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

S. Shekar, F. Freddi1\*, J. Ghosh2, N. Kotoky3 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

Passive control systems, such as buckling-restrained braces (BRBs),

**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. Buildings, primarily, old reinforced concrete buildings have experienced severe damage, and in some cases collapse, due to 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 **infrastructural 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: DETERIORATION AND FINITE ELEMENT MODELLING

From the post-earthquake investigations done by several researchers

## Description of Case-Study Frame

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

## Finite Element Modelling for As-built and Deteriorated Frame

A zero-length element (spring) is used to define the shear limit curve in OpenSees [24]. The shear limit curve (*limitCurve Shear* – in OpenSees) is adopted based on the model given by Elwood (2004) [29] which is derived empirically. This model can be applied for only shear failure columns [22], the frame is joint is combined with ASCE-41 [30] proposed force-controlled shear limit surface. This is incorporated in OpenSees using *LimitState* material model and *limitcurveShear* which helps capturing the failure when the shear limit or drift limit curve is reached [22] The shear limit in term of shear strength is calculated by the model proposed by Sezen and Moehle (2004) [31]. As shear failure is accompanied by cracking in the RC member, bond-slip phenomena in the longitudinal reinforcement is required to be captured while performing the cyclical test. The longitudinal bar slip causes additional strain in the fiber section which is given by bilinear stress-slip relationship established by Ghannoum and Moehle (2012) [32]. *zeroLengthSection* is used to incorporate the bar slip in the lateral load direction by multiplying the slip factor to the strain values in the *uniaxialMaterial* (concrete material) in OpenSees.

### 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) [33] |
| 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 |

 

**Figure 3.1 a**

 

**Figure 3.1 b**

~~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

This research was funded by UGC-UKIERI joint research program (Grant No. 2017-UGC-10070) and the Institute Post-doctoral fellowship granted by the Indian Institute of Technology Bombay. Their support is gratefully acknowledged. The authors would like to acknowledge the funding from Science and Engineering Research Board (statutory body under the Department of Science and Technology, India) through Grant No. MTR/2019/000287 for this work. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the funding agencies of the UGC-UKIERI research program.

# 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. Modelling failures in existing reinforced concrete columns. *Canadian Journal of Civil Engineering* 2004; **31**(5): 846–859. DOI: 10.1139/l04-040.

30. Pekelnicky R, Engineers SD, Chris Poland SE, Engineers ND. ASCE 41-13: Seismic evaluation and retrofit rehabilitation of existing buildings. *Proceedings of the SEAOC* 2012.

31. Sezen H, Moehle JP. Shear Strength Model for Lightly Reinforced Concrete Columns. *Journal of Structural Engineering* 2004; **130**(11): 1692–1703. DOI: 10.1061/(ASCE)0733-9445(2004)130:11(1692).

32. Ghannoum WM, Moehle JP. Dynamic collapse analysis of a concrete frame sustaining column axial failures. *ACI Structural Journal* 2012; **109**(3): 403.

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

# 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.