INFLUENCE OF CORROSION ON FAILURE MECHANISMS AND LIFETIME SEISMIC FRAGILITY ASSESSMENT OF LOW-DUCTILITY RC FRAMES

S. Shekhar, F. Freddi1\*, J. Ghosh2~~, N. Kotoky~~~~3~~ and D. Lad4

1*Department of Civil, Environmental & Geomatic Engineering, University College London, London, UK*

2*Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India*

3*Department of Civil Engineering, National Institute of Technology Meghalaya, Shillong, India*

4*Department of Civil, Environmental & Geomatic Engineering, University College London, London, UK*

\*Corresponding Author. Tel.: +447752360204. E-mail address: [*f.freddi@ucl.ac.uk*](file:///C:\Users\fredd\Dropbox\000_Now\00_IITB%20PostDoc%20Needhi\Journal%20Paper\f.freddi@ucl.ac.uk)

# ABSTRACT

**Keywords**: Corrosion; Reinforced concrete frames; Seismic retrofit; Fragility curves; Seismic risk variability.

# INTRODUCTION

**Earthquakes** are one of the major catastrophic events that render serious damage to the buildings and infrastructure systems. Across the globe, old reinforced concrete buildings have experienced substantial damage, and in some cases collapse, from seismic events. The **fatality and the monetary** losses directly depend on the exposure conditions of the area experiencing the seismic event [[1], [2], [3]]. The primary cause of building damage, of about 88%, is due to ground shaking which is the major reason for huge economic and human losses [4]. For example, the economic loss was about **120 Billion USD** in Japan due to the 1995 Kobe earthquake [4]. Such a high magnitude of losses can prove detrimental to the economy of the nation as it requires huge funds and time to restore to the pre-seismic conditions. This magnitude of the economic and human loss number can be higher if the **infrastructure systems** and buildings are **not designed for seismic forces** and ageing effects like corrosion*.* Recognizing this fact, a study in the domain of seismic hazard assessment of ageing infrastructure like bridges has been done by various researchers – as these are vital aspects economically and strategically for the nation [[5], [6], [7], [8]]. Hence, seismic vulnerability assessment for RC structures is important as they have exposure to high fatality numbers during an earthquake event.

RC structures, *viz.* buildings, can experience **corrosion** which causes deterioration of the structure over a long period which in turn reduces the life of the structure [[9,10]]. Corroded reinforced concrete (RC) structures are highly susceptible to extreme damage conditions compared to the new pristine structure (or recently constructed) during a seismic event; this is aggravated with low ductility which is designed as per the traditional codes (non-seismic design) [[11], [5], [12]]. When located in an aggressive environment, the seismic risk of the **existing RC building** increases with the level of corrosion which invariably reduces the service life of the building structure [[13], [14]]. Hence, exposure of such RC building to the future seismic event makes it vulnerable with the combined effect of non-seismic design and deterioration effect due to corrosion. Thus, it is necessary to carry out vulnerability checks to access the danger due to future hazardous events so that acceptable repair and retrofit measures can be done on this existing structure.

Corrosion of rebars in an RC member (especially columns of building) reduces the effective cross-sectional area of the rebars which invariably affects the strength and performance of the structure under lateral load.Corrosionin longitudinal reinforcement and transverse reinforcement have different deterioration effects on the failure mechanism. Experimental test carried on corroded columns based on percentage mass loss only in **longitudinal reinforcement** shows that there is a significant reduction in the flexural strength of columns, reduction in energy dissipation and drift capacity [[15], [16], [17]]. As **transverse reinforcement** has a higher probability of being corroded before the longitudinal reinforcement due to the smaller distance to the corrosive atmosphere, there is a significant change in the behavior of the column having corrosion in both reinforcements. This gap was studied by Vu and Li (2018) [[18], [19]] and it was found that the 25% corrosion level in transverse reinforcement (stirrups) can significantly reduce the lateral load capacity and, in addition, change the failure mechanism from flexure to **flexure-shear failure**. It was also found, in the same study, that under high axial load columns with high corrosion faced sudden **axial failure**. Thus, modelling of **shear properties** becomes imperative for studying the effect of corrosion on the shear capacity of the RC members. These modelling techniques for shear are discussed in various research papers [[20], [21], [22]] which accounts for the **flexure-shear interaction of columns** during the application of lateral or cyclic load on the columns.

Until now major research was done in **single-column** tested under axial load with cantilever action or double curvature. Few experimental research works were conducted to study the seismic performance of corroded **moment**-**resisting frames** considering the effect of corrosion. Karapetrou et al. (2016) [23] provided a detailed study on low, mid and high rise 2-dimensional frames by considering probabilistic modelling of corrosion for assessing the seismic performance using increment dynamic analysis (IDA). Modelling of 2D non-linear beam-column frames was done in OpenSees [24] with fiber sections with a fixed base and soil-structure interaction (SSI). It was found that by incorporating the SSI parameters will hugely affect the expected seismic fragility of the frames. The study, done by Couto et al. (2020) [25], carried out the sensitivity analysis of corrosion rate on the vulnerability assessment of RC building frames (three types – low, mid and high rise) in Portugal. Non-linearity in fiber section modelling and rebar area reduction was considered for studying the corrosion effect on these ageing frames while doing the vulnerability assessment. It was found that the seismic vulnerability increases by 20% due to corrosion. Another research by Di Sarno and Pugliese (2020) [26] had conducted a numerical evaluation of RC building frames for a different level of exposure, different field motions and degradation with smooth rebars. A new approach of defining material in the finite element modelling (FEM) was discussed in the paper to account for the degradation effects and surrogate modelling was used to capture maximum shear. It was shown that the seismic vulnerability increases by 39% to 63% at 25 years of age depending on the type of field motions adopted during the assessment. Afsar Disaj et al. 2021 [27] on the other hand plotted the fragility curves considering the combined effects of naturally occurring sequential main shock – aftershock (MS-AS) and progressive deterioration due to corrosion for single bay RC frame. This study incorporated the effect of bond-slip phenomena based on the model by Zhoa and Sritharan (2007) [28]. It was concluded that the seismic fragility is slightly higher for MS-AS analysis compared to MS analysis. These studies on RC frames do not comment on the shear failure that occurs in old structures which **are low in ductility due to non-seismic design**. Research work on single columns expounds on the change in the behavior in failure from flexure to flexure-shear under the influence of corrosion as discussed earlier. There arises a need to study the failure mechanism of existing RC frames due to seismic loading with low ductility which is vulnerable to shear failure. Hence, this study tries to fill the gap by modelling low ductile frames which predominantly fail under shear during a seismic event. Also, in the present study, non-linear time history analysis (NLTHA) and time-dependent fragility curves for corroded and non-corroded frames will be carried out to study the effect of the earthquake on the low ductile frame.

# FRAMEWORK FOR LIFETIME SEISMIC VULNERIBILITY ASSESSMENT

# CASE STUDY STRUCTURE: DESCRIPTION, DETERIORATION MECHANISMS AND FINITE ELEMENT MODELLING

~~From the post-earthquake investigations carried out by several researchers point out, critically, the strong beam/weak column joint present in the structure as the common failure mechanism. This type of failure is independent of the geometric and mechanical properties of the building which are predominantly not designed for the seismic loads [22,29]. The older version of the codes did not have sufficient seismic detailing which causes the designed frames/joints to be low in ductility. The building designed pre-1989 (ACI times) did not consider seismic forces, thus the columns are primarily designed for axial loading. But columns are important members to transfer the high lateral loads due to horizontal movement of the earthquake action which determines the seismic performance of the RC building [30].~~

~~Corrosion has been observed to be the most significant and primary environmental degradation factor (including corrosion due to chloride ingress and carbonation of concrete surface) which adversely affect building’s mechanical property, especially the strength over a long period which is considered as the ageing effect [31,32]. Corrosion of an RC frame causes reduction of ductility, loss of rebar area, breakage of the bond between rebar and the surrounding concrete, spalling of concrete cover which eventually leads to loss of cover and the rebar is exposed directly to the atmosphere. This reduces the noteworthy load-carrying capacity of the RC frame against the lateral load which leads to a precarious brittle failure mechanism [11,33,34].~~

~~This premature degradation of RC buildings due to corrosion is a major concern for safety against earthquakes and subsequently the negative environmental impact it has due to its material consumption in retrofit and repairs. This premature deterioration of RC structure due to corrosion only was found to be 70-90% of the investigated cases [32]. It was estimated that a total value of $2.5 trillion (USD) is the cost of corrosion globally, and this is equivalent to 3.4% of the global GDP. However, for some countries, it can be as high as 5% of their annual GDP [35]. This when combined with the seismic event, the corrosion cost can be much higher and, in addition, cause human losses. Thus, the present study considers a three-storey three-bay RC moment resisting frame which is a low ductile frame (~~*~~viz~~*~~. non-seismically designed) and low-rise building [22]. The frame is considered to be in the California region where it is exposed to significant seismic activity and corrosion due to coastal conditions.~~

The impact of corrosion deterioration on the lifetime seismic vulnerability of RC frame is demonstrated through a representative case-study RC frame assumed to be located in the coastal region of California, US. The case-study frame is non-seismically designed (low-ductility) and representative of typical constructions practices in several areas of the USA as well similar earthquake-prone regions in Europe, and Asia prior to the introduction of modern seismic design codes. Past experimental studies and earthquake investigation reports highlighted varied failure modes in these non-ductile frames [22,29]. Due to lack of seismic design, typically the failure modes in these buildings are related to strong beam/weak column hierarchy, with beams designed to resist the bending actions and columns sized to predominantly carry axial loads, and lack of seismic detailing, such as insufficient transverse reinforcement in columns and beam-column joints, inadequate anchorage length and hooks for reinforcement, lap splices in potential plastic-hinge regions of columns, among others. In addition to seismic hazard threats when located in close proximity to marine sources, the lateral load carrying capacity of these non-ductile buildings are further reduced during design service life due to corrosion deterioration. Corrosion of RC frame can cause significant reduction in the cross-sectional area of reinforcing steel and several secondary effects such as loss of cover and core concrete strength, reduction of yield or ultimate strength and ductility of steel reinforcement, and loss of bond strength, among others. Such effects significantly reduces the load-carrying capacity of the RC frame against the lateral load that may lead to a precarious brittle failure mechanism [11,33,34]. The following subsections first describe the representative case-study frame geometry. Next, the time-dependent deterioration modeling of the RC frame due to corrosion is discussed, followed by the finite element modeling approach.

## Description of the Case-Study Frame

Figure 1 shows the layout of the case study frame adopted from Bracci et al. [36]. The selected three-storey three bays RC moment resisting frame is representative of non-seismically designed (low-ductility) low-rise RC buildings. The frame has a total height of 10.75 m (35.3 feet) with an interstorey height of 3.66 m (12 feet) and a constant bay width equal to 5.49 m (18 feet). The building frame is designed for gravity loads only following the pre-seismic design provisions of ACI 318-89 [37]. The column sizes are 300 x 300 mm and the beam sizes are 230 x 460 mm at each floor. The concrete design compressive strength is 24 MPa, and the longitudinal reinforcing bar of steel Grade 40 has yield strength of 276 MPa. Further reinforcement details of the case study frame as shown in Figure 1 are adopted from Bracci et al. [36] and Aycardi et al. [38]. As evident from the figure, columns and beam-column joints have insufficient transverse reinforcement, inadequate anchorage length and hooks for reinforcement, and lap splices in potential plastic-hinge regions thereby highlighting lack of seismic detailing. The next subsection introduces the corrosion deterioration mechanism of the case-study frame.

|  |
| --- |
|  |
| Figure 1. Case-study frame layout adapted from Bracci et al. [CITE] |

## Time-Dependent Deterioration Modeling of the Case-Study Frame

When located in adverse environmental conditions, RC buildings are subjected to time-dependent aging and degradation. The aging and deterioration process of RC structures manifest in the form of corrosion, and other physical and chemical deterioration. Among these, corrosion deterioration due to the ingress of chloride ions constitutes a dominant form of degradation of RC structures [CITE Stewart and Rosowsky 1998a; Choe et al. 2009; Akiyama et al. 2011]. Sources of chlorides may stem from marine environments, or airborne chloride that constitute common exposure scenarios for RC buildings located in the coastal area of case-study region of California. Accordingly, this study considers chloride-induced corrosion as the primary form of time-dependent degradation of the case-study building frame. Corrosion pdeterioration in RC structures begins after a time interval known as the corrosion initiation time (*Tinit*). Chloride ions gradually penetrate the concrete cover during this time, depassivating the reinforcing steel and initiating corrosion. This study uses the widely adopted probabilistic model proposed by Duracrete [CITE] to predict corrosion initiation time represented as:



where, *cv* is the concrete cover depth in mm, *Dcl,*0 is the diffusion coefficient at *t*0 = 28 days in mm2/year determined from compliance test*, kt* is the correction factor of tests performed to estimate *Dcl*,0, *ke* and *kc* are environmental and curing factor, *ncl* is the age exponent considering densification of cement paste due to hydration chloride, *Cs* is the equilibrium chloride concentration at the exposed concrete surface, *Ccr* is the critical chloride concentration, and *erf* is the Gaussian error function. This study assumes marine splash environmental condition and probabilistic distribution of the parameters to estimate corrosion initiation time are adopted from Duracrete [CITE] and reported in **Table 1.**

**Table 1. Probability distribution of the parameters involved to estimate corrosion initiation time and rate of corrosion.**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***Dcl*,0: Reference chloride diffusion coefficient for *w/c* ratio = 0.50** [39] | | | | | | |
| Distribution: *Normal* (𝜇, 𝜎) | 𝜇 | | | 𝜎 | | |
| 473.0 *mm*2/*year* | | | 43.2 × 10-12 *m*2/*s* | | |
| ***ke*: Environmental correction factor** [39] | | | | | | |
| Distribution: *Gamma* (𝛼, 𝛽)† | 𝛼 | | | 𝛽 | | |
| 2.92 | | | 11.0 | | |
| † *Gamma* (𝛼,𝛽) refers to Gamma distribution with shape parameter 𝛼 and inverse scale parameter 𝛽 | | | | | | |
| ***kc*: Correction factor for curing time** **(*At age* 7 *days*)** [39] | | | | | | |
| Distribution: *Beta* (*a, b, p, q*)‡ | *a* | *b* | *p* | | | *q* |
| 1.0 | 4.0 | 2.15 | | | 10.7 |
| ‡*Beta* (*a, b, p, q*) refers to a four-parameter Beta distribution with *a* and *b* representing the upper and lower bounds, and *p* and *q* representing the shape parameters | | | | | | |
| ***ncl*: Aging factor or age exponent** [39] | | | | | | |
| Distribution: *Beta* (*a, b, p, q*) | *a* | *b* | *p* | | | *q* |
| 0.0 | 1.0 | 17.2 | | | 29.3 |
| ***Ccr*: Critical chloride concentration (% relative to binder)** [39] | | | | | | |
| Distribution: *Normal* (𝜇, 𝜎) | 𝜇 | | | 𝜎 | | |
| 0.50 | | | 0.10 | | |
| ***Cs*: Surface chloride concentration (% relative to binder)** (Duracrete, 2000) | | | | | | |
| Calculated as *Cs* = *Acs* (*w/b*) + *εcs*, where *w/b* is the water-binder ratio (assumed as 0.5 in this study), *Acs* is chloride surface content regression parameter and *εcs* is the error term for surface chloride concentration. These two parameters are described below. | | | | | | |
| ***Acs*: Chloride surface content regression parameter (% relative to binder)** (Duracrete, 2000) | | | | | | |
| Distribution: *Normal* (𝜇, 𝜎) | 𝜇 | | | | 𝜎 | |
| 7.76 | | | | 1.36 | |
| ***𝜺cs* : Chloride surface content error term** (Duracrete, 2000) | | | | | | |
| Distribution: *Normal* (𝜇, 𝜎) | 𝜇 | | | | 𝜎 | |
| 0 | | | | 1.11 | |
| ***cv*: Concrete cover depth (mm)** | | | | | | |
| Distribution: *Lognormal* (*λ, ζ*) | ***λ*** | | | | *ζ* | |
| 3.62 and 3.84 | | | | 0.2 | |
| Parameters *λ* and *ζ* are the mean and standard deviation of the corresponding Normal distribution. The reported values of the parameters correspond to a mean cover depth of 38.1 and 47.61 mm for transverse and longitudinal steel respectively, and a coefficient of variation of 0.20 | | | | | | |
| ***icorr* : Corrosion rate (µA/cm2)** (Duracrete, 2000) | | | | | | |
| Distribution: *Lognormal* (*λ, ζ*) | ***λ*** | | | | *ζ* | |
| 0.766 | | | | 0.60 | |
| Parameters *λ* and *ζ* are the mean and standard deviation of the corresponding Normal distribution. The reported values of the parameters correspond to a mean corrosion current density of 2.586 **(**µA/cm2**)** and a coefficient of variation of 0.60 | | | | | | |

Considering uncertainty of the above-mentioned parameters, a Monte Carlo simulation is carried out to estimate the mean corrosion initiation time for longitudinal and transverse reinforcement of columns. Figure 2 (a) shows the simulated corrosion initiation time for transverse steel reinforcement having mean cover depth of 38.1 mm. Using Lilliefors test, a lognormal distribution with mean of 10 years is found to be a good fit to the simulated data for corrosion initiation time of transverse steel reinforcement. In similar way, the mean corrosion initiation time for longitudinal steel reinforcement is estimated as 14 years. Note that a lower initiation time is expected for transverse steel as it is located closer to the outside environment as compared to longitudinal reinforcement (See column details in Figure 1).

|  |  |
| --- | --- |
|  |  |
| **(a)** | **(b)** |
| **Figure 2 (a) Distribution of corrosion initiation time for transverse reinforcement, and (b) Variation of mean longitudinal and transverse steel area with time along with the lower and upper limits of the uncertainty band representing 5th and 95th percentile confidence bounds.** | |

Following the initiation phase, the corrosion propagation phase is marked by the formation of small independent pits or cracks along the steel rebar that with time lead to wider cracks resulting in uniform corrosion [40] [CITE]. The cross-sectional area of reinforcing steel at time *t* [*Ast*(*t*)] can be estimated as:



where, *D*0 is the diameter of the uncorroded reinforcing steel, *t* is the elapsed time and *Tinit* is the corrosion initiation time [Equation ] in years, and *icorr* is the corrosion current density in µA/cm2. While several corrosion rate models are available in the literature [CITE], to maintain consistency with corrosion initiation model, the corrosion rate is also adopted from Duracrete [CITE] and reported in Table 1. Note that non-uniform pitting corrosion of steel reinforcement is not studied in this work for the sake of simplicity. However, based on recommendations of Dizaj et al. [CITE] when modelling uniform corrosion other implications of non-uniform pitting corrosion such as the reduction in steel strength and ductility are explicitly included in this work as elaborated later. Figure 2 (b) shows the variation of mean reinforcing steel area (longitudinal and transverse) with time along with the lower and upper limits of the uncertainty band representing 5th and 95th percentile confidence bounds after incorporating the uncertainties in the corrosion deterioration process, as mentioned in Table 1. The effect of area loss of reinforcement is more pronounced for smaller diameters [CITE], thus higher percentage area loss is observed for transverse steel as evident in the figure. At the end of 50 years, 19% and 38% reduction in area loss is observed for longitudinal and transverse reinforcement of columns, signifying the necessity of considering corrosion deterioration in the lifetime seismic vulnerability assessment of RC buildings.

In addition to the primary effect of corrosion deterioration through area loss of longitudinal and transverse reinforcement, the present study also considers several secondary effects such as the reduction in concrete core and cover strength, and reduction in steel strength and ductility. Expansive rust products formed due to rebar corrosion results in the generation of micro-cracks that can lead to a reduction in cover concrete strength and even spalling of concrete over time. The deterioration of cover concrete strength is evaluated using the model proposed by [41][CITE]. The concrete core strength is a function of the volumetric ratio of transverse reinforcement (stirrups) and undergoes a time-dependent reduction due to corrosion deterioration. This time-dependent loss in core concrete strength is estimated based on the modified theoretical stress-strain model proposed by [42][CITE], as subsequently adopted by other researchers [CITE]. Reduction in steel mechanical properties due to corrosion deterioration along the rebar length are manifested through changes in yield strength, ultimate strength, and ultimate strain. This study utilizes Du et al. [CITE] time-dependent model for steel strength reduction, in which yield and ultimate strength decreases linearly with mass loss. In contrast, the ultimate strain reduction in steel does not follow a linear reduction, as past research revealed that strain reduction values are scattered over a large range [CITE Andisheh et al. 2016]. As a result, this research incorporates Apostolopoulos and Papadakis [CITE] experimental findings, which imply a nonlinear reduction in ultimate strain with percentage mass loss of reinforcing steel. At the end of service life (50 years), the deteriorated RC columns also undergo XX%, XX%, XX%, and XX% mean reduction in the cover concrete strength steel strength, ultimate strain, and shear strength, respectively (Figure 3), signifying the need to consider these secondary effects in the lifetime performance assessment of RC frame buildings.

|  |
| --- |
|  |
| **Figure 3**. **Time-dependent variation of columns cover concrete strength steel strength, ultimate strain, and shear strength** |

In addition to the above secondary effects, corrosion deterioration in RC columns may also result in bond strength reduction, buckling strength reduction, and low-cycle fatigue degradation, among others [CITE Fang et al. 2004; Kashani et al. 2015]. This study neglects the inclusion of loss of bond strength for deteriorating columns, since such effects have insignificant influence on the seismic fragility of RC frames [CITE]. The phenomenological model for capturing buckling strength and low-cycle fatigue degradation due to corrosion [CITE Kashani et al. 2015] are applicable only for corroded bare reinforcing steel, and further experimental tests are needed to verify this model for corroded RC members, consequently not considered in this study. The next section of the paper explains the analytical modeling of the case-study aging building frame.

## Analytical Modeling of the Case-Study RC Frame

A two-dimensional high-fidelity finite element model of the case-study frame is developed using the finite element (FE) package OpenSees [CITE McKenna, Fenves, & Scott, 2000]. The FE model strategy for the case-study frame follows the modelling suggestions presented in Freddi *et al.* [CITE 2021] that focus on better prediction of the local seismic response of structural components, including brittle failure mechanisms that are typical of low-ductility RC MRFs. The adopted high-fidelity modeling strategy enables modelling of local failure mechanisms that helps to monitor the influence of corrosion deterioration of building components on the global response parameters. The following sections first provide details of finite element modeling of the pristine frame followed by discussion on incorporation of deterioration effects in the FE modeling of corroded frame. The next sub-section provides validation of FE model with past experimental results.

### FE modeling of case-study frame incorporating corrosion deterioration effects

Figure 4 shows the schematic representation of the FE model highlighting modeling details of the different components such as beam and column sections, interior and exterior beam-column joints, and shear and axial springs. The non-linear flexural response of columns is captured using *nonLinearBeamColumn* element that considers the spread of plasticity along the length of the element. The column section is modeled using a fiber section that includes cover and core concrete patches and layers of reinforcement (Figure 4). Both unconfined cover concrete and confined core concrete are modeled using *Concrete02* material, and confined concrete parameters are calculated based on Mander et al. (1988) [CITE]. Steel reinforcements are modelled using the *uniaxialMaterial Hysteretic* material capable of capturing pinching of force and deformation, damage due to ductility and energy, and degraded unloading stiffness based on ductility. The pinching, strength, and stiffness degradation parameters for case-study frame columns are calibrated based on experimental result of Aycardi et al. [CITE] and mentioned in Freddi et al. [CITE 2013]. Beams are modeled using *beamWithHinges* elementthat consists of a central elastic element and two plastic hinge regions at the elements ends defined by fiber sections. The plastic hinge of beams is evaluated based on model proposed by Panagiotakos and Fardis [CITE], and fiber sections are defined similar to the approach adopted in columns with *Concrete02* material used to model core and cover concrete and *uniaxialMaterial Hysteretic* material used to model steel reinforcement. The slab is modeled using unconfined concrete material model with an effective width equal to four times the beam's width, as recommended in the ACI 318-89 [CITE]. The rigid-floor diaphragm is modeled by assigning high axial stiffness to the beams. Gravity loads are distributed on the beams while masses are concentrated at the beam-column intersections.

|  |
| --- |
|  |
| Figure 4. Overview of the numerical modeling strategy for case-study frame. |

For the deteriorated RC beams and columns, the consequences of chloride-induced corrosion, such as area loss of steel and various secondary effects outlined previously in Section 3.2, are incorporated along with the associated uncertainties. The effect of corrosion is assumed to be uniformly distributed around the perimeter of beams and columns. The area loss of steel due to corrosion is modeled as a uniform reduction in rebar diameter along the circumference and includes the corrosion rate time-dependent uncertainty (Table 1 and **Figure 2**). The finite element modeling of the degraded frame also includes the outlined secondary effects of corrosion deterioration, such as rebar strength and ductility loss, as well as loss of cover and core concrete strength. The loss of strength and ductility of rebars is captured by calculated the time-dependent strength and ductility of reinforcement [Figure 3], and updating the parameters of the *uniaxialMaterial Hysteretic* material used to model reinforcing steel. The time-dependent core concrete strength due to corrosion of transverse reinforcement is incorporated by updating the parameters of *Concrete02* material model used to define the column core. The loss of cover strength due to the formation of expansive rust products is modeled by calculating the time-dependent strength of cover concrete [Figure 3], and then updating the parameters of *Concrete02* material used to define column cover concrete.

While the above fiber section-based modeling of a RC section is capable of capturing the nonlinear flexural deformation, non-seismically designed low-ductility frames may also exhibit nonlinear behaviour due to column shear failure and loss of gravity load-bearing capability [CITE Elwood 2004]. Consequently, a zero-length shear spring (element *zeroLength* in OpenSees) is placed in series with the column flexure element as shown in Figure 4. The *uniaxial* *LimitState* material model is assigned to these springs that monitors columns response and triggers only when column response reaches the pre-defined shear and axial failure curves, implemented within OpenSees as *limitCurve Shear* and *limitCurve Axial*, respectively. Note that the existing *limitCurve Shear* model is modified such that shear failure is triggered when column response reaches either the strength or drift limit curves [CITE Freddi et al. 2021]. While the shear strength limit curve is based on the model proposed in ASCE-41, the deformation limit curve is defined based on an empirically derived force-deformation controlled limit curve given by Elwood [CITE]. Both strength and drift shear limit curves depends on parameters such as column transverse reinforcement, column axial load, section dimensions, material properties, among others, and therefore, are affected by column corrosion deterioration. The considered FE modeling approach considers this degradation of shear limit curves during the nonlinear analysis. The degrading slope of the total response (*Ktdeg* in Figure XX) is calculated using the shear-friction model proposed by Baradaran-Shoraka and Elwood [CITE]. The degrading stiffness of shear spring response (*Kdeg* in Figure XX) is estimated from the degrading slope of the total response *Ktdeg* and the unloading stiffness of flexural response (*Kunload*) [CITE Elwood 2004]. Also, the residual strength is defined as 20 percent of the nominal shear strength to alleviate convergence issues in OpenSees [CITE Jeon et al. 2015].

To model the low-ductility joints for the RC frame, a two-node *zeroLength* rotational joint spring and four rigid offsets is used as illustrated in the work done by Jeon et al. [CITE]; and shown in Figure 4. In this model, beams and columns are continuous, while the joint model controls their relative rotation. Low ductility can arise due to insufficient traverse reinforcement and short embedded lengths of reinforcement within the beam-column joints. To account for the short anchorage length, a reduced shear strength is considered as suggested by Jeon et al. [CITE]. Also, to account for the pinching behavior *Pinching4* [24] material model is used in the beam-column joint response as shown in Figure 4. The present study doesn’t consider influence of corrosion deterioration of joints on seismic response and is left for future exploration.

### Validation with past experimental studies

For the purpose of validating the OpenSees [24] modelling technique of simulating the shear-critical response, four square RC columns are analyzed under cyclical loading to validate the flexure-shear response (*flexures-shear interaction FSI)*. The columns for validation are selected based on the flexure-shear failure and includes uncorroded and corroded specimens. Table 3.1 gives the basic details and properties of the selected specimens used for the validation exercise. Specimen U2 and C5 are of similar properties but U2 is tested without any corrosion and C5 is tested with corrosion of rebars [19]. Specimen S1 is a pristine column with no corrosion while CC1 is a short column with corrosion which is expected to observe shear failure. All the columns information is taken from the experimental test research so help verify the modelling aspect adopted in this study.

~~Figure 3.1a and 3.1b are the pushover and shear limit plots for each specimen; from the plots, it can be concluded all the specimens observe flexure-shear failure. That is, lateral load capacity for each specimen intersects with the shear limit curve calculated as per by Sezen Moehle 2004.~~

The plots of Figure 3.1a and 3.1b are hysteric plots for all the column specimens modelled as per the description in the above section. Particularly from Figure 3.1a – specimen S1 – it can be illustrated that the column with low ductility will have a sharp decrease in lateral load capacity after reaching the shear limit. The hysteric plot for S1 is a good match validating our aim of modelling shear element and bar-slip section for the analysis. However, the hysteric plot of C5, CC2 and U2 does not have a good match with the experimental results. Also, the peak lateral load of the test is always higher for these three specimens and the initial stiffness upto the elastic range is clearly visible to be higher than that of the stiffness observed in the experimental curve. Part of the reason can be attributed to the experimental setup where the ends are not fully rigid and there is a presence of rigid body rotation at the fixed end. Another reason for the overprediction of the peak lateral strength would be the inelastic deformation in the reinforcement bars. However, the deterioration and pinching phenomena is well captured in all of the hysteric plots, but the drawback remains in modelling which required manual inputs of these parameters to match with the experimental results. To summarize, the modelling discussed in the above section captures the flexure-shear failure in a satisfactory manner that can be extended to the frame under this study.

**Table 3.1 Database of the columns selected for the validation exercise**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Specimen | U2 | C5 | CC2 | S1 |
| Reference | Vu and Li (2018a) [19] | Vu and Li (2018a) [19] | Vu and Li (2018b) [18] | Sezen and Moehle (2006) [43] |
| Section, *b x h* (mm x mm) | 350 | 350 | 350 | 457 |
| Column length, *l* (mm) | 1780 | 1780 | 1080 | 2946 |
| Experiment test configuration | Double Curvature | Double Curvature | Double Curvature | Double Curvature |
| Shear span to depth ratio, (*a/d*) | 3.18 | 3.18 | 1.93 | 3.74 |
| Concrete strength (MPa) | 38.1 | 31.3 | 28.8 | 21.1 |
| Longitudinal reinforcement | 20φ – 8nos | 20φ – 8nos | 20φ – 8nos | 28.7φ – 8nos |
| Yield strength of long bar ( | 550 | 550 | 550 | 438 |
| Ultimate strength of long bar( | 635 | 635 | 635 | 645 |
| Transverse reinforcement | φ7.8@50 | φ7.8@50 | φ7.8@50 | φ8@305 |
| Yield strength of trans reinf. ( | 300 | 276.8 | 267.8 | 476 |
| Ultimate strength of trans reinf. ( | 465 | 465 | 465 | 645 |
| Nominal Cover, (mm) | 32.8 | 32.8 | 32.8 | 34.9 |
| Axial Load, *P* (kN) | 958.6 | 1165 | 352.8 | 667 |
| Corrosion level-transverse (%)\* | - | 15.5% | 21.4% | - |
| Corrosion level longitudinal (%)\* | - | 3.9% | 3.1% | - |
|  |  |  |  |  |
| Ductility ratio | 4.2 | 3.6 | 2.32 | 2.88 |
| Yield displacement, (mm) | 24.92 | 13.3 | 17.5 | 26 |

|  |  |  |  |
| --- | --- | --- | --- |
| **A** |  | **B** |  |
| **C** |  | **D** |  | |
| **Figure 3 – A) S1 B) U2 C) C5 D) CC2** | | | | |

~~Seismic importance~~

~~Experimental test of RC frames and discuss its results~~

~~Gap to be filled and motivation~~

* ~~Building deterioration versus the infra systems~~
* Recent studies on Building corrosion deterioration
* ~~Lacking in for RC building~~
* ~~Low ductile frames (cause of old of existing frames)~~

Key motivations – need to add more points

~~NON-ductile frame building; dollar loss; loss of due to non-ductile; close to marine conditions which aggravates corrosion. Several experimental of frames; ageing and corrosion may decrease life; recognizing this fact several experimental study;~~

~~Social impact of erthquake events~~

~~Seismic design evolution impact~~

6.2ht cm and 8.29 cm wt . Line width 1.5; Time new roman 16

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

# ACKNOWLEDGEMENT

# REFERENCES

1. Freddi F, Novelli V, Gentile R, Veliu E, Andreev S, Andonov A, *et al.* Observations from the 26th November 2019 Albania earthquake: the earthquake engineering field investigation team (EEFIT) mission. *Bulletin of Earthquake Engineering* 2021; **19**(5): 2013–2044. DOI: 10.1007/s10518-021-01062-8.

2. Rao A, Dutta D, Kalita P, Ackerley N, Silva V, Raghunandan M, *et al.* Probabilistic seismic risk assessment of India. *Earthquake Spectra* 2020; **36**(1\_suppl): 345–371. DOI: 10.1177/8755293020957374.

3. Rossetto T, Ioannou I, Grant D, Maqsood T. Guidelines for the empirical vulnerability assessment 2014.

4. Bird JF, Bommer JJ. Earthquake losses due to ground failure. *Engineering Geology* 2004; **75**(2): 147–179. DOI: 10.1016/j.enggeo.2004.05.006.

5. Shekhar S, Ghosh J, Ghosh S. Impact of Design Code Evolution on Failure Mechanism and Seismic Fragility of Highway Bridge Piers. *Journal of Bridge Engineering* 2020; **25**(2): 04019140. DOI: 10.1061/(ASCE)BE.1943-5592.0001518.

6. Panchireddi B, Ghosh J. Probabilistic seismic loss estimation of aging highway bridges subjected to multiple earthquake events. *Structure and Infrastructure Engineering* 2021; **17**(9): 1155–1174. DOI: 10.1080/15732479.2020.1801765.

7. Ranjkesh SH, Asadi P, Hamadani AZ. Seismic collapse assessment of deteriorating RC bridges under multiple hazards during their life-cycle. *Bulletin of Earthquake Engineering* 2019; **17**(9): 5045–5072. DOI: 10.1007/s10518-019-00647-8.

8. Zhang Y, DesRoches R, Tien I. Impact of corrosion on risk assessment of shear-critical and short lap-spliced bridges. *Engineering Structures* 2019; **189**: 260–271.

9. Broomfield J. *Corrosion of steel in concrete: understanding, investigation and repair*. CRC Press; 2003.

10. Poursaee A. Corrosion of steel in concrete structures. *Corrosion of Steel in Concrete Structures*, Elsevier; 2016. DOI: 10.1016/B978-1-78242-381-2.00002-X.

11. Yalciner H, Sensoy S, Eren O. Seismic Performance Assessment of a Corroded 50-Year-Old Reinforced Concrete Building. *Journal of Structural Engineering* 2015; **141**(12): 05015001. DOI: 10.1061/(ASCE)ST.1943-541X.0001263.

12. Shekhar S, Agarwal P. Seismic vulnerability analysis of bridge pier designed with different codal provisions. *The Bridge and Structural Engineer* 2015; **45**(1): 77–85.

13. Couto R, Requena-García-Cruz MV, Bento R, Morales-Esteban A. Seismic capacity and vulnerability assessment considering ageing effects: case study—three local Portuguese RC buildings. *Bulletin of Earthquake Engineering* 2021; **19**(15): 6591–6614. DOI: 10.1007/s10518-020-00955-4.

14. Faroz SA. Assessment and Prognosis of Corroding Reinforced Concrete Structures through Bayesian Inference. *PhD Thesis*. Indian Institute of Technology Bombay, Mumbai, India, 2017.

15. Goksu C, Ilki A. Seismic Behavior of Reinforced Concrete Columns with Corroded Deformed Reinforcing Bars. *ACI Structural Journal* 2016; **113**(5). DOI: 10.14359/51689030.

16. Yang SY, Song XB, Jia HX, Chen X, Liu XL. Experimental research on hysteretic behaviors of corroded reinforced concrete columns with different maximum amounts of corrosion of rebar. *Construction and Building Materials* 2016; **121**: 319–327. DOI: 10.1016/j.conbuildmat.2016.06.002.

17. Meda A, Mostosi S, Rinaldi Z, Riva P. Experimental evaluation of the corrosion influence on the cyclic behaviour of RC columns. *Engineering Structures* 2014; **76**: 112–123. DOI: 10.1016/j.engstruct.2014.06.043.

18. Vu NS, Li B. Seismic Performance Assessment of Corroded Reinforced Concrete Short Columns. *Journal of Structural Engineering* 2018; **144**(4): 04018018. DOI: 10.1061/(ASCE)ST.1943-541X.0001994.

19. Vu NS, Li B. Seismic Performance of Flexural Reinforced Concrete Columns with Corroded Reinforcement. *ACI Structural Journal* 2018; **115**(5). DOI: 10.14359/51702372.

20. Xu JG, Wu G, Feng DC, Cotsovos DM, Lu Y. Seismic fragility analysis of shear-critical concrete columns considering corrosion induced deterioration effects. *Soil Dynamics and Earthquake Engineering* 2020; **134**: 106165. DOI: 10.1016/j.soildyn.2020.106165.

21. Li Q, Niu D tao, Xiao Q hui, Guan X, Chen S jie. Experimental study on seismic behaviors of concrete columns confined by corroded stirrups and lateral strength prediction. *Construction and Building Materials* 2018; **162**: 704–713. DOI: 10.1016/j.conbuildmat.2017.09.030.

22. Freddi F, Ghosh J, Kotoky N, Raghunandan M. Device uncertainty propagation in low‐ductility RC frames retrofitted with BRBs for seismic risk mitigation. *Earthquake Engineering & Structural Dynamics* 2021; **50**(9): 2488–2509. DOI: 10.1002/eqe.3456.

23. Karapetrou S, Manakou M, Bindi D, Petrovic B, Pitilakis K. “Time-building specific” seismic vulnerability assessment of a hospital RC building using field monitoring data. *Engineering Structures* 2016; **112**: 114–132. DOI: 10.1016/j.engstruct.2016.01.009.

24. McKenna F, Fenves GL, Scott MH, others. Open system for earthquake engineering simulation. *University of California, Berkeley, CA* 2000.

25. Couto R, Requena-García-Cruz MV, Bento R, Morales-Esteban A. Seismic capacity and vulnerability assessment considering ageing effects: case study—three local Portuguese RC buildings. *Bulletin of Earthquake Engineering* 2020. DOI: 10.1007/s10518-020-00955-4.

26. Di Sarno L, Pugliese F. Numerical evaluation of the seismic performance of existing reinforced concrete buildings with corroded smooth rebars. *Bulletin of Earthquake Engineering* 2020; **18**(9): 4227–4273. DOI: 10.1007/s10518-020-00854-8.

27. Afsar Dizaj E, Salami MR, Kashani MM. Seismic vulnerability assessment of ageing reinforced concrete structures under real mainshock-aftershock ground motions. *Structure and Infrastructure Engineering* 2021: 1–17. DOI: 10.1080/15732479.2021.1919148.

28. Zhao J, Sritharan S. Modeling of strain penetration effects in fiber-based analysis of reinforced concrete structures. *ACI Materials Journal* 2007; **104**(2): 133.

29. Elwood KJ, Moehle JP. Drift Capacity of Reinforced Concrete Columns with Light Transverse Reinforcement. *Earthquake Spectra* 2005; **21**(1): 71–89. DOI: 10.1193/1.1849774.

30. Dai KY, Yu XH, Lu DG. Phenomenological hysteretic model for corroded RC columns. *Engineering Structures* 2020; **210**: 110315. DOI: 10.1016/j.engstruct.2020.110315.

31. Saetta A, Simioni P, Berto L, Vitaliani R. Seismic response of corroded rc structures. *International fib symposium, Amsterdam, the Netherlands*, 2008.

32. Angst UM. Challenges and opportunities in corrosion of steel in concrete. *Materials and Structures* 2018; **51**(1): 4. DOI: 10.1617/s11527-017-1131-6.

33. Rodriguez J, Ortega LM, Casal J. Load carrying capacity of concrete structures with corroded reinforcement. *Constr Build Mater* 1997; **11**. DOI: 10.1016/S0950-0618(97)00043-3.

34. Berto L, Vitaliani R, Saetta A, Simioni P. Seismic assessment of existing RC structures affected by degradation phenomena. *Struct Saf* 2009; **31**. DOI: 10.1016/j.strusafe.2008.09.006.

35. Koch G, Varney J, Thompson N, Moghissi O, Gould M, Payer J. International measures of prevention, application, and economics of corrosion technologies study. *NACE International* 2016; **216**: 2–3.

36. Bracci JM, Kunnath SK, Reinhorn AM. Seismic Performance and Retrofit Evaluation of Reinforced Concrete Structures. *Journal of Structural Engineering* 1997; **123**(1): 3–10. DOI: 10.1061/(ASCE)0733-9445(1997)123:1(3).

37. *Building Code Requirements for Reinforced Concrete and Commentary (ACI 318‐89/ACI 318R‐89)*. American Concrete Institute; 1989.

38. Aycardi LE, Mander JB, Reinhorn AM. Seismic resistance of reinforced concrete frame structures designed only for gravity loads: experimental performance of subassemblages. *Structural Journal* 1994; **91**(5): 552–563.

39. Duracrete. *Probabilistic Performance Based Durability Design of Concrete Structures: Final Technical Report*. The European Union – Brite EuRam III; 2000.

40. Broomfield J. *Corrosion of steel in concrete: understanding, investigation and repair*. 2006.

41. Coronelli D, Gambarova P. Structural assessment of corroded reinforced concrete beams: modeling guidelines. *Journal of Structural Engineering* 2004; **130**(8): 1214–1224.

42. Mander JB, Priestley M, Park R. Theoretical stress-strain model for confined concrete. *Journal of Structural Engineering* 1988; **114**(8): 1804–1826.

43. Sezen H, Moehle JP. Seismic tests of concrete columns with light transverse reinforcement. *ACI Structural Journal* 2006; **103**(6): 842.

(Baradaran Shoraka et al. 2013)

# REFERENCES

1. Rossetto T, Elnashai A. Derivation of vulnerability functions for European-type RC structures based on observational data. *Engineering Structures* 2003; **25**(10): 1241-1263.
2. Rao A, Dutta D, Kalita P, Ackerley N, Silva V, Raghunandan M, Ghosh J, Ghosh S, Brzev S, Dasgupta K. Probabilistic seismic risk assessment of India. *Earthquake Spectra* 2020; **36**(S1): 345–371.
3. Freddi F, Novelli V, Gentile R, Veliu E, Andonov A, Andreev S, Greco F, Zhuleku E. Observations from the 26th November 2019 Albania Earthquake: the Earthquake Engineering Field Investigation Team (EEFIT) mission. *Bulletin of Earthquake Engineering* 2020. DOI: 10.1007/s10518-021-01062-8
4. Soong TT, Spencer BF. Supplemental energy dissipation: state-of-the-art and state-of-the-practice. *Engineering Structures* 2002; **24**(3): 243–259.
5. Xie Q. State of the art of buckling-restrained braces in Asia. *Journal of Constructional Steel Research* 2005; **61**(6): 727–48.
6. Tremblay R, Bolduc P, Neville R, DeVall R. Seismic testing and performance of buckling-restrained bracing systems. *Canadian Journal of Civil Engineering* 2006; **33**(2): 183–198.
7. Zona A, Dall’Asta A. Elastoplastic model for steel buckling-restrained braces. *Journal of Constructional Steel Research* 2012; **68**(1): 118–125.
8. Di Sarno L, Manfredi G. Experimental tests on full-scale RC unretrofitted frame and retrofitted with buckling-restrained braces. *Earthquake Engineering and Structural Dynamics* 2012; **41**(2): 315–333.
9. Della Corte G, D'Aniello M, Landolfo R. Field testing of all-steel buckling-restrained braces applied to a damaged reinforced concrete building. *Journal of Structural Engineering (United States)* 2015; **141**(1): D4014004.
10. Wu A-C, Tsai K-C, Yang H-H, Huang J-L, Li C-H, Wang K-J, Khoo H-H. Hybrid experimental performance of a full-scale two-story buckling-restrained braced RC frame. *Earthquake Engineering and Structural Dynamics* 2017; **46**(8): 1223–1244.
11. Ozcelik R, Erdil EF. Pseudodynamic test of a deficient RC frame strengthened with buckling restrained braces. *Earthquake Spectra* 2019; **35**(3): 1163–118.
12. Fahnestock LA, Sause R, Ricles JM, Lu L-W. Ductility demands on buckling-restrained braced frames under earthquake loading. *Earthquake Engineering and Engineering Vibration* 2003; **2**(2): 255-268.
13. Di Sarno L, Manfredi G. Seismic retrofitting with buckling restrained braces: Application to an existing non-ductile RC framed building. *Soil Dynamics and Earthquake Engineering* 2010; **30**(11): 1279–1297.
14. Freddi F, Tubaldi E, Ragni L, Dall’Asta A. Probabilistic performance assessment of low-ductility reinforced concrete frames retrofitted with dissipative braces. *Earthquake Engineering and Structural Dynamics* 2013; **42**(7): 993–1011.
15. Güneyisi EM. Seismic reliability of steel moment resisting framed buildings retrofitted with buckling restrained braces. *Earthquake Engineering and Structural Dynamics* 2012; **41**(5): 853–874.
16. Morfuni F, Freddi F, Galasso C. Seismic performance of dual Systems with BRBs under mainshock-aftershock earthquake sequences. *In Proceedings of 13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP* 2019, Seoul, South Korea, 26-30 May 2019.
17. Freddi F, Tubaldi E, Zona A, Dall’Asta A. 2020. Seismic performance of dual systems coupling moment-resisting and buckling-restrained braced frames. *Earthquake Engineering and Structural Dynamics.* DOI: [10.1002/eqe.3332](https://onlinelibrary.wiley.com/doi/full/10.1002/eqe.3332).
18. Dall’Asta A, Ragni L, Tubaldi E, Freddi F. Design methods for existing RC frames equipped with elasto-plastic or viscoelastic dissipative braces. *In Proceedings of XIII Convegno Nazionale* ANIDIS 2009, Bologna, Italy.
19. Ragni L, Zona A, Dall’Asta A. Analytical expressions for preliminary design of dissipative bracing systems in steel frames. *Journal of Construction Steel Research* 2011; **67**(1): 102-113.
20. Sutcu F, Takeuchi T, Matsui R. Seismic retrofit design method for RC buildings using buckling-restrained braces and steel frames. *Journal of Constructional Steel Research* 2014; **101**: 304–313.
21. Barbagallo F, Bosco M, Marino EM, Rossi PP, Stramondo PR. A multi‐performance design method for seismic upgrading of existing RC frames by BRBs. *Earthquake Engineering and Structural Dynamics* 2016; **46**(7): 1099–1119.
22. Tubaldi E, Freddi F, Barbato M. Probabilistic seismic demand model for pounding risk assessment. *Earthquake Engineering and Structural Dynamics* 2016; **45**(11): 1743–1758.
23. Kwon OS, Elnashai A. The effect of material and ground motion uncertainty on the seismic vulnerability curves of RC structure. *Engineering Structures* 2006; **28**(2): 289–303.
24. Dolsek M. Incremental dynamic analysis with consideration of modeling uncertainties. *Earthquake Engineering and Structural Dynamics* 2009; **38**(6): 805–25.
25. Tubaldi E, Barbato M, Dall’Asta A. Influence of model parameter uncertainty on seismic transverse response and vulnerability of steel-concrete composite bridges with dual load path. *Journal of Structural Engineering* 2012; **138**(3): 363–374.
26. Dall’Asta A, Scozzese F, Ragni L, Tubaldi E. Effect of the damper property variability on the seismic reliability of linear systems equipped with viscous dampers. *Bulletin of Earthquake Engineering* 2017; **15**(11): 5025–5053.
27. Scozzese F, Dall'Asta A, Tubaldi E. Seismic risk sensitivity of structures equipped with anti-seismic devices with uncertain properties. *Structural Safety* 2019; **77**: 30–47.
28. Kotoky N, Freddi F, Ghosh J, Raghunandan M. (2019) BRBs uncertainty propagation in seismic retrofit of RC structures. *In Proceedings of 13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP* 2019, Seoul, South Korea, 26-30 May 2019.
29. EN 15129. Anti-seismic devices. *European Committee for Standardization* 2018; Brussels, Belgium.
30. ASCE/SEI 7-16. Minimum design loads and associated criteria for buildings and other structures. *American Society of Civil Engineers* 2016, Reston, VA.
31. ASCE 41-13. Seismic Evaluation and Retrofit Rehabilitation of Existing Buildings. *American Society of Civil Engineers* 2013, Reston, VA.
32. Lavan O, Avishur M. Seismic behavior of viscously damped yielding frames under structural and damping uncertainties. *Bulletin of Earthquake Engineering* 2013; **11**(6): 2309–2332.
33. Zona A, Ragni L, Dall’Asta A. Sensitivity-based study of the influence of brace over-strength distributions on the seismic response of steel frames with BRBs. *Engineering Structures* 2012; **37**(1): 179–192.
34. HAZUS-MH MR4. Technical manual- Earthquake model. *Federal Emergency Management Agency* 2003, Washington, DC.
35. Freddi F, Padgett JE, Dall’Asta A. Probabilistic seismic demand modeling of local level response parameters of an RC frame. *Bulletin of Earthquake Engineering* 2017; **15**: 1–23.
36. Rossetto T, Gehl P, Minas S, Galasso C, Duffour P, Douglas J, Cook O. FRACAS: A capacity spectrum approach for seismic fragility assessment including record-to-record variability. *Engineering Structures* 2016; **125**: 337–348.
37. Aljawhari K, Gentile R, Freddi F, Galasso C. Aftershock vulnerability assessment of Pre-Code and Special-Code RC frames. *Bulletin of Earthquake Engineering* 2020; <https://doi.org/10.1007/s10518-020-01006-8>.
38. Gutiérrez-Urzúa, L.F., Freddi, F., Di Sarno, L. Comparative Analysis of Code Based Approaches for the Seismic Assessment of Existing Steel Moment Resisting Frames. *Journal of Constructional Steel Research* 2021; https://doi.org/10.1016/j.jcsr.2021.106589.
39. Ghosh J, Sood P. Consideration of time-evolving capacity distributions and improved degradation models for seismic fragility assessment of aging highway bridges. *Reliability Engineering and System Safety* 2016; **154**, 197–218.
40. Cornell C, Jalayer F, Hamburger RO, Foutch DA. Probabilistic basis for 2000 SAC federal emergency management agency steel moment frame guidelines. *Journal of Structural Engineering* 2002; **128**(4): 526–533.
41. Paulay T, Priestley MNJ. Seismic Design of Reinforced Concrete and Masonry Buildings, *John Wiley & Sons, Inc*. 1992, New York.
42. Elwood KJ, Moehle JP. Drift capacity of reinforced concrete columns with light transverse reinforcement. *Earthquake Spectra* 2005; **21**: 71–89.
43. Bracci JM, Reinhorn AM, Mander JB. Seismic resistance of reinforced concrete frame structures designed for gravity loads: performance of structural system. *ACI Structural Journal* 1995; **92**(5): 597–608.
44. Aycardi LE, Mander JB, Reinhorn AM. Seismic resistance of reinforced concrete frame structures designed only for gravity loads: experimental performance of subassemblages. *ACI Structural Journal* 1994; **91**(5), 552–563.
45. ACI Committee 318. Building code requirements for reinforced concrete and commentary (ACI 318-89/ACI 318R-89). *American Concrete Institute*, Detroit, 1989.
46. McKenna F, Fenves GL, Scott MH. Open system for earthquake engineering simulation. *University of California* 2006, Berkeley, CA.
47. Scott MH, Fenves GL. Plastic hinge integration methods for force-based beam-column elements. *Journal of Structural Engineering* 2006; **132**(2): 244–252.
48. Panagiotakos TB, Fardis MN. Deformation of reinforced concrete members at yielding and ultimate. *ACI Structural Journal* 2001; **98**(2): 135–148.
49. Elwood KJ. Modeling failures in existing reinforced concrete columns. *Canadian Journal of Civil Engineering* 2004; **31**(5): 846–59.
50. Baradaran Shoraka M, Yang TY, Elwood KJ. Seismic loss estimation of non-ductile reinforced concrete buildings. *Earthquake Engineering and Structural Dynamics* 2013; **42**(2): 297–310.
51. Jeon J-S, Lowes LN, DesRoches R, Brilakis I. Fragility curves for non-ductile reinforced concrete frames that exhibit different component response mechanisms. *Engineering Structures* 2015; **85**: 127–143.
52. Sezen H, Moehle JP. Shear strength model for lightly reinforced concrete columns. *Journal of Structural Engineering* 2004; **130**(11): 1692–1703.
53. Gu Q, Zona A, Peng Y, Dall'Asta A. Effect of buckling-restrained brace model parameters on seismic structural response. *Journal of Construction Steel Research* 2014; **98**: 100-113.
54. Smerzini C, Galasso C, Iervolino I, Paolucci R. Ground motion record selection based on broadband spectral compatibility. *Earthquake Spectra* 2014; **30**(4): 1427–1448.
55. Loeppky JL, Sacks J, Welch WJ. Choosing the sample size of a computer experiment: A practical guide. *Technometrics* 2009; **51**(4): 366–376.
56. USGS. Design Ground Motions. <<https://earthquake.usgs.gov/hazards/designmaps/>> (Nov. 21, 2020).
57. Wen YK, Kang YJ. Minimum building life-cycle cost design criteria. I: Methodology. *Journal of Structural Engineering* 2001; **127**(3): 330–337.