Seismic Performance of Corroded Reinforced Concrete Structures

Luigi Di Sarno[a], Francesco Pugliese[b]
[a] *Department of Civil Engineering and Industrial Design, and Institute for Risk and Uncertainty, University of Liverpool, Liverpool and Department of Engineering, University of Sannio, Benevento, Italy*
[b] *Department of Civil Engineering and Industrial Design, and Institute for Risk and Uncertainty, University of Liverpool, Liverpool*

Keywords: corrosion; smooth rebars; earthquake engineering; seismic performance; structural modelling;

ABSTRACT

One of the leading causes of the Reinforced Concrete (RC) structure degradation is due to environmental factors, such as sea-splashing, salt de-icing and high rate of chloride contents, which can affect both the load-bearing capacity and seismic performance of those ordinary structures. This paper aims at analyzing the non-linear dynamic response of a typical RC building built in the 1950-1960s. Seismostruct was used to build the finite element model of a four-storey RC frame structure in order to assess its seismic performance when exposed to different levels of corrosion. Both columns and beams have been exposed to different corrosion scenarios during the analyses. The numerical simulations of the seismic performance of the RC building are conducted using real-ground motions that are selected based on their compatibility with the target Spectrum defined by a software called REXEL. The results showed that the seismic performance of the RC building decreases significantly with the increase of the corrosion levels. In particular, the numerical simulations illustrate the increase in the interstory displacements as well as the reduction in the shear strength and the ductility of the RC structure with the increase of the corrosion levels. Finally, the results show how the increase in the corrosion level accelerates the failure of the testbed structure.

1 INTRODUCTION

The lifetime and safety of the RC structure are among the major concerns of the design and maintenance for civil engineers. In fact, RC structures are exposed to harsh factors over the years, which can accelerate the process of degradation of a building and therefore its capacity to resist strong earthquake events. As a result, the seismic performance and consequently the economic loss and human health are the main concerns of the assessment of a RC building. One of the factors that can lead to extended damage in a RC structure is the corrosion of its steel reinforcements. Although, the concrete cover provides a protection barrier against physical and chemical agents, often the thickness is not sufficient, and therefore the RC structures become seismically vulnerable due to corrosion. The corrosion process starts when the RC structure is subjected to the chloride attack and/or carbonation of the concrete. As a result, the reduction of the mechanical properties of both the concrete and the steel reinforcements, cover spoiled-off and loss of bond are among the main consequences of corrosion. Many areas, both seismic prone or non-seismic prone, have RC building standing close to their coastlines, and therefore exposed to the steel reinforcement corrosion [Di Sarno and Pugliese (2019)]. As a result, many experimental tests were conducted on the behavior of corroded steel reinforcements, both embedded into the concrete and nude rebars, to evaluate the mechanical properties after the corrosion [Du et al. (2005), Morinaga (1996), Zhang et al. (1995), Andrade et al. (1991), Clark et al. (1994), Cairns et al. (2005) and Imperatore et al. (2017)]. All those experimental tests have demonstrated that corrosion reduces the mechanical properties of the steel rebars and therefore the behavior of an RC element. Furthermore, several tests have been conducted on the behavior of corroded RC components [Uomoto et al. (1988), Coronelli et al. (2006), Vu et al. (2018), Meda et al. (2014) and Ma et al. (2018)] and the results showed that the decrease in both shear strength and ductility are the main consequences of the impact of corrosion. A few numerical simulations have been carried out on the seismic performance of existing RC frame Structures [Biondini et al. (2011), Zhang et al. (2018)] and therefore this paper aims at analyzing the non-linear dynamic response of an existing RC building when exposed to different levels of corrosion.

2 MECHANICAL PROPERTIES OF THE MATERIALS

2.1 *Concrete*

The main consequences of corrosion are the increase in volume of the rust, the micro-cracking in the core, spoiling-off of the concrete cover and loss of the bond. Coronelli and Gambarova (2008) proposed a relationship for the evaluation of reduced concrete's compressive strength based on the numerical evaluation of the behaviour of RC beams and the theory proposed by Vecchio and Collins (1992):

$$\beta = \frac{f_c^*}{f_c} = \frac{1}{1+k\frac{2\pi X n_{bars}}{b\varepsilon_{c2}}} \tag{1}$$

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. Di Sarno and Pugliese (2019) proposed a new method to evaluate reduced concrete's compressive strength (Figure 2), which consists in dividing (Figure 1) the RC cross-section into three concrete blocks containing the concrete cover, the un-effective confined core and the effective enclosed core. The concrete cover represents the clear cover (CC) up to the transverse reinforcement, while the un-effective (UCC) and effective (ECC) confined concrete are respectively the area twice the diameter of the longitudinal reinforcement bars and the remaining uncorroded area of the concrete:

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

where f_{cc} is the confined compressive strength.

2.2 *Steel Reinforcements*

Experimental tests have been carried out to evaluate the impact of corrosion on the mechanical properties of corroded steel reinforcements, both embedded into the concrete and the bare rebars. As a results, yielding stress, ultimate stress and ultimate strain were defined with respect to the corrosion rate. The work of Di Sarno and Pugliese (2019) provides a comprehensive review of the models for corroded steel rebars (Figure 3) present in the literature and the most accurate relationship for use in the numerical evaluation of corroded RC components

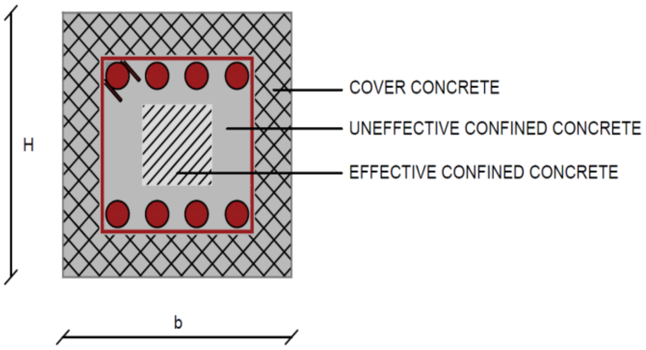

Figure 1. Concrete blocks

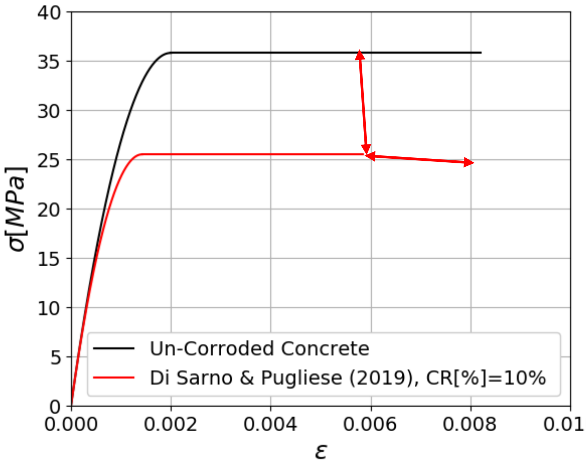

Figure 2. Stress-Strain for Concrete without/with corrosion

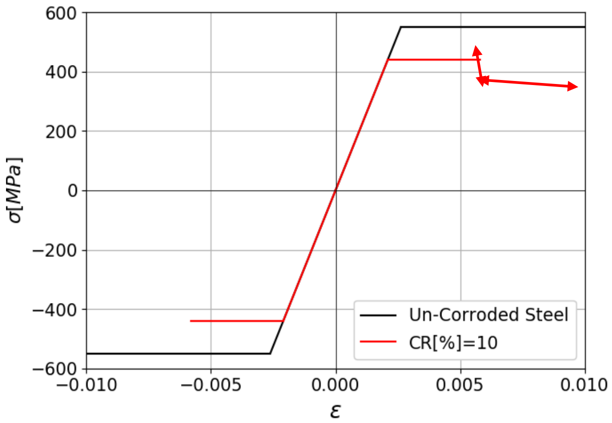

Figure 3. Steel Reinforcement bars with/without Corrosion

3 CASE STUDY: FOUR-STOREY RC BUILDING

An existing four-storey RC building was considered as testbed for this study. The building is situated in San Benedetto del Tronto (Italy), near the sea and consists of 7-bay along the x-axis and 3-bay along the y-axis. The typical square-cross-section of the column at the ground floor of the building is 350x350 mm2, while a square-cross-section of 300x300 mm2 is used for the other floors, both reinforced with 6 smooth rebars Φ16mm longitudinally and Φ6mm with spacing 150mm transversally. The beams have different cross-sections and longitudinal smooth reinforcements mostly consisting in Φ14 mm and Φ10 mm diameters. The concrete compressive strength was 16.3 MPa both for columns and beam, while the steel reinforcement had a yielding stress of 400 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-connections (All degrees of freedom are restrained) to the ground. An accurate loading analysis was conducted and applied on the beams (loading-range [6.51 kN/m; 10.42 kN/m]).

The model of the ordinary RC structures is given in Figure 4. Corrosion has been applied to the whole building: both columns and beams. Potentially, this procedure allows the evaluation of the impact of corrosion on different RC elements. Non-linear dynamic analyses have been conducted. 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 the signals that match the elastic spectrum provided by the Italian Code (2008). A reliable software called REXEL [Iervolino et al. (2010)] has been utilised for generating the spectrum-compatibility signals (Table 1 and Figure 5).

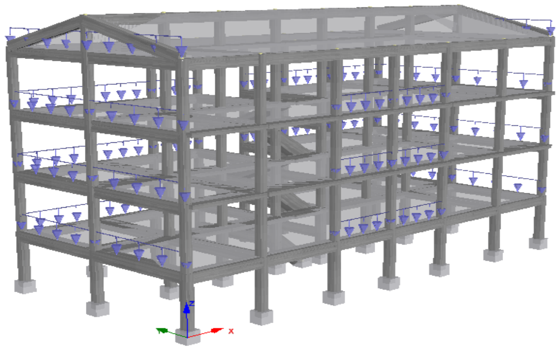

Figure 4. Finite Model of the sample Structure implemented in SeismoStruct

Table 1. Ground Motions used for the numerical simulations.

Earthquake ID	Date	$\mathrm{PGA_X}$ $[m/s^2]$	$\mathrm{PGA_Y}$ $[m/s^2]$	Mw
333	24/02/1981	2.26	3.04	6.6
1257	17/08/1999	2.90	2.39	7.6
1703	12/11/1999	3.70	5.04	7.2

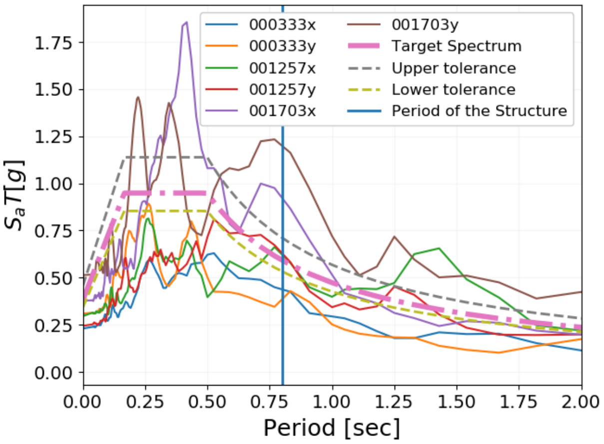

Figure 5. Spectrum-Compatible Accelerograms (Rexel Output)

3.1 *Time-History Analyses*

In order to predict the non-linear seismic response of a corroded RC structure when subjected to earthquake ground motions, non-linear dynamic analyses were performed using the so-called Finite Element approach. The RC structure was subjected to different levels of corrosion (5%,10%,15% and 20%) that may represent the natural exposure of an existing building to a chloride attack or carbonation of the concrete over its lifetime. The proposed stress-strain model for concrete of Chang and Mander (1994) and stress-strain model for steel reinforcement of Monti-Nuti (2000) were used to simulate the behaviour of both materials when corrosion occurs as explained in Pugliese et al. (2019). The results are herein presented by means of the top-ground relative displacements (Figure 9), the mean interstorey displacements (Figure 6, Figure 7 and Figure 8) and maximum base shear (Figure 10 and Figure 11) with respect to the corrosion rates. All the storey-displacements have been combined using the following formulation:

$$Displ = \sqrt{D_x^2 + D_y^2} \tag{3}$$

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.

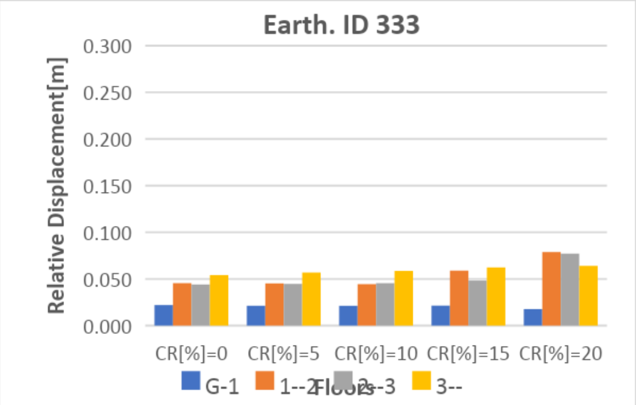

Figure 6. Relative Floor-displacements vs corrosion rate

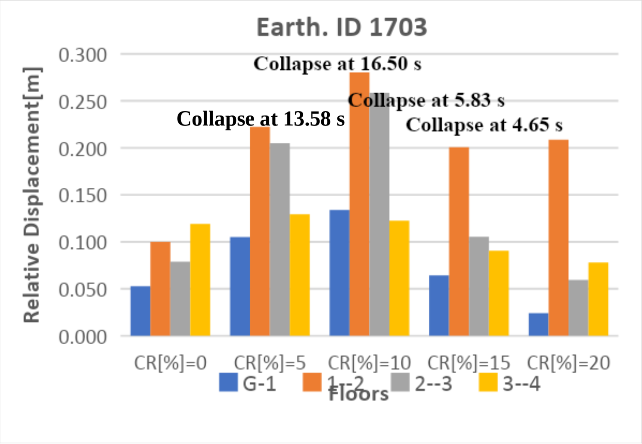

Figure 7. Relative Floor-displacements vs corrosion rate

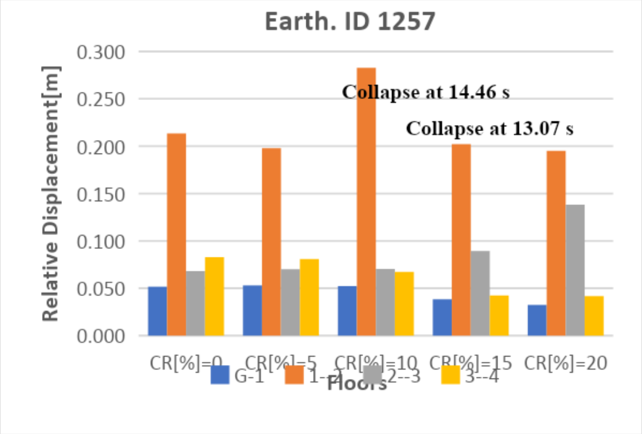

Figure 8. Relative Floor-displacements vs corrosion rate

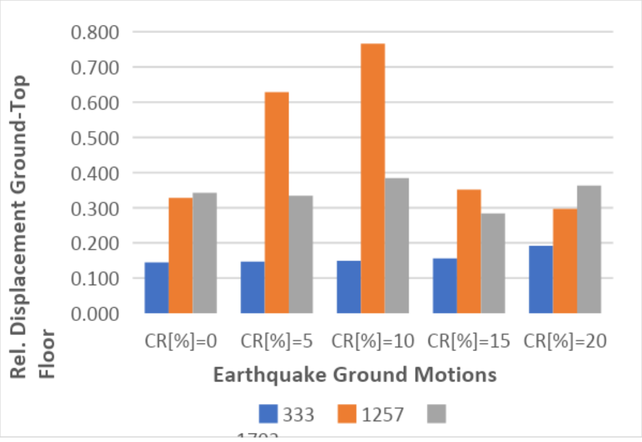

Figure 9. Relative Floor-displacements vs corrosion rate

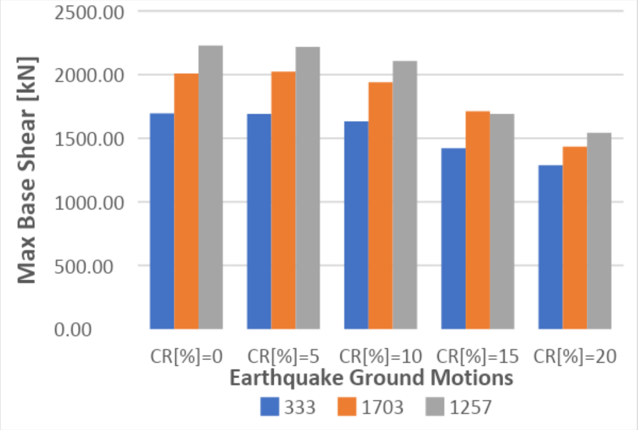

Figure 10. Max Base Shear along the x-axis vs Corrosion Rate

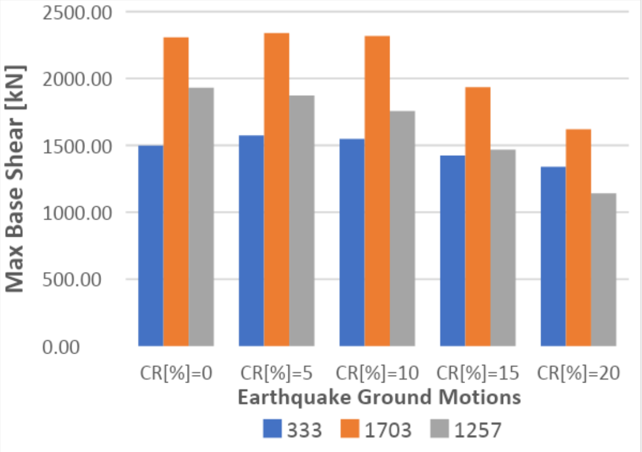

Figure 11. Max Base Shear along the y-axis vs Corrosion Rate

In this study, the records were chosen using the spectrum-compatibility analysis, which consists in retrieving all the real accelerograms compatible with the elastic spectrum defined by using the European 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 6, Figure 7 and Figure 8) clearly show an increase in the Storey displacement where the structure is less stiff over time. Moreover, the increase of the corrosion rate forces the structure to reach a failure condition after a few seconds from the event. The maximum relative displacement Ground-Roof floor (Figure 9) is mainly affected when the earthquake has a PGA greater than 0.23g (1703 and 1257 Events). As a result, the corroded RC structure can reach a collapse condition earlier than the un-corroded building. Finally, Figure 10 and Figure 11 showed how the base shear was influenced by the corrosion impact for the different ground motions herein considered.

4 CONCLUSIONS

The objective of the present study was the evaluation of the numerical response of an existing RC building when exposed to different levels of corrosion. The RC building was modelled by using the Finite Element Approach and implemented in Seismostruct. Both columns and beam were subjected to corrosion. The results of the non-linear dynamic analyses showed that the increase of the corrosion rate increases the interstorey displacements of the building, especially for strong earthquakes (1703 and 1257). In particular, the relative interstorey displacement increased by 50% for the event 333 when the corrosion rate ranged between 15% and 20% without reaching a failure condition, while the other two events (1703 and 1257) dramatically increased the relative floor-displacements, also when the building was exposed to low values of corrosion. Furthermore, the Structure reached a failure condition when exposed to low and high levels of corrosion as shown in Figure 12 and Figure 13, Figure 14 and Figure 15).

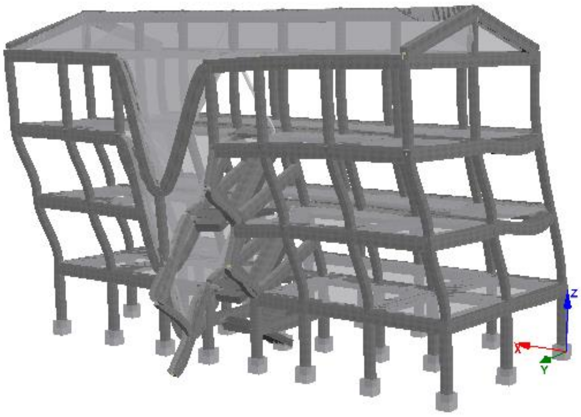

Figure 12. Event 1257 - Corrosion rate 20% - Failure Condition

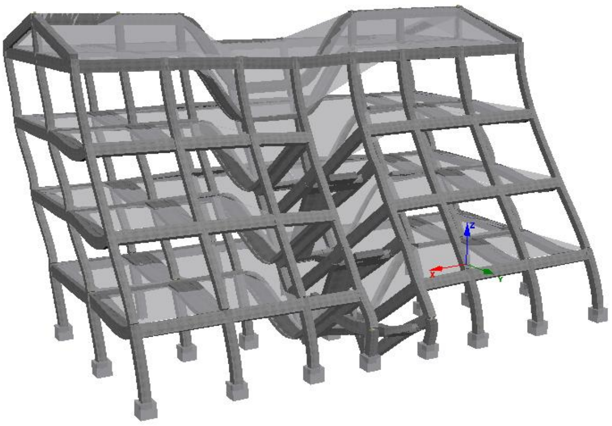

Figure 13. Event 1703 – Corrosion Rate 5% - Failure Condition

The results in Figure 9 showed a significant reduction of both the shear strength and the ductility of the building with the increase of the corrosion rate. As a result, the corroded RC structure demonstrated an early collapse when the corrosion rate ranged between 15% and 20% (for Events 1257 and 1703), and an increase of the top displacement un to 10% (about three times in the case of the event 1257) compared with the uncorroded building. Finally, the maximum base shear was plotted against the corrosion rate. The results showed a strong reduction of the base shear, both for direction x and y, when the corrosion rate was ranged between 15% and 20%, and the PGA was greater than 0.25g. Particularly, the maximum shear decreased from 1600 kN to 1350 when the structure was subjected to ground motion 333, while dramatic and significant reductions were noted when the building was subjected to ground motions 1703 and 1257. In fact, the maximum base shear was 2200 kN (Event 1703) when the building was uncorroded, while it was 1500 kN when the corrosion rate increased to 20%. The main results of the present study can be summarized in an earlier failure condition when the RC building is exposed to corrosion, especially for strong earthquakes (greater than 0.25g) and a significant decrease of the safety and lifetime of both RC structure and human health.

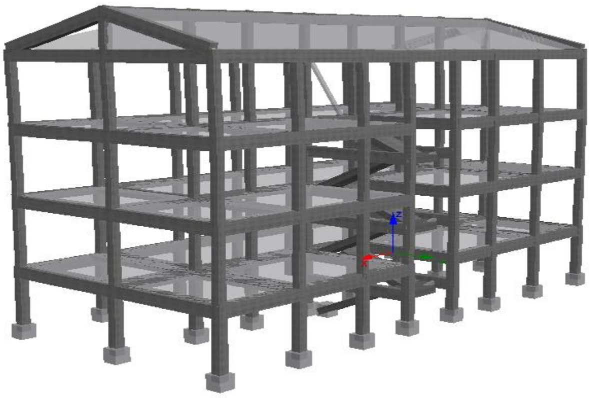

Figure 14. Event 333 – Corrosion Rate 10% - No-Failure Condition

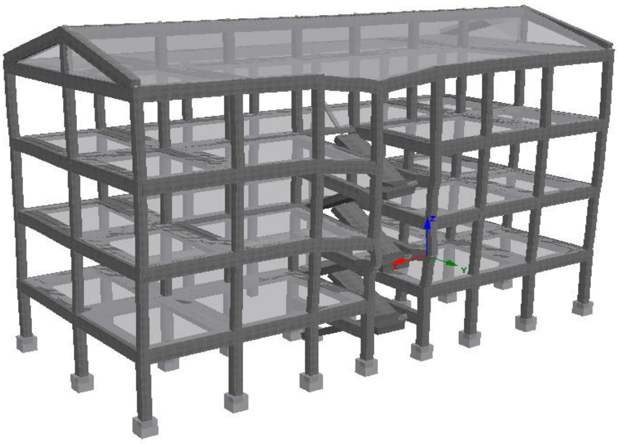

Figure 15. Event 333 – Corrosion Rate 15% - No-Failure Condition

5 ACKNOWLEDGMENTS

The authors would like to acknowledge the gracious support of this work through the EPSRC and ESRC Centre for Doctoral Training on Quantification and Management of Risk and Uncertainty in Complex Systems Environments Grant No. (EP/L015927/1). The authors would like also to thank Pierluigi Maria Fuccio whose gracious support and help during his internship at the University of Liverpool has been crucial and essential to complete this study.

REFERENCES

Andrade, C., Alonso, C., Garcia, F and Rodriguez, J. (1991), Remaining Lifetime of Reinforced Concrete Structures: Effect of Corrosion in the Mechanical Properties of the Steel, Life Prediction of Corrodible Structures, NACE, Cambridge, UK; pg. 12/1-12/11

A. Meda , S. Mostosi and Z. Rinaldi (2014), Experimental evaluation of the corrosion influence on the cyclic behaviour of RC columns, Engineering Structures,Volume 76, 1 October 2014, Pages 112-123

Biondini F., Alessandro Palermo and Giandomenico Toniolo (2011), Seismic performance of concrete structures exposed to corrosion: case studies of low-rise precast buildings, Structure and Infrastructure Engineering Vol. 7, Nos. 1–2, 109–11

Cairns, J., Plizzari, G., Du,Y. Law, D.W. and Franzoni C., (2005), Mechanical Properties of Corrosion-Damaged Reinforcement

Chang, G.A., and Mander, J.B., (1994) "Seismic Energy Based Fatigue Damage Ananlysis of Bridge Columns: Part 1 – Evaluation of Seismic Capacity," NCEER Technical Report No. NCEER-94-0006, State University of New York, Buffalo, N.Y.

Clark, L. A. and Saifullah,M. (1994), Effect of Corrosion Rate on the Bond Strength of Corroded Reinforcement, Corrosion and Corrosion Protection of Steel in Concrete, R.N. Swamy, Sheffield Academic Press, pg. 591-602

Coronelli and Gambarova (2004), Structural Assessment of Corroded Reinforced Concrete Beams: Modeling Guidelines, ASCE J. of Structural Engineering VOL 130 Issue 8

Du,Y,(2001) Effect of Reinforcement Corrosion on Structural Concrete Ductility, PhD Thesis, University of Birmingham,UK, 320 pg.

EN 1992-1-1 Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings E. for Standardization. Brussels, EN, CEN, (2005)

Iervolino I., Galasso C. and Coosenza E. (2010). REXEL: computer aided record selection for code-based seismic structural analysis. Bulletin of Earthquake Engineering, 8:339-362

Imperatore, S., Rinaldi, Z. and Drago C. (2017), Degradation Relationships for the Mechanical Properties of Corroded Steel Rebars, Construction and Building Materials, Vol. 148, pg. 219-230

L. Di Sarno and F. Pugliese (2019), Critical review of models for the assessment of the degradation of reinforced concrete structures exposed to corrosion, Conference SECED 2019, Earthquake Risk and Engineering towards a Resilient World

Ma, Li and Hwang (2017), Seismic behavior of low-corroded reinforced concrete short columns in an over 20-year building structure, Soil Dynamic and Earthquake Engineering, Vol. 106, Pag. 90-100.

Monti G., Nuti C. [1992] "Nonlinear cyclic behaviour of reinforcing bars including buckling," Journal of Structural Engineering, Vol. 118, No. 12, pp. 3268-3284.

Morinaga,S. (1996), Remaining Life of Reinforced Concrete Structures after Corrosion Cracking, Durability of Building Materials and Components, C. Sjostrom, ed., E&FN Spon, London 1996, pp. 127-137

Pugliese F. , Di Sarno L. and Mannis A.(2019), Numerical Evaluation of Reinforced Concrete Frames with Corroded Steel Reinforcement under seismic loading. A Case Study, Conference ICSBS 2019, 2nd International Conference on Sustainable Buildings and Structures

T. Uomoto and S. Misra (1988), Behavior of Concrete Beams and Columns in Marine Environment When Corrosion of Reinforcing Bars Takes Place, ACI Journal, Vol. 109 pg. 127-146

Vecchio and Collins (1986) The Modified Compression-Field Theory for Reinforced Concrete Elements Subjected to Shear, ACI Journal 83-22

Vu and Li (2018), Seismic Performance Assessment of Corroded Reinforced Concrete Short Columns, ASCE Journal of Structural Engineering, Vol. 144 Issue 4

Zhang,P. S., Lu, M. and Li, X. (1995), The Mechanical Behaviour of Corroded Bar, Journal of Industrial Buildings, Vol. 25, N°257. pg. 41-44

Zhang Meng, Ran Liu, Yaoliang Li, and Guifeng Zhao, “Seismic Performance of a Corroded Reinforce Concrete Frame Structure Using Pushover Method,” Advances in Civil Engineering, vol. 2018, Article ID 7208031, 12 pages, 2018. https://doi.org/10.1155/2018/7208031.