Life Cycle Damage Assessment of a Reinforced Concrete Structure under Multi-hazard Seismic and Wind Action

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ABSTRACT

This study evaluates the life cycle damage in reinforced concrete (RC) structure caused due to the action of earthquake and cyclonic wind, and their multi-hazard effects, by considering them as independent non-cascading hazards with and without considering the effects of chloride induced corrosion in the structural members. In performance-based design concept, it is important to simulate real time behavior of a structure under specific hazard, which may be incident during its design service life. In this study, a rectangular shaped 9-storey RC special moment-resisting frame, assumed to be located in a region which is prone to both, seismic and wind loads, has been designed for various load combinations prescribed by Indian standard design code. The structural damage is evaluated in terms of damage index, by performing nonlinear dynamic analysis for site-specific code compliant earthquake and cyclonic wind, with considering their cumulative effect on the structure as non-cascading independent hazards. Also, updated factor of safety for the base column has been determined after it had been exposed to different hazard scenario. It has been observed that the damage in the RC structure due to independent earthquake and wind can increase from 10 percent to even 200 percent if the effect due to chloride induced corrosion in the structural members is incorporated. Also, multi-hazard action on the structure results in 1.5 fold damage compared to damage due to individual hazards, when the effect of corrosion is considered. This holistic approach presents a more realistic behavior of the structure which should be considered while practicing design of structures for multiple hazards.

Keywords: Life cycle damage; Multi-hazard; Chloride Corrosion; Earthquake; Cyclonic Wind; Damage Index; Factor of Safety (FOS)

INTRODUCTION

Structures are being designed for the broad range of static and dynamic loads, arising due to natural and anthropogenic activities, so that it would not collapse (for the purpose of saving lives rather than preservation of the structure). This approach is fundamentally at the root of structural engineering. In India, design of a reinforced concrete (RC) structure is governed by
the worst possible load on the structure, which is arrived at using various load combinations given in Indian Standard (IS) 456: 2000. However, this approach may sometime result in uneconomical and unconservative design of a structure (Nikellis et al., 2019), as a typical structure is subjected to multiple natural hazards, of varying intensity, during its lifetime. Data indicate that frequency of these incidences has tripled over the last three decades (Chen et al., 2010). Duthinh and Simiu (2010) argued that risk of exceeding a limit state associated with multiple hazards could be twice as high as the risk associated with only one hazard. These observations affect not only the safety but also the cost of construction and insurance of the structure. An optimum design should, ideally, be derived through a life-cycle cost analysis that relates the performance of any structure during its lifetime with probable losses due to various loading conditions. Multi-hazards can be classified as concurrent (e.g., wind and surge), cascading (e.g., fire following earthquake, tsunami and earthquake), or independent and likely to occur at different times (e.g., wind and earthquake) (Gardoni and LaFave, 2016). Out of these, mutually non-cascading and independent hazard events are a significant threat to the civil infrastructures (Aly and Abburu, 2015). In this context, National Building Code (NBC) of India (2016) identified various locations within Indian subcontinent at which, there is a high probability of a structure being subjected to independent action of both, strong wind as well as earthquake forces, and therefore it is imperative to conduct multi-hazard analysis of structures at these locations. Extensive research has been carried for multi-hazard seismic and wind analysis of structures considering different approaches (Li and van de Lindt, 2012; Kameshwar and Padgett, 2014; Chulahwat and Mahmoud, 2017; Venanzi et al. 2018; Nikellis et al., 2019; Roy and Matsagar, 2019; Roy and Matsagar, 2020; Wang et al. 2020, etc.)

Reinforced Concrete (RC) structures are exposed to various environmental deterioration depending on their location, apart from several natural hazards of varying intensities during
their lifetime. Environmental deteriorating agents will lead to slow but continuous damage to the structural elements in the form of corrosion of reinforcement bars, crack propagation, spalling, etc. Corrosion of steel reinforcement is one of the major deteriorating mechanism in reinforced concrete (RC) for structures located nearby a water body. In such condition, the structure is continuously exposed to corrosion inducing species like H₂O, O₂, Cl⁻ and CO₂. The penetration of corrosive elements toward the inner reinforcement depends on the permeability and the finishing of the concrete surface, and once there is enough accumulation of these species around the reinforcement, process of corrosion gets initiated. Steel from the reinforcement bars (rebar) get consumed in the process of corrosion and rust start forming around the rebar. This results in increase in the overall volume of the reinforcement, which will lead to stress initiation in the surrounding region. Finally, cracks appear in the concrete, which further opens the path for corrosion by allowing faster propagation of the species to the reinforcement through the newly opened cracks. Chloride induced corrosion is hence a continuous process and causes widespread damage to the RC structure, resulting in significant reduction in the service life of the structure (Basheer et al., 1996). The effect of chloride induced corrosion in the structure has been studied widely by various researchers (Chen and Mahadevan, 2008; Pack et al., 2010; Otieno et al., 2016a; Otieno et al. 2016b; Cui et al., 2019).

Damage in the structural member is a subjective term, used to relate the cracking, crushing, buckling, possible fracture of longitudinal bars, or loss of anchorage (bond failure). In general, damage in RC member is related to irrecoverable (inelastic) deformations. Therefore, there is a need for common index which could quantify the cumulative damage caused by either the extreme events or the environmental deterioration. Various damage models have been developed by researchers based on some deformation quantity like strain, curvature, nodal displacement, forces, energy dissipated or absorbed, etc., review of whose
has been presented by Kappos (1997), Sinha and Shiradhonkar (2012), Cao et al. (2014), Zameeruddin and Sangle (2016), Hait et al. (2019), etc.

Many of these cited studies have shed light on the damage caused by either multiple earthquake hazards only, or even combined impact of the earthquake and wind hazards on the structure, but for a more realistic and as a further continuation of these studies, the impact of the environmental deteriorating agents like chloride current (major agent considering the structural location) need to be considered along with the impact of the multi-hazard during the lifetime of the structure. The main goal of this study is to promote mitigation of the impact of natural hazards on a RC structure by analyzing the damage to the structure under multi-hazard loading subjected to continuous chloride corrosion throughout the age of the structure. Hence, objectives of the current study can be specified as:

1. Modelling, analyzing, and designing a reinforced concrete (RC) building by conventional code-specified approach considering multi-hazard scenarios for the RC building design in earthquake- and wind-prone areas.

2. Life cycle response assessment of structure when subjected to non-cascading independent multiple hazards, earthquake, and wind, with and without considering effects of corrosion.

3. Life cycle damage assessment in terms of available factor of safety (FOS) for a structural member against permanent loads, when it is subjected to the non-cascading independent multiple hazards, earthquake, and wind, with and without considering effects of corrosion.

In order to achieve the above objectives, the current study is aimed to analyze the impact of continuous chloride corrosion in structural members on the damage caused due to earthquake and cyclonic wind in terms of cumulative damage index (DI). Incidence time of both the hazards, earthquake and wind, is kept as variable during the intended service life of the structure, i.e., 100 years. The cumulative impact of the multi-hazard effects on the structure is compared with the individual action of each hazard in presence and absence of
chloride induced corrosion in structural members. This impact is measured in terms of damage index and residual axial load carrying capacity of the base column to determine the change in the available factor of safety (FOS) value. Main assumption made in this study is that there is no repair or maintenance work carried out in the structure during its entire service life, as a result, there is continuous increase in the accumulated damage in the structure. This assumption not only helps one to understand the necessity of the timely repair and rehabilitation work in the structure but also to determine the extent of the repair required in the structure at any instance of time. Another assumption made is, there is a linear correlation between the damage index \((D)\) and modulus of elasticity \((E)\) of concrete, which is recommended by many researchers.

1. **NUMERICAL MODELLING**

In present study, the structure is considered located in Bhuj (Kachchh district, Gujarat, India), which is prone to both regular earthquake and high-speed wind hazards, as given in relevant Indian standards. This region is listed in Annex P of National Building Code (NBC) of India (2016) for being exposed to greater risk of multi-hazard effects of both, earthquake and wind. Furthermore, the presence of sea nearby supports the major deciding impact due to the chloride induced corrosion in structural members. Role played by the presence of the chloride corrosion current is shown by comparative analysis of the damage produced in the structure under the action of site-specific earthquake and cyclonic wind.

2.1 **Structural Modelling**

As the study focuses on structure exposed to both earthquake and cyclonic wind hazard, height of the structure is chosen as to capture the extensive impact from both the types of hazards in low to medium rise structures. As per IS 875 (Part 3): 2016, for structure having fundamental frequency less than 1 Hz or a structure with overall aspect ratio 5 or more, is to be designed with the inclusion of gust factor in the wind loading which result in relatively
more stiff structure, such structures are considered as high rise structures in this study, and hence, are beyond the scope of present study. Therefore, in this study, height of the structure is kept at 31.5 m considering 9 storey structure with floor-to-floor height of 3.5 m.

The plan dimension is also kept as 9 m × 12 m to with bay width of 4 m. Further, for the simplicity in the damage calculation, the column and beam dimensions are kept constant throughout the structure at 0.6 m × 0.6 m and 0.25 m × 0.5 m, respectively. Structural configuration is shown in the Fig. 1. Grade of concrete and reinforcement bars used for design of the structure is M30 and Fe415, respectively. Other material properties are derived using the guidelines given in IS 456: 2000. Table 1 provides the detail of the loads considered to be acting on the structure as per the relevant IS codes.

2.2 Structural Deterioration due to Chloride Corrosion

The mechanism of structural damage due to the onset of chloride induced corrosion is already discussed. The process of determination of corrosion induced damage in structure is explained in Equations 1-12. The rusted volume of steel per unit length (cm³) can be predicted as:

\[
A_s(t) = \frac{M_s(t)}{\rho_s} = 3.709 \times 10^{-5} i_c \pi d^2 (t) \Delta t
\]

where, the density of steel is 7.8 g/cm³ and \( M_s(t) \) is the mass loss of steel per unit length (g/cm) and is given as per the Faraday's Law:

\[
M_s(t) = \frac{mI}{zF}
\]

where, \( m \) is the atomic mass of iron (56 g for Fe), \( I \) is the chloride corrosion current (A), which can be expresses as the product of surface area of the steel bar (\( a_s \)) and the corrosion current density (\( i_c \)). For a unit length of a rebar, \( a_s = \pi d \). Further, \( t \) is the time after corrosion initiation (s), \( z \) is the ionic charge (2 for Fe\(^{2+} \)) and \( F \) is the Faraday's constant, i.e., 96,500 A·s
(Cui et al., 2019). After corrosion, the volume of rust added can be assumed equivalent to the loss of material from the rebar. Therefore, the remaining diameter of the rebar after $\Delta t$ time is given as:

$$d'(t) = \sqrt{d^2 - \frac{4A_s(t)}{\pi}}$$  \hspace{1cm} (3)

The chloride corrosion will also lead to an effective decrease in the yield and the ultimate strength of the reinforcement. Residual yield and ultimate strengths of the reinforcement bar can be calculated as given in Equation 4 and 5, respectively:

$$f'_y = (1 - 0.015 \cdot \eta_{100}) \cdot f^0_y$$  \hspace{1cm} (4)

$$f'_u = (1 - 0.015 \cdot \eta_{100}) \cdot f^0_u$$  \hspace{1cm} (5)

where, $f'_y$ and $f'_u$ are respectively the residual yield and ultimate strength of the reinforcement corresponding to the $f^0_y$ and $f^0_u$ of the original reinforcement bar. $\eta_{100}$ is the percentage of steel mass lose due to chloride corrosion over the time. Also, the ultimate strain of the corroded reinforcement can be calculated as:

$$\varepsilon'_{su} = (1 - 0.039 \cdot \eta_{100}) \cdot \varepsilon^0_{su}$$  \hspace{1cm} (6)

where, $\varepsilon'_{su}$ and $\varepsilon^0_{su}$ are respectively the ultimate strain of the corroded and the original reinforcement bar. Time step ($\Delta t$) of 10 years is considered in present study to get the revised damaged state of the structure. For this purpose, a constant chloride corrosion current density of 2 $\mu$A/cm$^2$ is assumed throughout the analysis. This has been taken after careful consideration to various studies including Otieno et al. (2016a) and Cui et al. (2019). The reduction in the compressive strength of concrete will depend on the magnitude of crack formed due to the process. According to a model by Vecchio and Collins (1986), the reduced concrete strength in the concrete cover can be represented as:
where, $K$ is the coefficient related to bar roughness and diameter [for medium-diameter ribbed bars a value of 0.1 is considered for $K$ (Coronelli and Gambarova, 2004); $\varepsilon_{co}$ is the strain at the peak compressive stress ($f_{ck}$); and $\varepsilon_1$ is the tensile strain in the cracked concrete at right angles to the direction of the applied compression. The strain $\varepsilon_1$ is evaluated by:

$$
\varepsilon_1 = \frac{b_t - b_0}{b_0}
$$

where, $b_0$ is the section width in the virgin state (no corrosion cracks); and $b_t$ is the beam width increased by corrosion cracking. An approximation of the increase of the beam width is given by:

$$
b_t - b_0 = n_{bars} w_c
$$

where, $n_{bars}$ is the number of bars in each layer and $w_c$ is the crack width for a given corrosion level during the period $\Delta t$, to be evaluated as:

$$
w_c = 2\pi (\nu_{rs} - 1) X
$$

where, $\nu_{rs}$ is the ratio of volumetric expansion of the oxides with respect to the virgin material, its value is taken as 2 (Molina et al., 1993); $X$ is corrosion penetration depth, which can be calculated as:

$$
X = 0.0115 i_{co} t
$$

where, $i_{co}$ is the corrosion current density (cm/year) and $t$ is the time after corrosion initiation (years). Further, the elastic modulus ($E_c$) of the concrete is related with its compressive strength ($f_{ck}$) at each time step using the relation proposed by Noguchi and Nemati (2007), as:

$$
E_c = \frac{f_{ck}}{\varepsilon_{co} + K \frac{\varepsilon_1}{E_{co}}}
$$
\[ E_c = 2.1 \times 10^5 \left( \frac{\gamma}{2.3} \right)^{1.5} \left( \frac{f_{ck}}{200} \right)^{0.5} \]  

(12)

where, \( E_c \) is the modulus of elasticity of the concrete in kgf/cm², \( \gamma \) is the unit weight of concrete in t/m³, and \( f_{ck} \) is the characteristic compressive strength of concrete in kgf/cm².

The effect of the corrosion current density on mechanical properties of reinforced concrete structure is shown in Fig. 2. This behavior is expected as there will be rapid deterioration in the material properties with increase in corrosion current, as a result, there will be decrease in strength and stiffness of the structural members, in absence of timely maintenance and repair.

2.3 Damage Index

As discussed in Section 1 of this article, there are several damage models developed by researchers in the world, based on different damage parameters. Sinha and Shiradhonkar (2012) compared damage index values resulting from most popular damage models and concluded that each of the damage model results in similar values for a structure under medium intensity of dynamic loading. Therefore, simple damage model, based on displacement deformation characteristics of a member, developed by Park et al. (1985) is used to quantify structural damage in the current study. It is expressed as:

\[ D = \left( \frac{d_{\text{cal}} - d_0}{d_u - d_0} \right)^\alpha \]  

(13)

where, \( d_{\text{cal}} \) is the value of the damage variable calculated from analysis, \( d_0 \) is a threshold value for the damage variable, below which elastic behavior of the concrete is observed, \( d_u \) is the value of the damage variable at which failure is assumed to occur, and \( \alpha \) is an exponent which, is the absence of conclusive experimental data, may be taken as unity. To obtain the elastic \( (d_0) \) and ultimate \( (d_u) \) displacement points, the moment resisting frame (MRF) is subjected to lateral displacement to obtain a static pushover curve. Beams and columns are modelled as non-linear frame elements by assigning concentrated M3 and P-M3 plastic
hinges respectively at a distance of 0.05 times the total length of the member from both its end. Hinges represents the localized force-displacement relation of a member through its elastic and inelastic phases under cyclic loads. A static pushover analysis curve obtained through displacement control loading on the structure until the hinge yields for the 9-storey structural model (discussed in Section 2.1) is shown in the Fig. 1c. For the pushover curve, a predefined hinge in a beam at the topmost floor level is monitored for the base reaction developed as the displacement is applied to it. The same reference hinge is used for all the following multi-hazard analysis calculation carried out in this study. The peak base reaction that the hinge can take before it fails, is the ultimate strength point for that hinge element. The corresponding displacement in the X-axis for the ultimate strength point gives the ultimate inelastic displacement \(d_u\) as used in the Equation 13 for the calculation of the damage index of the structure. For example, the value of \(d_u\) in the Fig. 1c is 0.4718 m. Next, the point at which the pushover curve deviates from linearity will give the elastic limit point for that reference hinge, and any base reaction on the structure up to this point will not produce any permanent damage to the structure. The corresponding value of the elastic limit displacement will give the \(d_0\) value as used in the Equation 13 for the calculation of the damage index. Here, the value of the \(d_0\) in Fig. 1c is 0.0368 m.

The effect of the damage index on the structure is taken as the degradation of the elastic stiffness of the concrete induced by plastic straining. Therefore, the reduced elastic modulus, \(E_c^*\), is expressed in term of damage index as (Cui et al., 2019):

\[
E_c^* = (1 - D) \times E_c
\]

where, \(E_c\) is the initial modulus of concrete and \(D\) is the damage to the structure caused by events like earthquake and cyclonic wind as expressed as damage index. The other way round, due to the formation of the cracks in the concrete because of the continuous exposure
to chloride current density also leads to the reduction in the elastic modulus of the concrete ($E_c$), which can then be expressed in terms of damage to the structure as damage index using Eq. 14.

2. LIFE CYCLE DAMAGE ANALYSIS OF THE STRUCTURE

3.1 Structural Damage due to Single Hazard

In this case, it is assumed that the structure is subjected to only one of the hazards, either earthquake or cyclone, during its lifetime, while being continuously exposed to chloride induced corrosion. As per earthquake resistant design philosophy, structural damage under the action of frequent or minor earthquakes are supposed to be negligible. Hence, the structure is excited against a medium level site-specific synthetic earthquake in this study as the probability of occurrence of such earthquakes is more than the extreme earthquakes and the extent of damage in a structure range in slight to moderate level so that structure could be used with little or no repair. Ferreira et al. (2020) developed algorithm to generate site specific earthquake of any intensity in compliance with Eurocode-8. The same algorithm is modified to obtain the site-specific earthquake ground motion in compliance with IS 1893 (Part 1): 2016. Thus, the peak ground acceleration (PGA) obtained for medium soil strata for medium intensity earthquake (return period = 475 years) is $3.028 \text{ m/s}^2$ observed at 47.195 s. The time history plot and its response spectrum curves are shown in Fig. 3a and b, respectively. Wind loading on the structure is considered in the form of cyclonic wind loading on a side face (Section A-A in Fig. 1b) of the structure. The time history cyclone data is generated from the NatHaz online wind simulator tool at 75 m/s 3s-gust speed. The average wind speed is at top floor is 58.2 m/s, and the maximum and minimum wind speed are 83.3 m/s and 34.8 m/s respectively. This range of cyclonic wind speed is in line with the India Meteorological Department (IMD) classification of cyclones in that region. Fig. 3c shows the wind speed time history data plot and Fig. 3d shows its frequency content plot.
Let $t_e$ and $t_c$ represent the age of the structure at the time of incidence of earthquake and cyclonic wind, respectively. Structural damage due to the earthquake and cyclonic wind action, as a function of time, has been shown in Fig. 4. The damage observed due to singular action of earthquake or wind load is effectively increasing with the increase in the age of the structure, which is as expected in the real scenario as well. At points there is also an decrease in the damage by the earthquake occurring at a later stage which is because of the uncertainty involved in any natural and manmade hazard and the damage is amplified significantly when the frequency of the hazard matches with the natural frequency of vibration of the structure. It is important to note that the structural damage observed, with due consideration given to chloride induced corrosion, is as much as 1.5 times and even more, in some cases, of the damage caused without considering chloride corrosion. This proves the importance of consideration of the current state of the structure while evaluating the possible damage due to earthquake or wind loading. The impact of one of these extreme events on the future service life of the structure is shown in Fig. 5a and 5b. It is important to note from the same figure that for the structure which is exposed to earthquake or cyclonic wind may exhibit lesser service life depending on the time and magnitude of occurrence of the hazard. This again emphasizes the fact that due consideration should be given to continuous structural degradation under the action of chloride induced corrosion to determine the post-hazard service life of a structure.

**3.2 Structural Damage due to Multiple Hazards**

The possibility of occurrence of the failure in the structure increase when it is under the action of multiple hazards of minor or medium intensity, such as earthquake and wind, though it is designed for the extreme cases of either of the two. This could be because medium level hazards are more probable, and minor structural damages caused by them often go unnoticed. However, when their cumulative effect is considered over a period, the
resultant damage is several folds than what is expected. The parametric study has been carried out for independent non-cascading earthquake and wind actions on the structure, by varying the time of incidence of the two, and by considering the effects of corrosion induced damages in the structure. The extent of structural damages are expressed in terms of damage index, evaluated at the time of occurrence of the hazard, and are tabulated in Table 2 and 3. Age of the structure at the time of occurrence of the first hazard has been kept constant at 20 years, for earthquake as well as wind, for comparable analysis of the results, for the structure hasn't gone through significant damage in the first 20 years. There could be several combinations over the time of occurrence of multiple hazard; however, the trend in the result would be similar, though damage values may not be same. To deduce reliable results from the current analysis, three separate cases ($t_c = 40, 60, \text{ and } 80$ when $t_e = 20$, and vice-versa) are studied in each of the possible combination. It is already stated that the effect of earthquake or cyclone increases when effects of corrosion are considered. The similar trend is observed in multi-hazard analysis, as well. However, structural degradation due to corrosion have more severe effects (around 1.5 times) on the multi-hazard analysis as that was for single hazard analysis. The same has been shown in Fig. 6. Another interesting observation can be made from the Table 2 that as the time gap between the occurrence of 1st and 2nd hazard increases, the post-hazard damage due to chloride corrosion increases, thus producing an overall higher damage in the structure. As the hazard considered in the study were of medium to smaller level, the structure is not completely damaged in none of the case, except for when $t_e = 20$ and $t_c = 100$. In the last case the structure fails at 100 years of age, when hit by a cyclone, causing a sudden collapse due to hazard. A sudden structural failure is always the most dangerous and catastrophic event. This arises the need for a comprehensive multi-hazard analysis and monitoring for designing a RC structure safe against the worst multi-hazard combination as the structure looked relatively safe with little expectation of a sudden collapse with damage
only up to 72% at 90 years of age. Similar inferences from Table 3 can also be drawn when cyclonic action is considered prior to the earthquake. From comparing both the Table 2 and 3, it is observed that the structure suffers larger damage when hit by earthquake (higher damage causing event in this case) in the initial age and then latter by the cyclone.

For checking the severity of the earthquake and wind hazard, post hazard behavior has been studied in terms of residual capacity-demand ratio or the factor of safety (FOS) for an internal base column. Demand is the function of permanent loads, i.e., dead and live loads, which will be always present on the structure. The load carrying capacity of the structural members is a function of compressive strength of concrete, $f_{ck}$ and rebar strength, $f_y$, which would decrease over a period of time, as discussed earlier. Results are tabulated in Table 4 and 5 for multi-hazard earthquake and cyclonic wind action with difference in time of incidence. One of the cases within Table 4 and 5 has been plotted in Fig. 7 to show the nature of post-hazard vulnerability in the structure. The corrosion and the no damage curves show the difference in the impact on the members of the structure created by the chloride corrosion. The difference is negligible in the initial age of the structure and becomes significant as the structure is hit by either of the hazard. Further, the corrosion + $t_c = 20 + t_c = 50$ case verifies the earlier observation of the larger overall impact on the structure when the structure is first hit by an earthquake (higher damage producing event). The already damaged structure shows a significant fall in the FOS even at point of occurrence of the cyclone at $t_c= 50$ years. Any unprecedented loading of the structure after this point can cause many members of the structure to fail as FOS approaches 1. This also shows the importance of the regular structural repair even when the structure seems to be less damaged, as an another hazard at any time can trigger the sudden collapse of the structure leading to loss of life and property.

3. CONCLUSION
The main aim of the study is to show the significance of the damage caused by multi-hazard loading, including the chloride deterioration, earthquake, and cyclonic wind loading. With the increase in the environmental and anthropogenic events, the reinforced concrete structures are likely to face various hazards during their service life which may increase its possibility of failure before its intended service life. Also, the structure designed as per the current code guidelines for governing of the two loads, wind, or earthquake, may not be sufficient to survive the medium scale multi-hazard impact of the two.

The study has also shown that not only the magnitude of the hazard, but also the order of occurrence (Table 2 and 3) of the same multiple hazards, and the time gap between the hazard occurrences can also be a significant factor in deciding the life cycle damage in the structure. The results from the study shows that the occurrence of the earthquake (larger damage producing event, in this case) prior to the wind hazard (lesser damage producing event, in this case) will cause severe damage to the structure due to the post-earthquake increase in the structural damage, allowing higher wind damage to the more damaged structure. This can also come across situations when the structure may look less damaged, however a sudden occurrence of the second lesser intense hazard can lead to complete collapse of the structure (Table 2, \( t_c = 100 \) years case), thus causing catastrophe.

Further, the study shows the impact of considering the degradation of structure due to chloride induced corrosion as a deciding factor in the life cycle damage in the structure. From Fig. 6, it can be stated as damage due to multi-hazard impact on the structure is almost 1.5 times the impact when the chloride induced degradation is not considered. This also opens up the future scope where the impact of many other degradation factors can be studied in order to accurately capture the real time behavior of the structure to many hazards.

Finally, an analysis of the residual capacity to demand ratio or the factor of safety (FOS) of an inner base column member is carried out to analyze the post damage behavior of the
structure. A medium scale event, which is not producing significant damage, can weaken the structural member to the extent that it will not be able to fulfill its intended function against the action of permanent loads, which are always existing. Hence, in some cases the damage index may not show the actual damage as columns may collapse under the action of permanent loads, even before the damage index reaches the value 1.

The impact of other environmental deteriorating agents like carbonation, sulphate attack, alkali aggregate reaction, corrosion, freeze-thaw, etc. can be significant as well, depending on the location of the structure. However, this requires an effort beyond the scope of the current study and their impact can be analyzed in further research in this field.

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Figure 1: (a) Section A-A; (b) Floor plan; (c) Static pushover curve for a selected hinge on the roof, in undamaged state, of the structure.
Figure 2: Change in: (a) longitudinal reinforcement bar diameter; (b) crack width; (c) compressive strength, and (d) modulus of elasticity, with three different constant corrosion current density across the age of the structure.
Figure 3: (a) Site-specific medium intensity synthetic earthquake accelerogram for Bhuj; (b) Response spectrum of the synthetic earthquake accelerogram at Bhuj; (c) Wind velocity time history data plot at roof level of 9-storey structure in Bhuj; (d) Fast Fourier Transform (FFT) of Wind velocity time history data plot at roof level of 9-storey structure in Bhuj, and (e) Power spectral density (PDS), Wind velocity time history data plot at roof level of 9-storey structure in Bhuj.

Figure 4: Life cycle damage index of 9-storey structure located in Bhuj under the action of site-specific earthquake and cyclonic wind for constant corrosion current density of 2 μA/cm².
**Figure 5:** Life cycle damage estimation due to: (a) single earthquake event, and (b) single cyclonic wind action with change in time of incidence, across the age of the structure. The line is a guide to the eye. $t_e$ and $t_c$ are the time of occurrence of earthquake and cyclone, respectively.
Earthquake alone, $t_e = 20$
Cyclone alone, $t_c = 80$
Multi-hazard, $t_e = 20 + t_c = 80$

Damage index

<table>
<thead>
<tr>
<th></th>
<th>Without corrosion</th>
<th>With corrosion</th>
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<tbody>
<tr>
<td>(1)</td>
<td>0.255</td>
<td>0.001</td>
</tr>
<tr>
<td>(2)</td>
<td>0.256</td>
<td>0.042</td>
</tr>
<tr>
<td>(3)</td>
<td>0.278</td>
<td>0.413</td>
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Figure 6: Life cycle damage estimation of structure, with and without considering the effects of corrosion action on the structure, when it is hit by: (a) earthquake at $t_e = 20$ years, and cyclone at $t_c = 40$ years; (b) earthquake at $t_e = 20$ years, and cyclone at $t_c = 60$ years; (c) earthquake at $t_e = 20$ years, and cyclone at $t_c = 80$ years; (d) cyclone at $t_c = 20$ years, and earthquake at $t_e = 40$ years; (e) cyclone at $t_c = 20$ years, and earthquake at $t_e = 60$ years, and (f) cyclone at $t_c = 20$ years, and earthquake at $t_e = 80$ years.

Figure 7: Comparison of factor of safety (FOS) of an inner base column under permanent loads, when the structure is subjected to multiple hazards.
Table 1: Summary of the loading on RC moment resisting frame under study.

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<th>Sl No.</th>
<th>Load Pattern</th>
<th>Load cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dead Load</td>
<td>(a) Self-weight of frame (( \rho = 25 \text{ kN/m}^3 ))&lt;br&gt; (b) 14 kN/m wall load on the beams of each non-roof floors&lt;br&gt; (c) 2.5 kN/m(^2) slab loads on each floor&lt;br&gt; (d) 1 kN/m(^2) super dead load</td>
</tr>
<tr>
<td>2</td>
<td>Live load</td>
<td>(a) 2.5 kN/m(^2) on each non-roof floors&lt;br&gt; (b) 0.75 kN/m(^2) on roof</td>
</tr>
</tbody>
</table>
| 3      | Wind load    | Basic wind velocity = 50 m/s; Risk coefficient, \( k_1 = 1.08 \);
Terrain roughness and height factor, \( k_2 = 1.065 \);
Topography factor, \( k_3 = 1.0 \); Importance factor for cyclonic region, \( k_4 = 1.0 \). |
| 4      | Earthquake load | Zone V (location - Bhuj); Importance factor, \( I = 1 \);
Response reduction factor, R=5; medium soil strata
mass source = Dead load + 0.25 \times Live load |

Table 2: Damage index when the structure is first hit by earthquake at \( t_e = 20 \) years, and then later by cyclone at \( t_c \) (variable), when the structure is under continuous exposure to chloride induced deterioration.

<table>
<thead>
<tr>
<th>( t_c )</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.049</td>
<td>0.377</td>
<td>0.479</td>
<td>0.528</td>
<td>0.578</td>
<td>0.627</td>
<td>0.676</td>
<td>0.725</td>
<td>0.774</td>
<td>0.824</td>
</tr>
<tr>
<td>40</td>
<td>0.049</td>
<td>0.377</td>
<td>0.426</td>
<td>0.545</td>
<td>0.594</td>
<td>0.643</td>
<td>0.692</td>
<td>0.742</td>
<td>0.791</td>
<td>0.840</td>
</tr>
<tr>
<td>50</td>
<td>0.049</td>
<td>0.377</td>
<td>0.426</td>
<td>0.475</td>
<td>0.606</td>
<td>0.655</td>
<td>0.704</td>
<td>0.753</td>
<td>0.802</td>
<td>0.852</td>
</tr>
<tr>
<td>60</td>
<td>0.049</td>
<td>0.377</td>
<td>0.426</td>
<td>0.475</td>
<td>0.524</td>
<td>0.673</td>
<td>0.722</td>
<td>0.771</td>
<td>0.820</td>
<td>0.869</td>
</tr>
<tr>
<td>70</td>
<td>0.049</td>
<td>0.377</td>
<td>0.426</td>
<td>0.475</td>
<td>0.524</td>
<td>0.573</td>
<td>0.749</td>
<td>0.798</td>
<td>0.847</td>
<td>0.896</td>
</tr>
<tr>
<td>80</td>
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<td>0.377</td>
<td>0.426</td>
<td>0.475</td>
<td>0.524</td>
<td>0.573</td>
<td>0.623</td>
<td>0.807</td>
<td>0.856</td>
<td>0.905</td>
</tr>
<tr>
<td>90</td>
<td>0.049</td>
<td>0.377</td>
<td>0.426</td>
<td>0.475</td>
<td>0.524</td>
<td>0.573</td>
<td>0.623</td>
<td>0.672</td>
<td>0.891</td>
<td>0.940</td>
</tr>
<tr>
<td>100</td>
<td>0.049</td>
<td>0.377</td>
<td>0.426</td>
<td>0.475</td>
<td>0.524</td>
<td>0.573</td>
<td>0.623</td>
<td>0.672</td>
<td>0.721</td>
<td>1.001</td>
</tr>
</tbody>
</table>
Table 3: Damage index when the structure is first hit by cyclone, at $t_c = 20$ years, and then later by earthquake at $t_e$ (variable), when the structure is under continuous exposure to chloride induced deterioration.

<table>
<thead>
<tr>
<th>$t_c$</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
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<td>0.105</td>
<td>0.459</td>
<td>0.508</td>
<td>0.557</td>
<td>0.606</td>
<td>0.655</td>
<td>0.705</td>
<td>0.754</td>
<td>0.803</td>
</tr>
<tr>
<td>40</td>
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<td>0.105</td>
<td>0.154</td>
<td>0.522</td>
<td>0.571</td>
<td>0.620</td>
<td>0.669</td>
<td>0.719</td>
<td>0.768</td>
<td>0.817</td>
</tr>
<tr>
<td>50</td>
<td>0.049</td>
<td>0.105</td>
<td>0.154</td>
<td>0.203</td>
<td>0.559</td>
<td>0.608</td>
<td>0.658</td>
<td>0.707</td>
<td>0.756</td>
<td>0.805</td>
</tr>
<tr>
<td>60</td>
<td>0.049</td>
<td>0.105</td>
<td>0.154</td>
<td>0.203</td>
<td>0.252</td>
<td>0.631</td>
<td>0.680</td>
<td>0.730</td>
<td>0.779</td>
<td>0.828</td>
</tr>
<tr>
<td>70</td>
<td>0.049</td>
<td>0.105</td>
<td>0.154</td>
<td>0.203</td>
<td>0.252</td>
<td>0.302</td>
<td>0.715</td>
<td>0.764</td>
<td>0.813</td>
<td>0.862</td>
</tr>
<tr>
<td>80</td>
<td>0.049</td>
<td>0.105</td>
<td>0.154</td>
<td>0.203</td>
<td>0.252</td>
<td>0.302</td>
<td>0.351</td>
<td>0.771</td>
<td>0.821</td>
<td>0.870</td>
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<td>90</td>
<td>0.049</td>
<td>0.105</td>
<td>0.154</td>
<td>0.203</td>
<td>0.252</td>
<td>0.302</td>
<td>0.351</td>
<td>0.400</td>
<td>0.854</td>
<td>0.903</td>
</tr>
<tr>
<td>100</td>
<td>0.049</td>
<td>0.105</td>
<td>0.154</td>
<td>0.203</td>
<td>0.252</td>
<td>0.302</td>
<td>0.351</td>
<td>0.400</td>
<td>0.449</td>
<td>0.931</td>
</tr>
</tbody>
</table>

Table 4: Factor of safety (FOS) of an interior base column when the structure is first hit by earthquake at $t_e = 20$ years, and then later by cyclone at $t_c$ (variable), under continuous exposure to chloride induced deterioration.

<table>
<thead>
<tr>
<th>Age of the structure (years)</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.677</td>
<td>3.677</td>
<td>3.677</td>
<td>3.677</td>
<td>3.677</td>
<td>3.677</td>
<td>3.677</td>
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</tr>
<tr>
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<td>1.926</td>
<td>1.926</td>
<td>1.926</td>
<td>1.926</td>
<td>1.926</td>
<td>1.926</td>
<td>1.926</td>
</tr>
<tr>
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<td>1.806</td>
<td>1.806</td>
<td>1.806</td>
<td>1.806</td>
<td>1.806</td>
<td>1.806</td>
<td>1.806</td>
</tr>
<tr>
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<td>1.508</td>
<td>1.705</td>
<td>1.705</td>
<td>1.705</td>
<td>1.705</td>
<td>1.705</td>
<td>1.705</td>
</tr>
<tr>
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<td>1.619</td>
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<td>1.619</td>
<td>1.619</td>
</tr>
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<td>1.545</td>
<td>1.545</td>
</tr>
<tr>
<td>70</td>
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<td>1.294</td>
<td>1.264</td>
<td>1.219</td>
<td>1.153</td>
<td>1.483</td>
<td>1.483</td>
<td>1.483</td>
</tr>
<tr>
<td>80</td>
<td>1.287</td>
<td>1.245</td>
<td>1.215</td>
<td>1.171</td>
<td>1.105</td>
<td>1.085</td>
<td>1.431</td>
<td>1.431</td>
</tr>
<tr>
<td>90</td>
<td>1.246</td>
<td>1.204</td>
<td>1.175</td>
<td>1.131</td>
<td>1.066</td>
<td>1.046</td>
<td>0.965</td>
<td>1.388</td>
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<td>1.213</td>
<td>1.171</td>
<td>1.142</td>
<td>1.099</td>
<td>1.035</td>
<td>1.014</td>
<td>0.934</td>
<td>0.804</td>
</tr>
</tbody>
</table>
Table 5: Factor of safety (FOS) of an inner base column when the structure is first hit by cyclone at $t_c = 20$ years, and then later by earthquake at $t_e$ (variable), under the continuous exposure to chloride induced deterioration.

<table>
<thead>
<tr>
<th>Age of the structure (years)</th>
<th>$t_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
</tr>
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<td>3.677</td>
</tr>
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</tr>
<tr>
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<td>1.498</td>
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</tr>
<tr>
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<tr>
<td>90</td>
<td>1.274</td>
</tr>
<tr>
<td>100</td>
<td>1.240</td>
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</tbody>
</table>