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A NOVEL PROBABILISTIC FRAMEWORK OF RC CORRODED STRUCTURES UNDER DYNAMIC LOADING

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A NOVEL PROBABILISTIC FRAMEWORK OF RC CORRODED STRUCTURES UNDER DYNAMIC LOADING

Abstract

Steel corrosion in reinforced concrete structures can lead to severe deterioration damage under static and seismic loads. In practice, it is essential to mitigate failure risk by quantifying the extent of damage and simulating the structural response of damaged structures. However, numerical modeling of the dynamic behavior of corroded structure is challenging due to high nonlinearity of the problem and its multidisciplinary nature. In addition, corrosion damage exhibits various sources of uncertainty that impede accurate deterministic modeling of the dynamic response of RC structures. Therefore, this study presents a simplified framework, to simulate the non-linear response of corroded structures under seismic excitation, in a statistical setting. The presented scheme employs set of state-of-art experiments and numerical investigations of corrosion effect and response to capture the generic non-linear response. The presented scheme is utilized to conduct reliability analysis for corroded structures under earthquake loads by incorporating different sources of uncertainties associated with the used mathematical models and model parameters. The power of the suggested probabilistic scheme is illustrated on two simulated structures, where two different statistical properties are considered; the initial statistical parameters and a real-time monitored statistic for the rate of corrosion.

Keywords

Corrosion, Reinforced Concrete, Reliability Analysis, Seismic Analysis and dynamic loads.

1. INTRODUCTION

Reinforced concrete structures are distinguished by their high durability, but they are often affected by various natural conditions and extreme loads, which can significantly reduce their life expectancy. During the operational life of reinforced concrete structures, they are exposed to a corrosion damage mechanism that can lead for accelerated deterioration. The interaction of concrete with reinforcing steel bars is a complex phenomenon subjected to different damage processes, the most common is the corrosion of reinforcement. Corrosion is a long-term natural process that attack steel bars and threaten the reinforced concrete structures. This damage panorama ranges from corrosion initiation, to the corrosion propagation, generating longitudinal cracks, volume expansion, loss of capacity and spalling the concrete cover (Blomfors, Zandi, Lundgren, & Coronelli, 2018). When the reinforcement is subjected to induced corrosion in concrete, internal stresses will be developed due to volume expansion upon formation of iron oxides. As the corrosion damage propagates, it miscarries the induced tensile stresses, generating longitudinal splitting cracks. Most of the structural problems are greatly exacerbated by corrosion damage under static and dynamic loads. Corrosion alters the structural behavior under static and dynamic loads, as it not only reduces the shear and moment capacity, but also affects the bond between concrete and steel (Cabrera, 1996). In fact, many structures are exposed to dynamic loadings such as earthquakes, as the structure will behave nonlinearly causing degradation in the mechanical properties of the structure. When, the reinforced concrete structures subjected to seismic damage combined with corrosion damage, it can accelerate degradation leading to premature failure (Lee & Cho, 2009).The reduction in the bond, capacity and rigidity between corroded reinforcement and concrete, leads to significant change in the structural behavior especially under dynamic loads. Also, this reduction may cause an accelerated deterioration in which it causes brittle failure before attaining the yield capacity. Accordingly, at the advanced stages of corrosion, it is difficult to estimate the global effect of corrosion on the structural behavior, and the change occurred in the nonlinear response of the structures. New studies suggest using Metakolin to reduce corrosion by enhancing strength, reducing shrinkage, and increasing durability (Khatib, Baalbaki, & ElKordi, 2018).However, a very limited number of studies have been considering both the effect of corrosion damage and the effect of dynamic loads on the structural behavior (Fang, Gylltoft, Lundgren, & Plos, 2006). The lack of experimental data to simulate the effect of corrosion on the behavior of a structure under dynamic loads often results in limited designs that cannot withstand the dynamic effects of longer natural periods. Throughout previous studies, there are limited real-time measurements and numerical models that can precisely predict the complexity of the corrosion damage under dynamic loadings. Therefore, the challenge is to estimate the residual operating life of the structures and early recognition of risks, by modeling the response of corroded structures under dynamic and static loads which may encounter various sources of uncertainty that impede accurate estimation. The intention of this paper is to present a full model based on estimating the effect of nonlinear effect of corrosion under dynamic loads through a probabilistic setup that includes all sources of uncertainty. The implemented framework is illustrated by two different structural properties, with initial statistical parameters and a real-time monitored statistic of the corrosion rate.

2. NUMERICAL MODELING

2.1. Hysteretic Model

Structures exposed to intense excitations from natural hazards such as earthquakes may show a hysterical response (Ismail, Ikhouane, & Rodellar, 2009).Modeling this dynamic behavior under different corrosion levels will lead to different sources of uncertainty. Research has suggested various mathematical models that describe the nonlinear response and reduce the resulting errors. The hysteresis behavior is simulated using mathematical models either numerical models or experimental models, and this generates a mathematical framework for predicting the structural response and identifying its errors (Ikhouane & Rodellar, 2007).To describe this hysterical behavior of the structure, various mathematical models exist, including those of the Duhem hysteresis operator, the central difference method and the Bouc-wen model. The Duhem model is used in electromagnetic hysteresis where its functions and parameters are fined-tuned to match experimental results (MACKI, NISTRI, & ZECCA, 1993).The central difference method is based on the approximation of velocities and acceleration with known displacement and it is conditionally stable with a very small interval (0.0001 s) (Oudni & Bouafia, 2015). This paper suggested using the Bouc-Wen model to estimate the nonlinear behavior of the structure, as this method is most commonly used to describe hysterical behavior under low and high excitation. This mathematical model was adopted to analyze structural response and predict the remained capacity under nonlinear behavior (Ikhouane & Rodellar, 2007).Bouc-Wen's model was extensively encountered in modeling hysterical behavior using nonlinear differential equations relating the input restoring force to the displacement outputs (Ismail, Ikhouane, & Rodellar, 2009).Therefore, the equation of motion is expressed as the following:

Eq. (1) $$M\ddot{y} + C\dot{y} + R_T = F(t)$$

Where M is the mass of the system, C is the damping, the over dots in $y(t)$ variables show the derivatives with respect to time, where $\ddot{y}$ and $\dot{y}$ represent acceleration and velocity respectively and $F(t)$ is the applied force. R_T is the system nonlinear restoring force is expressed as:

Eq. (2) $$R_T = \alpha k_i y(t) + (1-\alpha)k_i z(t)$$

Where $\alpha k_i y(t)$ represents the linear component, while $(1-\alpha)k_i z(t)$ is the hysteretic components; k_i is the elastic stiffness of the system , α is the stiffness ratio and $z(t)$ is the hysteretic displacement, which is differentiated to become

Eq. (3) $$\dot{z}(t) = A\dot{y}(t) - (\beta|\dot{y}||z(t)|^{n-1}\, z(t) + \gamma\dot{y}(t)|z(t)|^{n})$$

with the initial conditions $z(0) = 0$ and the parameters A, α , β , γ and n control the shape of hysteresis loops.

Then, the equation of motion according to the Bouc-Wen model is expressed

Eq. (4) $$M\ddot{y} + C\dot{y}(t) + \alpha K y(t) + (1-\alpha)Kz(t) = -M\ddot{u}_g(t)$$

In order to integrate the ordinary differential equations, we used Runge–Kutta integration to determine the response of the system by estimating the displacements and velocities. Runge–Kutta is a well-known method that integrates differential equations and is suitable for simulating long-term transformations and it is well-developed interpolation in a variable step as it is used for higher order differential equations (Cash & Karp, Sept. 1990).The mathematical equations are integrated as the following:

Eq. (5) $$\begin{cases} y = x(1) \\ \dot{y} = x(2) \\ z = x(3) \end{cases}$$

The equations in Eq. (5) they are substituted in the previous equations and rearranged to obtain:

Eq. (6) $$dxdt(1) = \dot{y}$$

Eq. (7) $$dxdt(2) = \frac{1}{M}[f(t) - c - \alpha(x(1))(t)]$$

Eq. (8) $$dxdt(3) = D^{-1}(Ax(1) - \beta x(1)|x(3)|^{n-1} - \gamma x(1)|x(3)|^{n})$$

Solving these nonlinear ordinary differential equations numerically to obtain the displacement and velocities due to the hysterical behavior of the structure.

2.2. Alteration of Structural Properties

2.2.1 Loss of cross-sectional area

The durability of concrete is designed to last its lifetime if the environmental conditions to which it is exposed are properly predicted (Ghanem, Trad, Dandachy, & ElKordi, 2018). Corrosion damage is a natural process that alters the structural response under seismic excitations, so it is important to study the effect of corrosion on the cracking, loss of cross-sectional area, and bond strength. Therefore, it is necessary to conduct corrosion rate model to determine the impact of corrosion on the overall drift.

Throughout literature there are different corrosion rate models to estimate the propagation of corrosion. According to various studies, the time-increasing model shows no restrictions in early and late cracking stage as this model also shows a promising trend in reducing errors between expected and measured data in predicting corrosion at different stages (Bichara, Saad, & Slika, 2019).The time-increasing model of corrosion rate is calculated as below:

Eq. (9) $$i_{corr} = CA\,ln(t) + CB$$

Where, CA is equal to 0.3686 and CB equals to 1.1305 according to the Li's model (Li, Lawanwisut, & Zheng, 2005) i_{corr} is a time variable model based on accelerated conditions of corrosion. There are different forms of corrosion, with uniform corrosion, the load-carrying capacity will decrease, while pitting corrosion will produce local yield at certain locations (Ou & Chen, 2014). This study highlights the global influence of corrosion on the structural response to estimate the overall drift, and for this purpose, it is assumed that the penetration of corrosion is uniform. This study also focused on discovering the global deflection that affects the structural serviceability with no concern for failure in specific locations (Abou Shakra, Joumblat, Khatib, & Elkordi, 2020).

Sound Reinforcement **Corrosion of Reinforcement**

Fig.1: Schematic representation of corroded reinforcement
Reference: (Lee & Cho, 2009) and (Li, Lawanwisut, & Zheng, 2005)

The corrosion rate estimates the remaining area of the corroded reinforcement, by integrating the rate of corrosion over time, and the rust penetration in order to estimate the pitting depth as follows (El Hassan, Bressolette, Chateauneuf, & El Tawil, 2010):

Eq. (10) $$p(t) = \int 0.0116\ R_{pit}\, i_{corr}(t)dt$$

Where, $p(t)$ is the maximum pit depth along a reinforcing bar and it is expressed in (mm), R_{pit} is the ration between pitting and uniform corrosion depth it is assumed to be $1\ uA/cm^2$ as the study assumed that the corrosion penetration is uniform and t is the time in years. The Eq. (10) considers Faraday's law where the corrosion rate induces a uniform corrosion penetration of $11.6\ \mu m/year$ (Stewart, 2004). After calculating the pitting depth, the remaining area of steel is calculated as follow:

Eq. (11) $$D_{remaining} = D_0 - p(t)$$

Eq. (12) $$\%A_{lost} = \left(1 - \frac{D_{remaining}{}^2}{D_0{}^2}\right) \times 100$$

Where, D_0 is the initial bar diameter in mm, $D_{remaining}$ is the bar diameter after estimating the maximum pitting corrosion depth and A_{lost} is the relative loss of area in percentages (Dizaj, Madandoust, & Kashani, 2018).

2.2.2 Loss of bond strength between concrete and steel:

Several studies have been conducted to quantify the loss of bond strength induced by corrosion and its effect in generating additional slippage of reinforcement bars. In this study, a newly proposed model is used to demonstrate the realistic behavior of corrosion as the bond strength initially increases to the maximum value, but eventually decreases as corrosion levels become higher. This newly proposed model estimates the propagation of realistic corrosion while avoiding any overestimation or underestimation (Chung, Kim, & Yi, 2008).

Eq. (13) $$u_b = 16.87 \qquad for\ C_0 \leq 2.0$$

Eq. (14) $$u_b = 24.7\ C_0^{-0.55}\ \ for\ C_0 > 2.0$$

Where u_b is the bond strength, C_0 is the corrosion level in %.

2.3. Total Drift

Appropriate consideration of the effects of corrosion on reinforced concrete structures is extremely important for assessing the seismic safety of existing buildings (Inci, Goksu, Ilki, & Kumbasar, 2013). This approach is to consider the effect of corrosion damage and cumulative seismic damage on the overall drift.

Eq. (15) $$\Delta\, total = \Delta\, earthquake + \Delta\, slippage$$

$\Delta\, total$ is the total drift in (mm), $\Delta\, earthquake$ is the drift due earthquake loadings and $\Delta\, slippage$ is the drift due to additional slippage caused by corrosion.

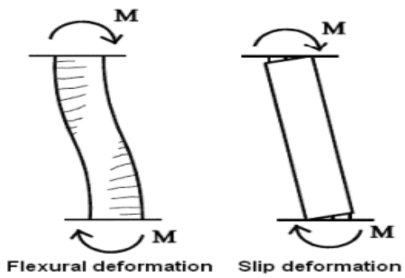

Fig.2: Flexural and slip deformations in reinforced concrete columns
Reference: (Sezen & Setzler, 2008)

Modeling the structural response under lateral loads of reinforced concrete structures is a complex process. The total lateral deformation of a column is composed of flexural drift and slip bar drift. For accurate prediction of the overall structural response, the two components must be considered. This indicates that if the effect of reinforcement slippage is ignored in the member analysis, the expected lateral deformation would be greatly underestimated. Quantifying the effect of the two deterioration mechanisms may allow for an optimized estimate of the modal parameters and reduced uncertainties.

All the floors were assumed to undergo ground excitation of the El-Centro earthquake, represented by the Bouc-Wen model to estimate the displacement and velocities resulting from hysterical behavior.

Corrosion damage generated the slip rotation which can be computed using the moment-curvature relationship, to estimate the actual rotation at the column end.

Eq. (16) $$\theta_s = \frac{\varepsilon_s f_s d_b}{8u_b(d-c)}\ for\ \varepsilon_s \leq \varepsilon_y$$

where d_b is the tensile steel bar diameter , c is the depth of the neutral axis, d is the depth to tensile reinforcement from top of section.u_b is the bond strength in steel calculated previously, f_s the stress in steel bars, and ε_y being the yield strain steel. Moments are triggered through deformations or lateral displacement on the building columns. The moment at the end of the column is the product of lateral load and the column height. The lateral displacement due to slip is calculated by

Eq. (17) $$\Delta\, slippage = \theta_s \times L$$

where θ_s is the slip rotation at the column end and L is the column height.

3. UNCERTAINTY QUANTIFICATION

The modeling of the complexity of the corroded structures subjected to earthquake loads may attain different sources of uncertainties. The corrosion damage leads to parametric variability, as these parameters are not perfectly known due to the complexity of the nonlinear behavior of the structures, even though these types of uncertainty alter the overall structure reliability (Cherng & Wen, 1994). Also, the inadequacy of mathematical models and inconsistency in the input data generate several sources of uncertainty (Slika & Saad, 2016). The various factors that the structures exposed to such as the corrosion damage, the aging factors and the seismic excitation may intensify these errors until premature failure occurs. There are two main sources of uncertainty, the physical and the model uncertainty affecting structural behavior. The physical uncertainty is generated by the loads, dimensions, and the model properties, while the model uncertainty is produced by the mathematical models that relate the variables with each other. All of these sources of uncertainty lead to sudden failure and reduction in the safety assessment, this paper conduct a reliability analysis to quantify the different sources of uncertainty (Sankararaman & Mahadevan, 2011).

3.1. Model Error

Table 1: Initial Parameter Statistics

Parameters	Mean	Coefficient of Variation	Distribution	References
β	12.5	COV=5%	Normal	(Nasr, Slika, & Saad, 2018)
γ	1.2	COV=2.4%	Normal	(Nasr, Slika, & Saad, 2018)
C	$2\sqrt{KM}$	COV=0.8%	Normal	(Nasr, Slika, & Saad, 2018)
E	$4600\sqrt{f'_c}$	COV=12%	Normal	(Mirza & MacGregor, 1979)
K	$\frac{12\,EI}{h^3}$	COV=14%	Normal	(Nasr, Slika, & Saad, 2018)
CA	0.3686	COV=25%	Normal	(Li, Lawanwisut, & Zheng, 2005)
CB	1.1305	COV=25%	Normal	(Li, Lawanwisut, & Zheng, 2005)
C_0	0.5 (mm)	COV=20%	Lognormal	(Han-Seung & Young-Sang, 2002)

As indicated in Table 1, the uncertainty quantification of parametric variables presented in the motion equation and the increasing-time model of corrosion. This table shows the mean value of each parameter according to various numerical and experimental studies, as it also presents the coefficient of variation for each parameter. The initial statistical parameters that were used in this table are the same as monitored parameters except corrosion rate is taken from experimental study that performed the real-time monitoring to estimate the corrosion statistics over time (Bichara, Saad, & Slika, 2019). The identification of errors generated by the models used to present the response of corroded structures under dynamic loads is listed in the table below.

Table 2: Model error Identification

Models	Distribution	mean	Standard Deviation	References
Bouc-Wen model	Normal	0	2.5% of the estimated value	(Smyth & Wu, 2007)
Corrosion rate	Normal	0	5% of the estimated value	(Bichara, Saad, & Slika, 2019)
Slippage and rotation effect	Normal	0	5% of the estimated value	(Bichara, Saad, & Slika, 2019)

This table presents the error quantification for each model used in the structural analysis. The model state vectors are updated using Ensemble Kalman Filter equations and Polynomial Chaos Kalman Filter. This is demonstrated using two numerical examples with different floor levels. The main objective was to identify all sources of randomness suggested in experimental data or mathematical models to ensure safety.

4. NUMERICAL EXAMPLE

This numerical example is used in this paper to simulate the effect of corrosion under seismic excitations on concrete structures. This paper will consider two case studies, a structure with primary statistical parameters and a structure with real-time monitoring statistic of the corrosion rate. The present model uses experimental data conducted through monitoring techniques to estimate corrosion rate statistics over time (Bichara, Saad, & Slika, 2019).The whole framework for modeling the nonlinear behavior of the building is implemented in MATLAB with three main functions:

1. Estimate the effect of damage mechanisms such as corrosion, dynamic loads and reinforcement slip.
2. Conduct a reliability assessment to quantify all the sources of uncertainty associated with the adopted mathematical models and modeling parameters.
3. Comparing the results of structures with real time monitored data and structures with initial statistical knowledge illustrated by the mathematical models.

The five floor building supposed to undergo the excitation of the El-Centro earthquake with ground acceleration equals to 0.25 times gravity. For simplicity, the mass of each floor is equal to 9.5 tons and it is assumed that there are no shear walls in the building as the main focus was to estimate the structural response under dynamic loads. Two models were conducted to estimate the behavior of the structural building. The first model is the Bouc-Wen model as it used to estimate the total displacement and velocities resulting from the earthquake and the second model is the increasing-time corrosion rate where it is used to estimate the severity of damage caused by corrosion and the generation of slip effect. The state vector of uncertainties and their derivative are stated below in the two following equations:

Eq. (20) $Y = [u_1\ u_2\ u_3\ u_4\ u_5\ \ \dot{u}_1\dot{u}_2\dot{u}_3\dot{u}_4\dot{u}_5\ \ z_1z_2z_3z_4z_5\ \ \beta_1\beta_2\beta_3\beta_4\beta_5\ \ \gamma_1\gamma_2\gamma_3\gamma_4\gamma_5\ \ k\ \ c\ E\ \ ic]^T$

Eq. (21) $\dot{Y} = [\dot{u}_1\ \dot{u}_2\ \dot{u}_3\ \dot{u}_4\ \dot{u}_5\ \ddot{u}_1\ \ddot{u}_2\ \ddot{u}_3\ \ddot{u}_4\ \ddot{u}_5\ \dot{z}_1\ \dot{z}_2\ \dot{z}_3\ \dot{z}_4\ \dot{z}_5\ \dot{\beta}_1\ \dot{\beta}_2\ \dot{\beta}_3\ \dot{\beta}_4\ \dot{\beta}_5\ \ \dot{\gamma}_1\ \ \dot{\gamma}_2\ \dot{\gamma}_3\ \dot{\gamma}_4\ \dot{\gamma}_5\ \ k\ \ c\ E\ ic]$

The initial values of Bouc-Wen model before damage occurrence are assumed to be $\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 2.5$ and $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = 1$.Afterfive floor building subjected to excitation and damage, there is a slight increase in Bouc-Wen hysteretic shape parameters to become $\beta = 3.3$ and $\gamma = 1.8$. It should be noted that sensitivity analysis was performed to obtain the number of used time steps that is equal to 2000 with a fixed time step $dt = 0.01$ seconds. u , $\dot{u}$ and z are the result of the mathematical models used in this numerical example, where the input parameters are k , c and E. The initial guess errors of the displacements u_i, velocities $\dot{u}_i$ and evolutionary hysteretic vector z_i for both buildings of five and eight degrees of freedom are assumed to be as the following :

Eq. (22) $u_{01} = u_{02} = u_{03} = u_{04} = u_{05} = 0$

Eq. (23) $\dot{u}_{01} = \dot{u}_{02} = \dot{u}_{03} = \dot{u}_{04} = \dot{u}_{05} = 0$

Eq. (24) $z_{01} = z_{02} = z_{03} = z_{04} = z_{05} = 0$

The probability distribution for both models corrosion and Bouc-Wen are normally distributed. The model error of Bouc-Wen is estimated to be 2.5% and the initial guess error for corrosion rate is equal to $i_{corr} = 0.25$ and the coefficient of variation for all other parameters is estimated to be 5%.

In general, the drift limits in this numerical model follow the normal distribution at two performance levels. At the service level, the drift limits are affected by elastic deformations according to studied cases, the functional drift limit is about 1.08% with low coefficient of variance equal to 10.5% as it provides a deterministic estimation. The probabilistic drift limits at ultimate level vary in 3.0-7.8% and coefficient of variance ranges from 30-45% (Lu, Gu, & Guan, 2005).

4.1. Model Verification

A model performance verification is a complicated and challenging task in the current generic setting. The difficulty lies in benchmarking against real-time experimental measurements that quantify the effect of corrosion and earthquake on real structures. However, different numerical and experimental benchamrks are used to validate the presented model, as described below:

- First, the nonlinear behavior of the uncorroded initial state is verified against dynamic analysis in ETABS. The comparison was based on maximum sway and inter-story drift in the adopted Bouc-wen model and the ETABS model under the same gravity and dynamic loading (El-Centro earthquake). The results showed good agreement between these two models with a maximum variation of around 12%.
- To simulate the effect of corrosion damage, this study utilizes the experimentally verified approach in (Bichara, Saad, & Slika, 2019) (Vu, Yu, & Li, 2016) to simulate the effect of steel loss and slippage under seismic loading.
- Last, the generic dynamic performance of the suggested approach is compared with the experimental program of four double-curvature columns presented in (Sezen & Setzler, 2008). In this study, as presented in details in the next section, the effect of slip deformations is estimated between 23-35% of the total displacement between 50-75 years (around 35% to 45% mass loss). These results align with the findings of the experimental program in (Sezen & Setzler, 2008), where the slip deformations contribution, due to corrosion damage, was found to be from 25% to 40% of the total lateral displacement.

4.2. Results and Discussion

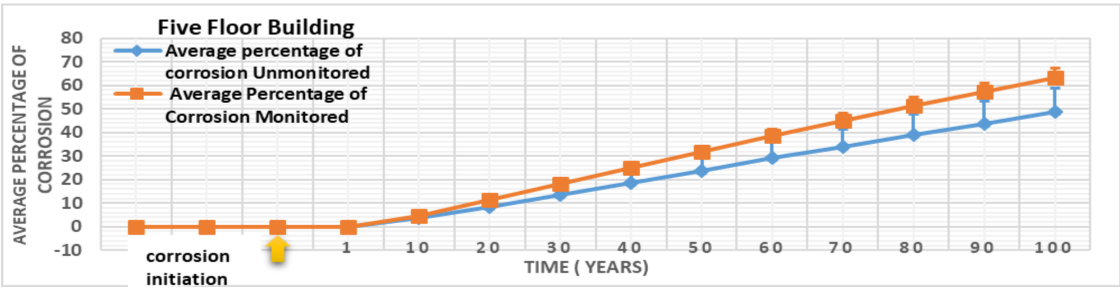

Fig.3: Average Percentage of corrosion after 100 years of corrosion initiation for five floor building using monitored and unmonitored data.

This figure shows the average percentage of corrosion conducted for five floor building, using both monitored and unmonitored data 100 years after corrosion initiation. It is shown that the average corrosion percentage is increasing over time. Where the coefficient of variance at the maximum corrosion percentage using monitored data equal to 0.059 and for unmonitored data COV= 0.207 of the five floor building. The error bars presented in this graph to show the standard deviation for percentage of corrosion estimated using monitored and unmonitored data.

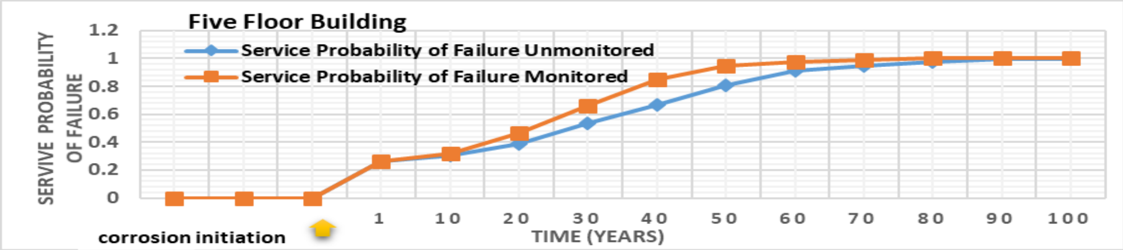

Fig.4: The Service Probability of Failure of the five floor building using both monitored and unmonitored data over 100 years from corrosion initiation.

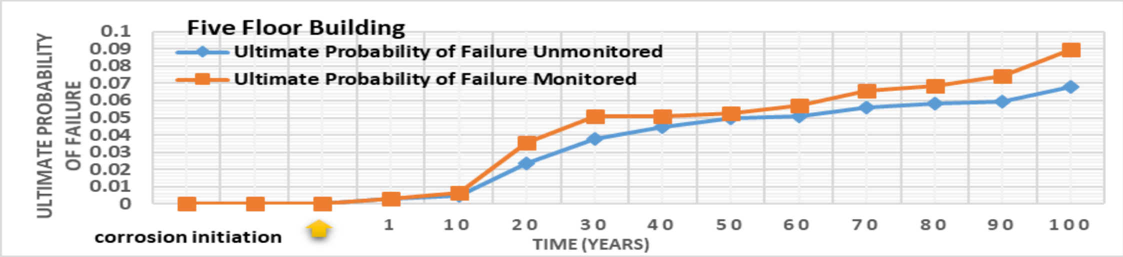

Fig.5: The Ultimate Probability of Failure of the five floor building using both monitored and unmonitored data over 100 years from corrosion initiation

Fig.4 and Fig.5 represent the service probability and ultimate probability of failure respectively for five floor building using both monitored and unmonitored data over 100 years after the initiation of corrosion. Applying the reliability analysis to estimate the probability of failure associated to ultimate and functional limit states under nonlinear behavior. When evaluating structural analysis, the service life of the structure must be estimated to ensure the safety of the building. Performance reliability at two levels, the limit of serviceability drift that mainly depends on the elastic deformations and the ultimate drift limit associated with collapse and other forms of structural failure. These two figures also suggest that probability of failure using monitored data cannot be ignored to avoid underestimation of the probability of failure.

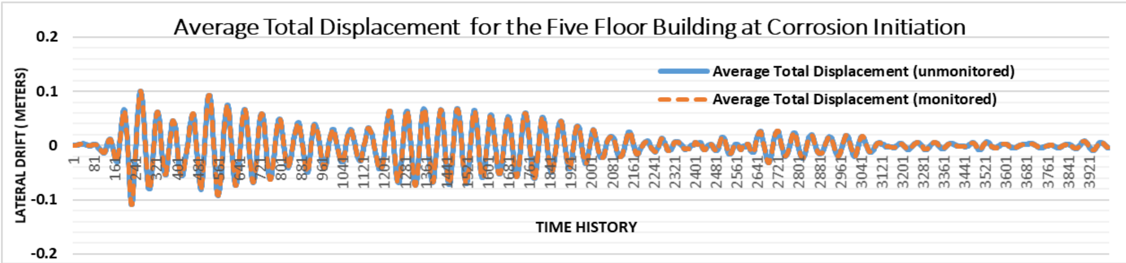

Fig.6: Average Total Displacement for five floor Building and Eight Floor Building using Monitored and Unmonitored data at Corrosion Initiation

This figure shows the average total displacement for the five floor building upon initiation of corrosion using both monitored and unmonitored data. The results of the five floor building are illustrated in two cases of the study, one with initial statistical parameters indicating unmonitored data and the other with a real-time monitored corrosion rate refereed to monitored data. Upon initiation of corrosion, the effect of the corrosion on the total displacement was slightly recognized. This indicates that the use of monitored and unmonitored data showed proximate results because the corrosion was not significant at its initiation. However, the coefficient of variance for the five floor building at the maximum standard deviation is 0.2659 using both monitored and unmonitored data.

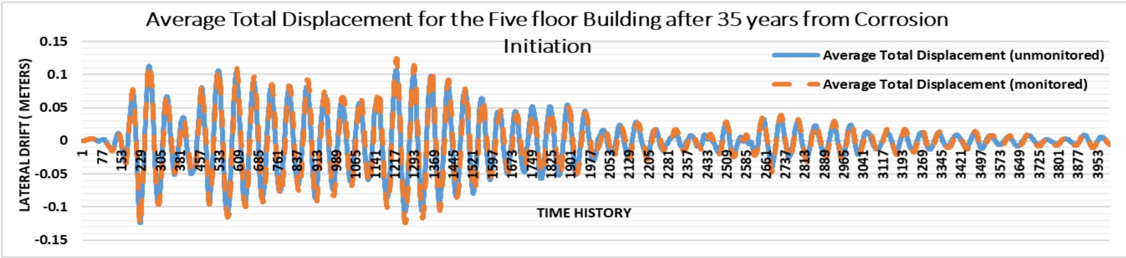

Fig.7: Average Total Displacement for Five Floor Building using Monitored and Unmonitored Data After 35 years of Corrosion Initiation

This figure indicates the total displacement on the last floor of this building after 35 years of corrosion initiation using both monitored and unmonitored data. These results showed a significant effect of corrosion on old structures as corrosion is widely recognized over the long-term life cycle of the structure. The coefficient of variance for the five floor building at the maximum Displacement is 0.253 for the monitored data and 0.2711 for the unmonitored data, The mathematical modeling illustrated the seismic performance of corroded structures and their influence on structural response, to ensure safety requirements (Ervin, Kuchma, Bernhard, & Reis, 2009).

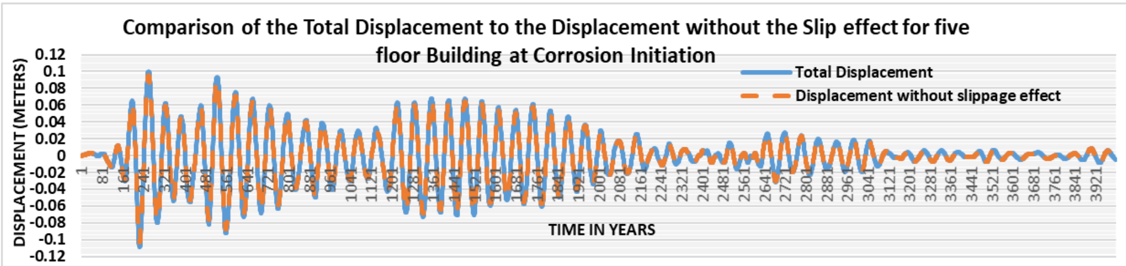

Fig.8: Comparison of the Total Displacement to the Displacement without the slip effect at corrosion initiation

Fig.8 shows the slippage effect for the five floor building at corrosion initiation. These results show that the contribution of slippage effect on the total lateral displacement is significant (Sezen & Setzler, 2008). In addition to flexural deformations due to seismic excitation or corrosion damage, the bar slip deformations should be considered in modeling and analysis the reinforced concrete structures. If the influence of slippage deformations on the total lateral drift are ignored in the structural analysis, the estimated lateral deformation would be greatly underestimated. For this reason, it is important to consider the contribution of slip and rotation deformations to the structural response to reduce the risk of failure. The contribution of slippage at the maximum total displacement was 5.3% at corrosion initiation for the five floor building.

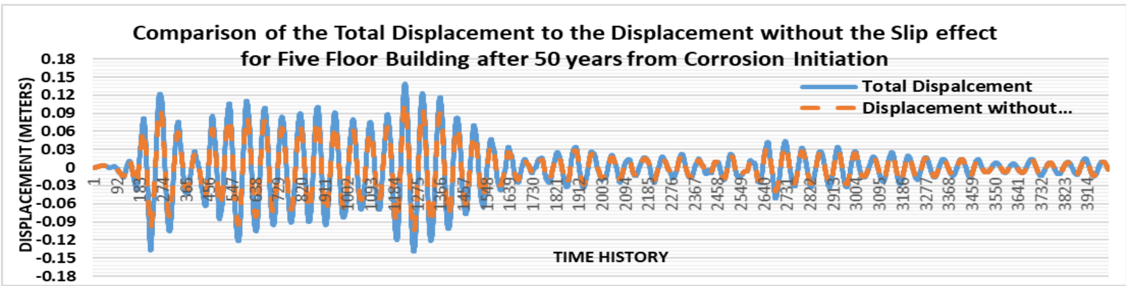

Fig.9: Comparison of the Total Displacement to the Displacement without the slip effect after 50 years from Corrosion Initiation

Fig.9 represents the slippage effect of the five floor building 50 years after initiation of corrosion. The slip deformations contribute 22.9% to total displacement 50 years after corrosion initiation, as this percentage significantly affect the overall lateral drift. For this reason, it is important to quantify the influence of reinforcement slippage in the total lateral displacement. Additionally, when estimating the actual rotation θ_s at the end of the columns, it is essential to consider the effect of the slip rotation as well. Therefore, the slippage of the reinforcement contributes significantly to the total lateral displacement in the structural members.

5. CONCLUSIONS

This study provides a framework for the prediction of seismic performance of corroded structures considering all sources of uncertainty to achieve high reliability. The study findings revealed that the mathematical models are acceptable and can be adopted to estimate the performance of corrosion damage under seismic loads. The main results are summarized as follows:

- This study conducted a complete model for assessing the seismic performance and evaluating the corroded reinforced concrete structures, taking into account within the sectional analysis all the effects of corrosion on reinforcement slippage and on the structural response.
- The proposed framework is simple and accurate tool for predicting the remaining service life to assess the state of health of the structure.
- The presented model was illustrated using the numerical application that includes all sources of uncertainty that are exposed to it. The numerical model was performed using the monitored data and with an initial guessing error. The results of the study also showed that using monitored data in mathematical modeling has significant variation.
- Reliability assessment is highlighted using a comparative study to predict the structural response under various damage mechanisms, as the findings of this analysis can be used in structural health monitoring based on physical data model.

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