynote*: SD = Severe Damage; LD = Limited Damage).

To further investigate the seismic vulnerability of typical RC structures, an optimal and reliable IM should comply with some feasible criteria, such as efficiency, proficiency, practicality and sufficiency that have been introduced in literature over the last decades (Luco et al. (2007); Padgett et al. (2008), among others). To estimate the parameters of such criteria, a regression power line of the form $\mathrm{EDP} = \beta\ \mathrm{IM}^{\alpha}$($\alpha,\beta$ are the coefficient of the regression analysis) was fitted through the structural response obtained by non-linear time-history analyses considering un-scaled records. Figure 1 illustrates the relationships between the IMs and the EDP through the fitting curve.

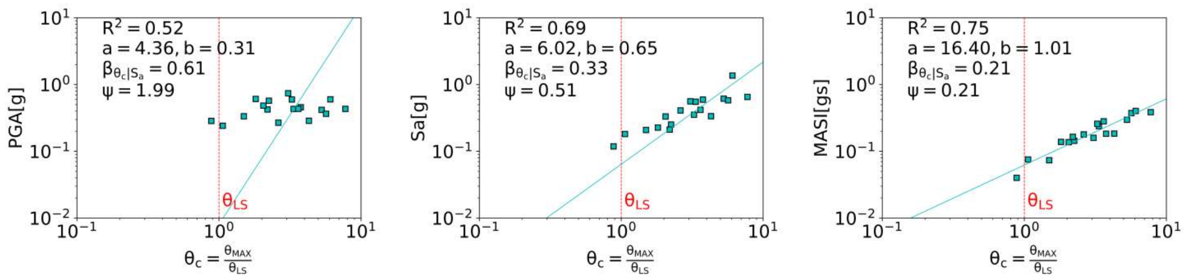

Figure 1. EDP-IM, CR [%] = 10 (mainshock)

The values of the maximum inter-storey drift ratios (MIDRs) obtained from the analyses were normalized to the limit state SD. However, it can be demonstrated that each limit state leads to similar results. It was observed that the MASI appeared to be the most efficient seismic intensity measure as it fitted the data better than the other IMs. Besides, it demonstrated a high efficiency due to the lowest values of the standard deviation of the residuals, which could probably lie in the relevant inelastic effects of the higher modes, included in the period range between T_1 and $2T_1$, that allowed to capture the degree of non-linearity of the structural response. A comparison between the slopes of the regression lines for all IMs showed that MASI produced the highest values. By contrast, PGA showed the largest dispersion and the lowest effectiveness for efficiency, proficiency and practicality. The last finding could be an indication of its weak correlation with structural parameters, i.e. inter-storey displacements and vibrations modes, among others. The modified acceleration spectral intensity was found to be the most proficient IM having the smallest values of the ratio between the standard deviation and the slope of the regression line.

The sufficiency criterion was also used to investigate the independence of the proposed IM from ground motion parameters, i.e. magnitude. This criterium referred to the slope of the regression line. The smaller the slope, the higher is the sufficiency given by the IM.

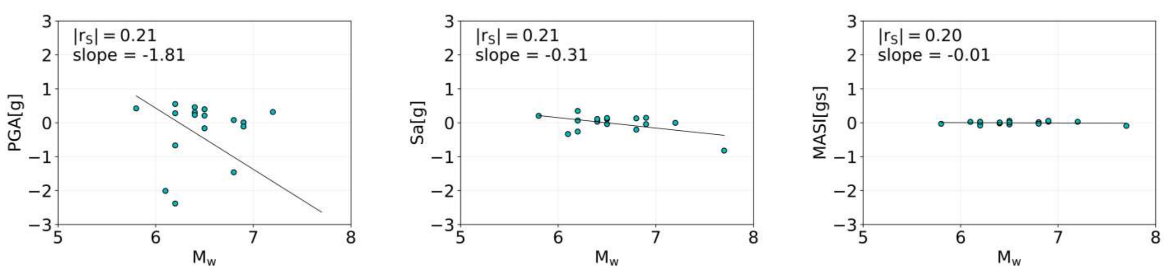

Figure 2. Sufficiency of IMs as a function of the ground motion magnitudes for CR [%] = 10

Figure 2 shows that the IMs ($Sa[T_1]$ and MASI) were sufficient according to the slope of the regression line, while PGA was strongly correlated to the ground motion parameters. These outcomes demonstrated that the IM provided in this study seemed to eliminate the dependency from the magnitude of the ground motions employed in the structural analysis.

The fragility assessment for a typical case study RC multi-storey building with ageing effects, as further discussed in Di Sarno and Pugliese (2020), is provided hereafter for the two limit states, namely SD and LD, to reliably assess the seismic response of the sample building. Three levels of corrosion ratios (CRs) were considered: 0% (un-corroded), 10% and 20%. Results for CR [%] = 0 were taken as a reference for computing the differences of the failure probabilities and evaluating the impact of corrosion on the seismic vulnerability.

Limited Damage

Figure 3 illustrates the comparison of the fragility curves for the RC building subjected to earthquake sequences (MS-AS). The vulnerability of the existing building subjected to multiple excitations decreased over time due to the damage accumulation and the effect of corrosion degradation. The range of values that would cause the exceedance of the limit state decreased, while the damage probabilities for all IMs increased. The dramatic increment of the seismic vulnerability was equal to approximately 80% and 83% for Sa[T_1] and MASI, while 45% for PGA. Strong mainshocks and subsequent comparable aftershocks forced the structure to undergo high inter-storey drift ratios and residual displacements, which led to high failure probability for typical non-seismic designed RC structures under MS-AS sequences.

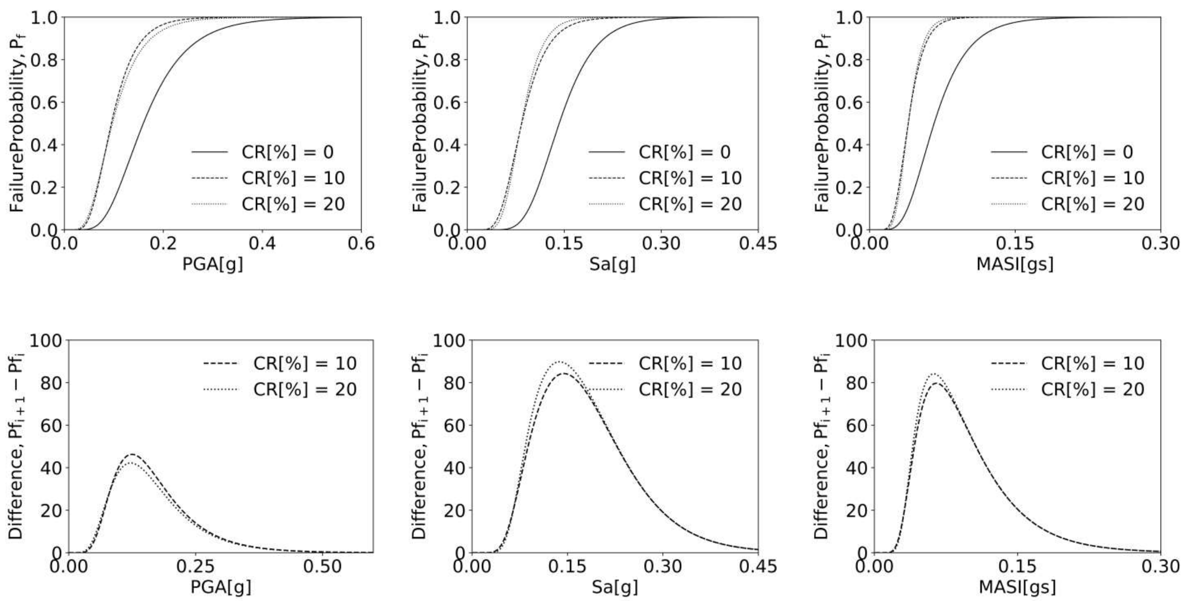

Figure 3. a) Fragility curves – sequence; b) Failure Probability difference (CR [%] = 0 as a benchmark)

Severe Damage

The threshold defined from Eurocode 8 (2004) for SD is commonly equal to 2% for MIDRs. This limit was modified to account for the level of corrosion damage and the reduced mechanical properties of concrete and steel reinforcement.

Figures 4 presents the comparison of the seismic failure probability for the RC building subjected to earthquake sequences (MS-AS) for the SD limit state. From the comparison, it was evident that the seismic performance of the existing building decreased over time due to the combination of the multiple excitations and corrosion damage. The most substantial increase of the seismic vulnerability could be observed for the Sa[T1] and MASI, which were highly correlated to the inelastic response of the structure.

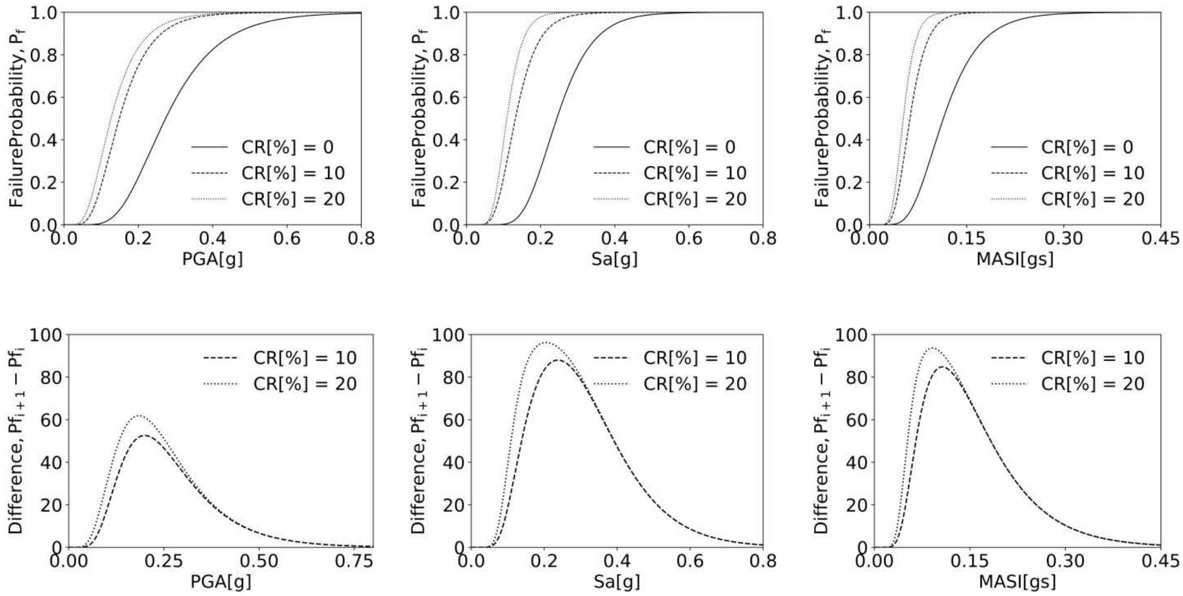

Figure 4. a) Fragility curves - sequence; b) Failure Probability difference (CR [%] = 0 as a benchmark)

According to Figures 4, the probability of failure reached values of 100% greater than the un-corroded counterparts, both for $Sa[T_1]$ and MASI. The use of PGA indicated that the impact of corrosion increased the seismic vulnerability by 60% and 50%, respectively. Such large increments were caused by a significant spreading of the inelasticity in the structure. Inelastic performance of the building showed large residual displacements, as well as stiffness and strength reduction; thus, strong aftershocks could bring the structure to either failure or strongly affect the immediate occupancy.

3. CONCLUSIONS

This study presents an overview of on structural performance assessment of a typical existing RC building under multiple excitations and various level of corrosion via a probabilistic approach. A new seismic intensity measure, based on the acceleration spectral intensity and accounting for the elongation period, was introduced. The outcomes of preliminary numerical analyses are summarised as follows:

- The newly introduced seismic intensity measure, i.e. the modified acceleration spectral intensity (MASI), is accurate for predicting the seismic fragility of corroded RC structures under mainshock-aftershock sequence;
- Results for all the limit states demonstrated that corrosion had a significant impact on the seismic vulnerability of a typical existing RC building. Particularly, multiple excitations forced the structure to undergo large inelastic displacements, which, in turn, increased the failure probability by more than 80% for Sa[T1] and MASI. PGA showed the lowest values of the failure probability, which may result in overestimation of the seismic capacity;
- Modern seismic specifications are no longer conservative in the assessment of existing RC structures under multiple excitations and various levels of corrosion. Limit states defined by these technical codes demonstrated that they are safe only in some cases and for un-corroded structures under a single strong motion.

The present numerical study has focused on the most relevant causes of concrete deterioration and degradation, such as corrosion and mainshock-aftershock sequences. However, additional investigations of the uncertainty in the structural model should also be employed when analysing RC structural systems with ageing; thus, accounting for cover concrete depth, yielding steel stress, concrete compressive strength random distributions among the others.

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