Numerical Evaluation of Reinforced Concrete Frames with Corroded Steel Reinforcement under seismic loading. A Case Study

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ABSTRACT: This paper presents a numerical evaluation of reinforced concrete (RC) framed structures exposed to different levels of corrosion. A non-linear finite element fibre-based approach is used. The numerical model utilized in the numerical simulations was first compared and validated against a set of experimental test results from the literature. The framed model is then assessed with respect to the European Standards in order to evaluate the impact of corrosion on the damage associated to different Limit States. The results showed that the corroded RC columns are subjected to a significant reduction, especially for high levels of corrosion and total exposure of the column, both of shear strength and ductility. Finally, a typical existing RC building located in Italy was analyzed through linear and non-linear analyses to evaluate the response of an actual building when exposed to aggressive environments. The results showed that corrosion reduces both the base shear capacity and ductility of the sample framed building. Particularly, while corroded columns decrease mainly the base shear capacity, corroded beams reduce significantly the ductility of the aged building. Moreover, time-history analyses showed that earthquakes with a Peak Ground Acceleration (PGA) of greater than 0.23 g increased the inter-storey displacements of the corroded RC structure, while earthquakes with a PGA of less than 0.23 had a hardly noticeable influence.

1 INTRODUCTION

Many reinforced concrete (RC) structures built in the 60s and 70s tend to be in poor condition and functionally obsolete due to ageing and degradation phenomena, which are related to the exposure to chemical and physical aggressive agents, either in seismic prone-zone [Bhide, (1999)] or non-seismic prone-zone [Di Sarno & Pugliese, (2019)]. The durability of RC structures, which is strictly related to the environmental exposure of the structure, is the capacity of the concrete to protect steel reinforcements from corrosion processes due to the attack of aggressive agents present in the air, water and soil. As a result, to guarantee the integrity of the RC structures, it is essential to study the concrete composition in terms of consistency and environmental exposure. Standards and codes (EN 1992-1-1 and D.M. 14-01-2008) provide some important measures to ensure the durability of RC structures over the years, especially for damage due to carbonation-induced and chloride-induced corrosion. However, many RC structures show significant deficient conditions due to high levels of corrosion. As a result, the reduction of the mechanical properties of both concrete and steel rebars are among the main consequences of the corrosion impact [Francois et al., 2018; Coronelli & Gambarova, (2004); Zhang et al., (1995); Andrade et al., (1991)]. A few studies have been conducted on the seismic performance of RC sample framed buildings exposed over the years [Zhang et al., (2018); Biondini et al., (2011)], but many gaps remain to bridge. This paper aims to analyse the seismic response of typical RC frames exposed to different levels of corrosion. Additionally, a case study representing an ordinary RC building located in Italy is presented. Pushover and time-history analyses were conducted to seismic performance of a common RC structure when exposed to corrosion.

2 MECHANICAL PROPERTIES OF CONCRETE AND STEEL REINFORCEMENT

2.1 *Concrete*

Due to the effect of corrosion, the increase in volume of the rust, micro-cracking in the core and cover spoiling-off are the main consequences of the concrete deterioration. Generally, concrete is affected by two different exposures: direct exposure, such as carbonate-based and indirect exposure, such as chloride-based. As a result of these two exposures, the reduction of the concrete compressive strength is the leading cause of the damaged concrete. Although, Coronelli & Gambarova, (2014) proposed a method to account for the impact of corrosion on the concrete compressive strength based on the numerical evaluation of corroded RC beams, this relationship does underestimate the ultimate capacity of corroded RC columns.

$$\beta = f_c^* / f_c = \frac{1}{\left[1 + \left(K \frac{2\pi X n_{bars}}{b \varepsilon_{c2}}\right)\right]} \tag{1}$$

where f_c^* represents the corroded compressive strength, f_c the uncorroded compressive strength, K a constant equal to 0.1 for medium rebar, X the corrosion penetration, b the width of the cross-section, ε_{c2} strain at the peak and n_{bars} the number of steel reinforcement in the compressive zone. Therefore, a new method, which consists in splitting the concrete cross-section into three different blocks whilst accounting for the impact of corrosion on the uneffective and effective concrete core, has been proposed by Di Sarno & Pugliese, (2019). This has been validated against experimental results providing efficient and accurate results and is herein used.

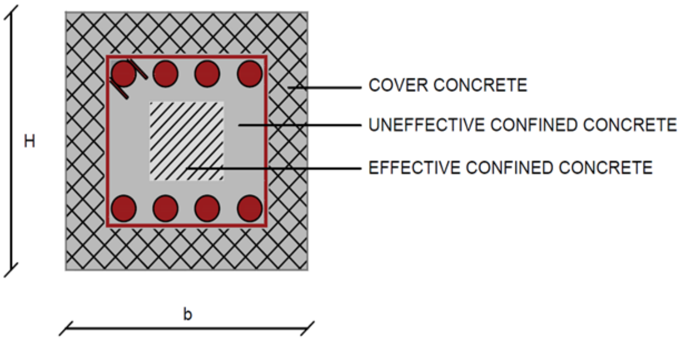

Figure 1. Concrete blocks.

Accordingly:

$$f_c^* = \frac{\beta f_c A_{CC} + \beta f_c A_{UCC} + f_c A_{ECC}}{A_{CC} + A_{UCC} + A_{ECC}} \tag{2}$$

where f_{cc} is the confined compressive strength.

2.2 *Steel Reinforcement*

Many experimental campaigns have been conducted to evaluate the impact of corrosion on both bare and embedded into concrete steel reinforcements (more details can be found in Di Sarno & Pugliese, (2019)). As a result, different relationships for yielding stress, ultimate stress and ultimate strain related to the rate of corrosion have been proposed. A comprehensive review of the models for corroded steel rebars present in the literature has been carried out by Di Sarno

& Pugliese, (2019) who provided an accurate relationship for use in the numerical evaluation of corroded RC components. The general equations have the same form, i.e.:

$$f_y^* = f_y\left[1-\beta CR[\%]\right] \tag{3}$$

where f_y^* is the corroded yielding stress, f_y, the un-corroded yielding stress, β, the experimental coefficient and CR[%] = $(M_0-M_C)/M_0$, the mass loss based on mass before (M_0) and after corrosion (M_C). The relationship proposed by Imperatore et al., (2017) is herein used to take into account the different rate of corrosion.

3 NUMERICAL EVALUATION OF A CORRODED RC COLUMN

3.1 *Reference Test*

As a reference test, the corroded RC column under cycling loading tested by Meda et al., (2014), which represents a typical column of a RC structure built in Italy in the 1960s was used. The column had a cross-section of 300 x 300 mm^2 with a concrete compressive strength of 20 MPa and four Φ16 mm longitudinal ribbed steel reinforcements with a yielding stress of 521 MPa and hardening ratio of 0.005. The transverse reinforcements consist of Φ8 mm stirrups with a spacing of 300 mm. One column was kept as a non-corroded reference, while the second was subjected to a theoretical 20% corrosion on the longitudinal reinforcement. The results were shown in the load-drift ratio plot both for un-corroded and corroded column.

3.2 *Numerical Modelling*

The RC column has been implemented in an advanced Finite Element Software [SeismoStruct] through a non-linear Fibre-frame element by using five Gauss-Lobatto points of integrations. The concrete has been modelled using the stress-strain relationship given by Chang & Mander, (1994). This concrete model is able to simulate the behavior of both core and cover concrete by modifying the peak strain and the compressive strength as the shape of the constitutive model remains the same. The steel rebars were modelled by using the constitutive model of Monti & Nuti, (1992) with the mechanical properties provided by Meda et al., (2014). Hence, the concrete and steel models were modified through the relationships given by Di Sarno & Pugliese, (2019) and Imperatore et al., (2017) respectively. Finally, monotonic pushover analyses were performed along x and y, in positive and negative directions, and the outcomes were validated against experimental results (Figure 2).

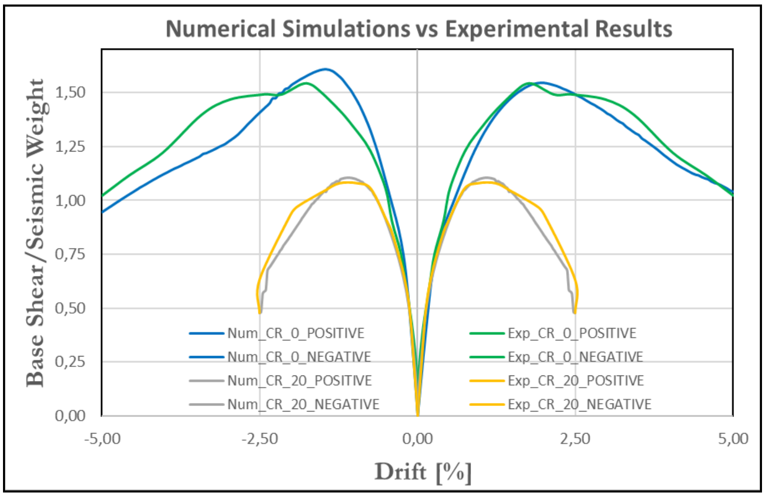

Figure 2 Monotonic Negative-Positive Pushover.

The results related to both corroded and un-corroded RC column are summarised in the load-drift diagram. The model is able to predict with an excellent accuracy the response of the corroded RC column exposed to a monotonic loading with an error less than 3% in terms of shear strength.

4 CASE STUDY: THREE-STOREY RC STRUCTURE

4.1 *Description*

A three-storey RC ordinary building was considered as testbed for this study. The building is situated in Ortona (Italy), near the sea and consists of 9 columns per floor with a cross-section of 400x900 mm^2 reinforced with Φ18mm and Φ16mm longitudinally and Φ8mm with spacing 300mm transversally. The beams have different cross-sections and longitudinal ribbed reinforcements composed mostly by Φ16 mm and Φ14 mm. The concrete compressive strength was 20 MPa both for columns and beam, while the steel reinforcement had a yielding stress of 444 MPa. The decks have been implemented through rigid-diaphragms so that they have infinite in-plane stiffness properties, and exhibit neither membrane deformation not report the associated forces, while all the joints were connected through fully-supported-rigid-connection (All degrees of freedom are restrained) to the ground. An accurate loading analysis was conducted and the masses implemented into each node (loading-range [2.38 tons; 45.54 tons]). Corrosion has been applied to different scenarios: only columns, only beams and, both columns and beams. Potentially, this procedure allows the evaluation of the impact of corrosion on different RC elements. Two different analyses have been conducted: Non-Linear Static Analysis (Pushover Analysis) and non-linear time-history analysis. The latter time-history analyses have been conducted through real-ground motions using the so-called spectrum-compatibility analysis. Basically, the spectrum-compatibility analysis allows the user to consider all signals that match the elastic spectrum provided by the Italian Code [D.M. 14-01-2008]. A reliable software called REXEL [Iervolino et al., (2009)] has been utilised for generating the spectrum-compatibility signals (Figure 4). The model of the ordinary RC structures is given in Figure 3.

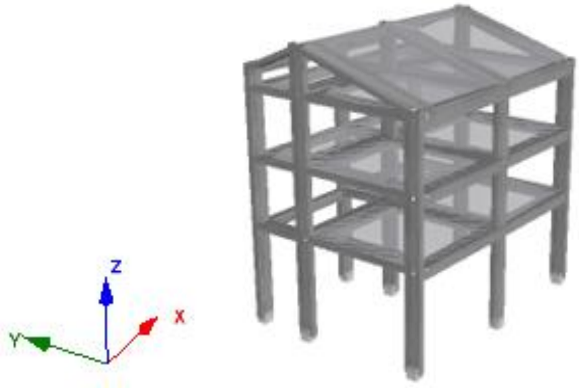

Figure 3. Finite Model of the sample Structure implemented in SeismoStruct.

4.2 *Pushover Analysis*

The non-linear Static Analysis (most commonly known as Pushover Analysis) is the most common method used in Structural Engineering to evaluate the response of a RC structure to a lateral load pattern. The non-linearity was assigned through the Fibre-based element frame that spreads the non-linearity through the cross-section. The Pushover analyses were performed in both x and y directions considering the mass distribution of the modal shapes of the RC structure (Adaptive Pushover Analysis) five levels of corrosion rate (CR [%] = [0, 5, 10, 15, 20]).

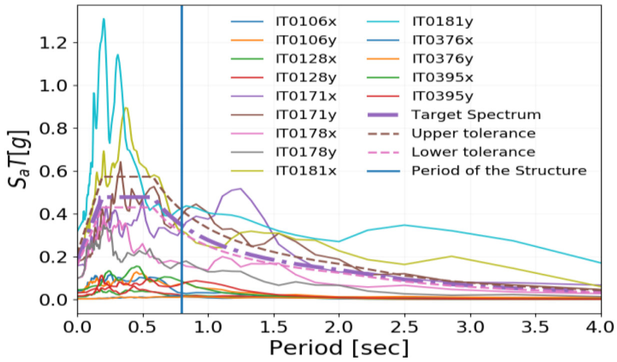

Figure 4. Spectrum-Compatible Accelerograms (Rexel Output).

The Pushover analyses were performed in both x and y directions considering the mass distribution of the modal shapes of the RC structure (Adaptive Pushover Analysis) five levels of corrosion rate (CR [%] = [0, 5, 10, 15, 20]). The results have shown that the base shear along the x-axis is reduced by 17% as the corrosion rate increases, while the ductility remains essentially the same (Figure 5a). On the other hand, the capacity curves along the y-axis showed both a reduction of the base shear (15%) and ductility, which becomes critical when the corrosion rate reaches 15% and 20% (Figure 5b). Moreover, the impact of corrosion was also considered for the beams to evaluate the response of a RC structure under different corrosion expositions (Figure 6a and Figure 6b). The results, as expected, showed a reduction of the base shear by 15% along x-axis and 12% along y-axis as the corrosion rate goes up. However, ductility is more significant in the case of all beams exposed to corrosion. Particularly, the ductility is reduced by half when the corrosion rate is between 15% and 20%.

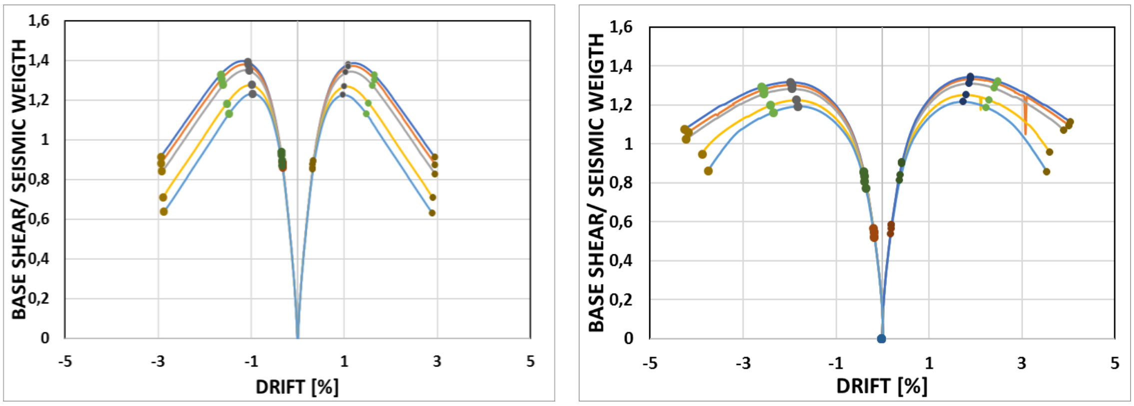

Figure 5. Capacity Curve: a) X-axis b) Y-axis (Only Columns exposed)

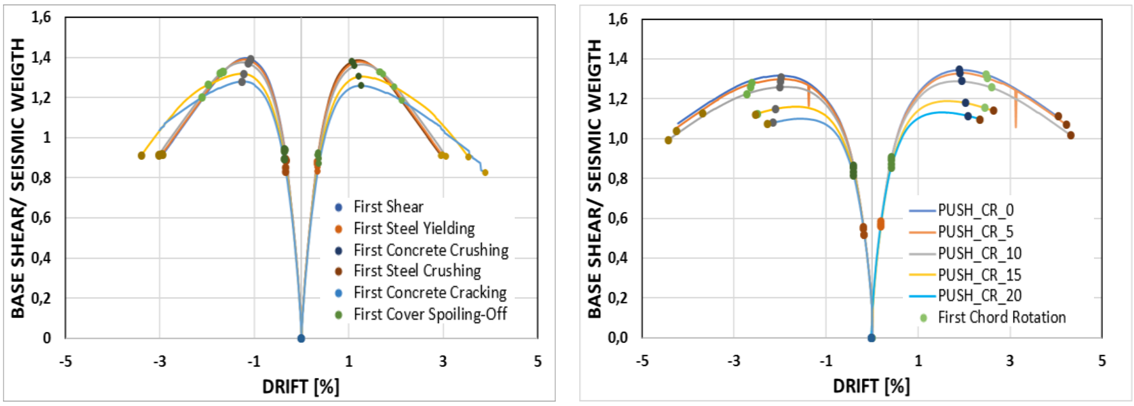

Figure 6. Capacity Curve: a) X-axis b) Y-axis (Only Beams exposed)

4.3 *Time-History Analyses*

Dynamic non-linear analysis is commonly used to predict the nonlinear response of a structure subjected to earthquake ground motions. The results are herein presented in terms of Mean-Relative Storey-Displacements (Figure 9, Figure 10a and Figure 10b) Maximum Base Shear (Figure 11 and 12) and Maximum Displacement at the top of the building (Figure 8a and Figure 8b). All the storey-displacements have been combined using the following formulation:

$$Disp = \sqrt{D_x^2 + D_y^2} \tag{4}$$

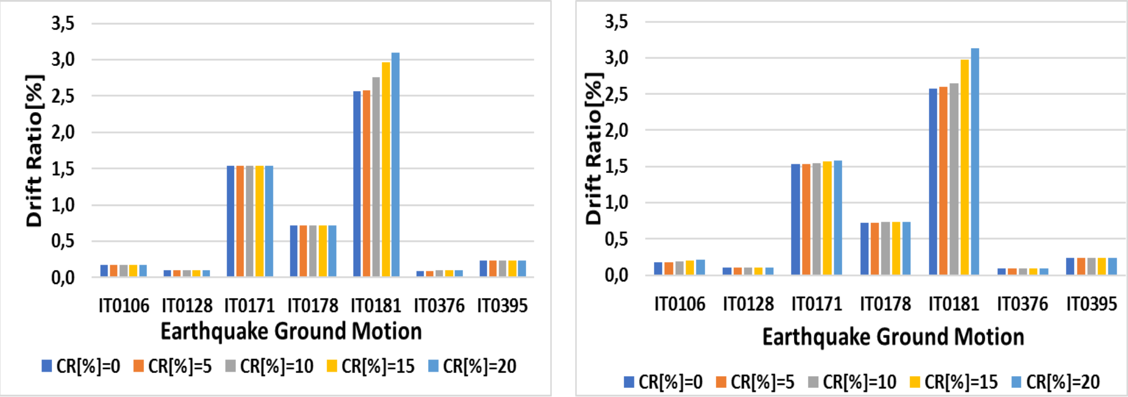

Figure 7. Top Displacement; a) Columns Corroded b) Beams Corroded

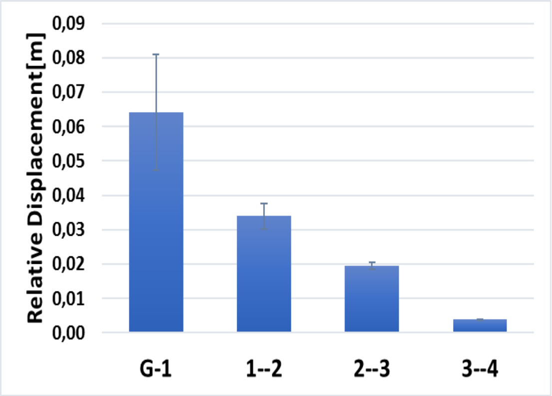

Figure 8. Mean Relative Storey-Displacements (Uncorroded Structure)

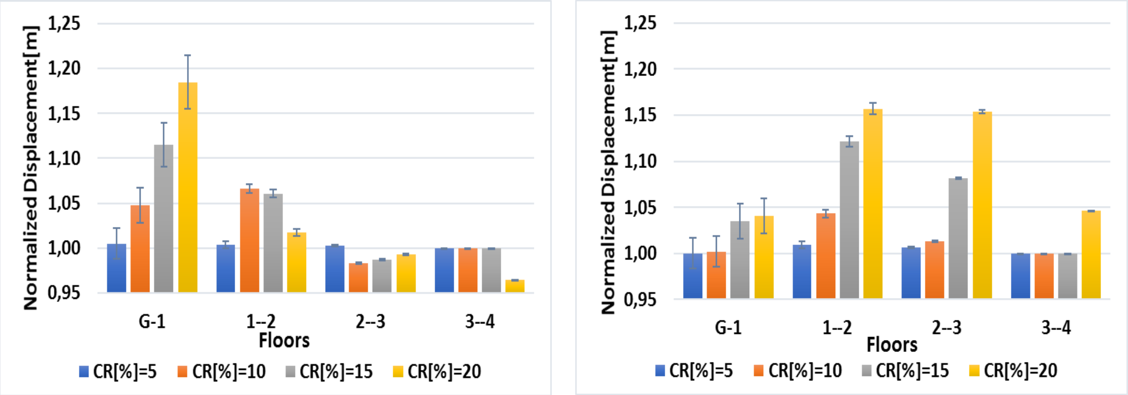

Figure 9. Mean-Relative Storey-Displacements. a) Corroded Columns b) Corroded Beams

The time-history analyses provided an essential response of the corroded structure by means of Base Shear, Max Displacement at the top of the building and Storey-Displacements. In this study, the records were chosen using the spectrum-compatibility analysis, which consists of retrieving all the real accelerograms compatible with the elastic spectrum defined by using the

Italian Code during the Limit State of the Collapse. Storey displacements, which are considered as the most useful response for time-history analysis, were obtained along the height of the RC building and presented in the Storey Displacement-Time plots. The plotted curves (Figure 14,15,16,17 and 18) clearly show an increase in the Storey displacement where the structure is less stiff over time. The maximum relative displacement Ground-Roof floor (Figure 12 and 13) is mainly affected when the earthquake has a PGA more than 0.23g (IT0181 Event). As a result, the corroded RC structure can reach a collapse condition earlier than the un-corroded building. Finally, Figure 19 and Figure 20 showed how the base shear was influenced by the corrosion impact for the different ground motions herein considered.

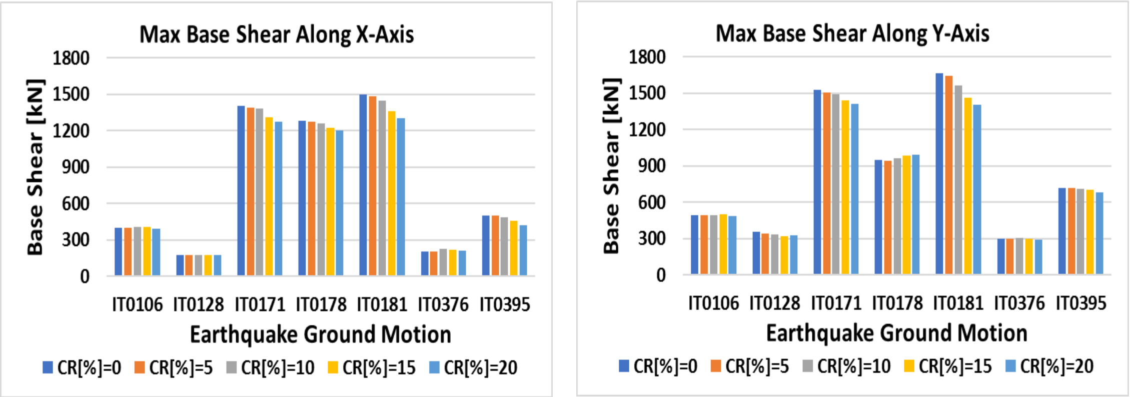

Figure 10. Max Base Shear for all the signals (Only Columns Corroded)

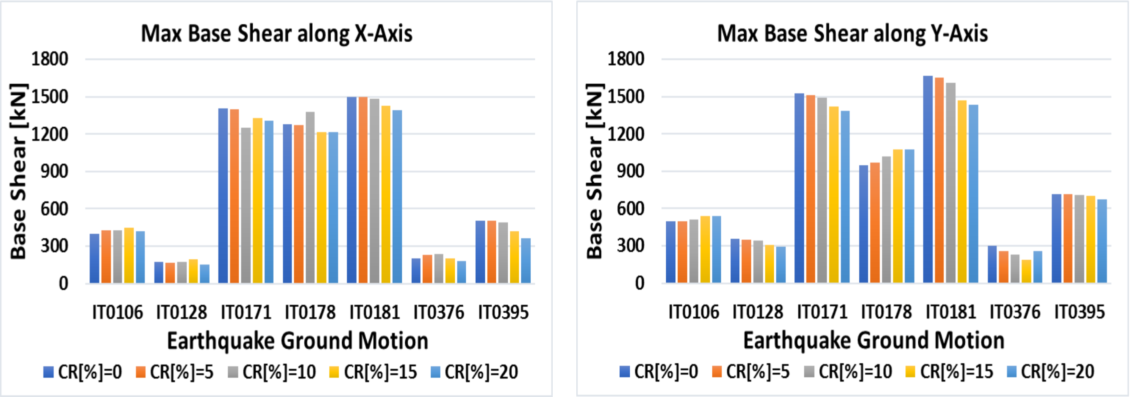

Figure 11. Max Base Shear for all the signals (Only Beams Corroded)

5 CONCLUSIONS

The objective of the present study was to evaluate the numerical response of a RC building affected by different values of the corrosion rate. The results of the Pushover analyses have shown that the base shear decreases with the increase of the corrosion rate when both beams and columns are exposed to aggressive environments. In particular, the maximum reduction of the base shear when only the columns of the RC building are exposed to corrosion is 17%, while the beams showed a smaller reduction equal to 15%. In addition to this, the ductility was examined. The results showed that the ductility was mainly affected by the impact of the corrosion on the beams. In particular, the ductility was reduced by half when the corrosion rate was 15% or 20%, especially along y-axis where the structure is less stiff. On the other hand, smaller variations of ductility, which can be seen especially along y-axis, were obtained when the case of corroded columns was considered. Moreover, time-history analyses were performed using the Spectrum-Compatibility analyses and seven ground motions were accounted. The main results were plotted using the Storey-displacements and the base shear. The Storey-Displacements were combined using the equation (4). The increase of the corrosion up to 20% had significant results only when the PGA of the ground motion was more than 2.3%, while signals with a PGA less than

2.3 had an irrelevant influence. In particular, the ground motion IT0181 showed an increase of the Storey-Displacement of 19% as the corrosion goes up until 20%. The results also showed the increase of the mean interstorey displacements, which are higher (15% and 18%) for corroded columns compared with corroded beams (12% and 15%), when the structure is exposed to a significant corrosion rate. Finally, the base shear of the corroded RC building showed a relevant decrease as the corrosion increased, especially for corrosion rates of 10%,15% and 20%, i.e. moving from 1600 kN to 1400 kN in the IT0181 Earthquake. The main consequences of these results can be summarized in earlier failure condition compared with an uncorroded RC building, and thus a significant decrease of the safety and the lifetime of a RC Structure.

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