# SEISMIC VULNERABILITY ASSESSMENT AND RETROFITTING OF REINFORCED CONCRETE FRAME STRUCTURES


**BIRENDRA KUMAR KARAIYA**

**DEPARTMENT OF CIVIL ENGINEERING**

**INDIAN INSTITUTE OF TECHNOLOGY DELHI**



**MAY 2019**

# SEISMIC VULNERABILITY ASSESSMENT AND RETROFITTING OF REINFORCED CONCRETE FRAME STRUCTURES

*by*


**BIRENDRA KUMAR KARAIYA**

**Department of Civil Engineering**


***Submitted***
***in fulfilment of the requirements of the degree of Doctor of Philosophy***
***to the***

**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**MAY, 2019**

# CERTIFICATE

This is to certify that the thesis entitled, ***"Seismic Vulnerability Assessment and Retrofitting of Reinforced Concrete Frame Structures"*** being submitted by ***Birendra Kumar Karaiya*** to the Indian Institute of Technology Delhi, for the award of degree of ***Doctor of Philosophy*** is a bonafide record of research work carried out by him under our supervision and guidance. The thesis, in our opinion has reached the requisite standard, fulfilling the requirements for the award of degree of ***Doctor of Philosophy***.

The research report and results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of any degree or diploma.

**Prof. Dipti Ranjan Sahoo**
*Associate Professor*
Department of Civil Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016 (INDIA)

**Prof. Ashok Gupta**
*Professor*
Department of Civil Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016 (INDIA)

# ACKNOWLEDGEMENTS

My deep gratitude goes to Prof. Dipti Ranjan Sahoo and Prof. Ashok Gupta, who expertly guided and supported me through my PhD program. This dissertation would never have been completed without their persistence, understanding, and kindness. My appreciation also extends to Structural Engineering Laboratory staff Mr. Nitin Chourasia and Mr. Biri Singh and other supporting staffs who helped me in different stages of my experimental program.

My appreciation also extends to my friends and colleagues (Oinam Romanbabu Meetei, Saurabh Sharma, P. Gautham, Abhishek Verma, Adil, Rajesh, Fayaq, Ruban, Suraj, Pratik, and P. C. Ashwin Kumar) for their support and understanding. Their help in solving technical problem has been especially valuable of this dissertation.

I am indebted to my parents and family for their mental, physical, and emotional support. Without their love, support, and encouragement, I would not have finished this dissertation. In the end, I thank God for all his blessings.

**Birendra Kumar Karaiya**

# ABSTRACT

Reinforced concrete (RC) frame structures are widely used adopted in India and other countries in building constructions. These frames are very often infilled with masonry walls in some or all floors. The discontinuities in the masonry infill walls result in the arbitrary change in the force transfer path which may lead to the poor performance under seismic loading. Moreover, the frame members are designed without considering the lateral load-resisting characteristics of masonry infill walls and are adopted in the infilled RC frames regardless of their arrangements. Therefore, there is a need to study the seismic performance of low-to-high rise RC frames with and without masonry infill walls and also to investigate the effectiveness of some strengthening techniques suitable for the deficient RC frame structures.

This study is focused on seismic performance of 4-story, 8-story, and 20-story RC frames, representing the low, medium and high-rise frames, with different masonry infill configurations over the frame heights. Three different arrangements considered for each frame are bare frame (i.e., without masonry infill walls), fully-infilled frame (i.e., with masonry walls in all stories), and open ground story frame (i.e., with masonry infill walls in all stories except the ground story). The open ground story RC frame also represents a typical soft/weak-story problem in which the seismic demand is concentred at a particular story having the smaller lateral stiffness and/or lateral strength. Nonlinear static and dynamic analyses are carried out to investigate the lateral strength, overstrength, displacement ductility, failure mechanism, and drift response of all study frames. Seven spectrum-compatible ground motions are considered for dynamic analyses of these frames. Later, the collapse performance assessment of these study frames are carried out in accordance with FEMA P695 (2009) guidelines. The collapseconsistent twenty recorded ground motions are normalized and scaled for the collapse performance assessment of the study frames. Incremental dynamic analyses are conducted to determine the collapse margin ratios and collapse fragility curves of the study frames.

The open ground story frames of 4-story, 8-story, and 20-story RC structures are strengthened using buckling-restrained braces (BRBs) in order to enhance their seismic performance. These frames are designed for the same design base shear assuming the BRBs to resist the entire design lateral load. Nonlinear static and dynamic analyses ae carried out to investigate the seismic performance in terms of lateral strength, interstory drift response, hinge mechanism and displacement-time response.

An experimental investigation has been conducted on a severely-damaged half-scale two-story RC frame with open ground story. The shear-damaged ground story columns are repaired with micro-concrete and later retrofitted with carbon fibre polymer (FRP) jacketing. The initial lateral stiffness and the modal properties of the retrofitted frame are evaluated experimentally. Slow-cyclic test is conducted on the retrofitted frame under the gradually-increasing reversed-cyclic lateral displacements to investigate its collapse performance. The main parameters investigated are lateral force vs. floor displacement (hysteretic) response, lateral strength, energy dissipation and damping potential, and failure mechanism. Both strengthening techniques (i.e., BRB and FRP wrapping) exhibited the significantly improved seismic performance of the undamaged and damaged RC frames. Conclusions drawn based on the results of the numerical and experimental studies are presented.

# सार

प्रबलित कंक्रीट (आरसी) फ्रेम संरचनाओं का व्यापक रूप से निर्माण और निर्माण के निर्माण में अन्य देशों में अपनाया जाता है। ये फ्रेम अक्सर कुछ या सभी मंजिलों में चिनाई दीवारों से घिरे होते हैं। चिनाई infill दीवारों में विघटन के परिणामस्वरूप बल हस्तांतरण पथ में मनमाने ढंग से परिवर्तन होता है जो भूकंपीय लोडिंग के तहत खराब प्रदर्शन का कारण बन सकता है। इसके अलावा, फ्रेम सदस्यों को चिनाई infill दीवारों की पार्श्व लोड प्रतिरोधी विशेषताओं पर विचार किए बिना डिजाइन किए गए हैं और उनकी व्यवस्था के बावजूद infilled आरसी फ्रेम में अपनाया जाता है। इसलिए, चिनाई infill दीवारों के साथ और बिना कम से उच्च वृद्धि आरसी फ्रेम के भूकंपीय प्रदर्शन का अध्ययन करने की आवश्यकता है और कम आरसी फ्रेम संरचनाओं के लिए उपयुक्त कुछ मजबूत तकनीकों की प्रभावशीलता की जांच करने की आवश्यकता है।

यह अध्ययन फ्रेम की ऊंचाइयों पर विभिन्न चिनाई infill विन्यास के साथ, 4-story, 8- story, और 20- story आरसी फ्रेम के भूकंपीय प्रदर्शन पर केंद्रित है, जो कम, मध्यम और उच्च वृद्धि फ्रेम का प्रतिनिधित्व करता है। प्रत्येक फ्रेम के लिए तीन अलग-अलग व्यवस्थाएं बेयर फ्रेम (यानी, चिनाई infill दीवारों के बिना), पूरी तरह से infilled फ्रेम (यानी, सभी कहानियों में चिनाई दीवारों के साथ), और खुली जमीन कहानी फ्रेम (यानी, सभी कहानियों में चिनाई infill दीवारों के अलावा) जमीन की कहानी)। खुली जमीन की कहानी आरसी फ्रेम भी एक सामान्य मुलायम / कमजोर कहानी की समस्या का प्रतिनिधित्व करती है जिसमें भूकंपीय मांग एक विशेष कहानी पर केंद्रित होती है जिसमें छोटे पार्श्व कठोरता और / या पार्श्व शक्ति होती है। नॉनलाइनर स्थिर और गतिशील विश्लेषण पार्श्व शक्ति, अतिस्तरीय, विस्थापन लचीलापन, विफलता तंत्र, और सभी अध्ययन फ्रेम की बहाव प्रतिक्रिया की जांच के लिए किए जाते हैं। इन स्पेक्ट्रम के अनुकूल गति के लिए सात स्पेक्ट्रम-अनुकूल ग्राउंड मोशन माना जाता है। बाद में, इन अध्ययन फ्रेम के पतन प्रदर्शन मूल्यांकन फेमा पी 695 (200 9) दिशानिर्देशों के अनुसार किए जाते हैं। पतन-लगातार बीस दर्ज ग्राउंड मोशन सामान्यीकृत होते हैं और अध्ययन फ्रेम के पतन प्रदर्शन मूल्यांकन

के लिए स्केल किए जाते हैं। पतन मार्जिन अनुपात निर्धारित करने और अध्ययन फ्रेम के नाजुकता घटता को रोकने के लिए वृद्धिशील गतिशील विश्लेषण आयोजित किए जाते हैं।

4- story, 8- story, और 20- story आरसी संरचनाओं की खुली ग्राउंड स्टोरी फ्रेम को उनके भूकंपीय प्रदर्शन को बढ़ाने के लिए बकलिंग-प्रतिबंधित ब्रेसिज़ (बीआरबी) का उपयोग करके मजबूत किया जाता है। ये फ्रेम उसी डिज़ाइन बेस कतरनी के लिए डिज़ाइन किए गए हैं जो बीआरबी को पूरे डिजाइन पार्श्व लोड का विरोध करने के लिए मानते हैं। पार्श्व शक्ति, इंटरस्टोरी बहाव प्रतिक्रिया, कताई तंत्र और विस्थापन-समय प्रतिक्रिया के संदर्भ में भूकंपीय प्रदर्शन की जांच करने के लिए गैरलाइन स्थिर और गतिशील विश्लेषण किए गए हैं।

खुली जमीन की कहानी के साथ एक गंभीर रूप से क्षतिग्रस्त आधे पैमाने पर दो मंजिला आरसी फ्रेम पर एक प्रयोगात्मक जांच आयोजित की गई है। कतरनी क्षतिग्रस्त ग्राउंड स्टोरी कॉलम को माइक्रो-कंक्रीट के साथ मरम्मत की जाती है और बाद में कार्बन फाइबर पॉलिमर (एफआरपी) जैकेटिंग के साथ फिर से लगाया जाता है। प्रारंभिक पार्श्व कठोरता और रेट्रोफिट फ्रेम के मोडल गुणों का प्रयोग प्रायोगिक रूप से किया जाता है। धीमी गति से चलने वाले फ्रेम पर धीरे-धीरे बढ़ते हुए रिवर्स-साइक्लिक पार्श्व विस्थापन के तहत अपने पतन प्रदर्शन की जांच के लिए स्लो-चक्रीय परीक्षण आयोजित किया जाता है। जांच के मुख्य पैरामीटर पार्श्व बल बनाम फर्श विस्थापन (hysteretic) प्रतिक्रिया, पार्श्व शक्ति, ऊर्जा अपव्यय और नमी क्षमता, और विफलता तंत्र हैं। दोनों मजबूत तकनीक (यानी, बीआरबी और एफआरपी रैपिंग) ने अवांछित और क्षतिग्रस्त आरसी फ्रेम के उल्लेखनीय सुधारित भूकंपीय प्रदर्शन का प्रदर्शन किया। व्यापक संख्यात्मक और प्रयोगात्मक अध्ययन के परिणामों के आधार पर तैयार किए गए निष्कर्ष प्रस्तुत किए जाते हैं।

# TABLE OF CONTENTS

**Description** **Page No.**

*Certificate……………………………………………………………………….…………….……….......i*
*Acknowledgements…………………………………………………………….……………….........iii*
*Abstract……………………………………………………………………………………….….........v*
सार …………………………………………………………………………………….……...............*vii*
*Table of Contents…………………………………………………….………………….….….......ix*
*List of Figures..………………………………………………………….……………….….…......xv*
*List of Tables...……………………………………………………….………….…….……….…….xxi*
*List of Symbols...………………………………………………….……………….…….…………......xxiii*

**CHAPTER 1 .....................................................................................................1**

1.1 General........................................................................................1

1.2 Seismic Strengthening of Soft-story RC Buildings ...............................5

1.3 Motivation of Study.......................................................................6

1.4 Objectives and Scope of Present Study ...........................................7

1.5 Organization of the Thesis..............................................................7

**CHAPTER 2 .....................................................................................................9**

2.1 General........................................................................................9

2.2 Seismic Vulnerability Assessment ..................................................9

2.2.1 Empirical Methods.......................................................................11

2.2.2 Screening Methods.......................................................................27

2.2.3 Analytical/mechanical methods .....................................................30

2.2.4 Collapse Mechanism-based Methods..............................................34

2.2.5 Capacity Spectrum-based Methods ........ 35

2.2.6 Direct Displacement-based Methods ........ 35

2.3 Strengthening of RC Frames ........ 37

2.3.1 Conventional Steel Braces ........ 38

2.3.2 Buckling-restrained Braces ........ 41

2.3.3 Reinforced Concrete Shear Wall ........ 44

2.3.4 Composite Jacketing ........ 46

2.4 Behaviour of Masonry Infill Walls ........ 51

2.4.1 Stiffness of Masonry Infills ........ 52

2.4.2 Strength of Masonry Infills ........ 54

2.4.2.1 Sliding shear failure ........ 55

2.4.2.2 Compression failure: ........ 57

2.4.2.3 Diagonal tension cracking failure: ........ 58

2.4.2.4 General Shear failure: ........ 59

2.4.3 Modelling Techniques ........ 59

2.5 Summary ........ 62

**CHAPTER 3 ........ 65**

3.1 General ........ 65

3.2 Design of Study Frames ........ 66

3.3 Numerical Investigation ........ 73

3.3.1 Section Capacities ........ 73

3.3.2 Numerical Modelling ........ 75

3.3.3 Analysis Procedures ........ 80

3.3.4 Selected Ground Motions ........ 80

3.4 Analysis Results ........ 83

3.4.1 Linear Modal Analysis ........ 83
3.4.1.1 Fundamental time periods ........ 84
3.4.1.2 Mode shapes ........ 85
3.4.2 Pushover Analysis ........ 86
3.4.2.1 Capacity curves ........ 86
3.4.2.2 Peak lateral strength ........ 88
3.4.2.3 Hinge mechanisms ........ 90
3.4.3 Time-history Analysis ........ 92
3.4.3.1 Roof displacement-time response ........ 92
3.4.3.2 Hinge mechanism ........ 95
3.4.3.3 Inter-story drift response ........ 103
3.4.3.4 Residual drift response ........ 104
3.5 Summary ........ 106

**CHAPTER 4 ........ 107**

4.1 General ........ 107
4.2 Procedure for Collapse Performance Assessment ........ 108
4.2.1 Selection of Ground Motions ........ 108
4.3 Estimation of Structural Performance Factors ........ 113
4.3.1 Over strength Factor ........ 113
4.3.2 Period-based Ductility ........ 114
4.4 Incremental Dynamic Analysis ........ 115
4.4.1 Computation of Collapse Margin Ratio ........ 115
4.4.2 Calculation of Adjusted Collapse Margin Ratio ........ 116
4.4.3 Calculation of Total System Collapse Uncertainty ........ 117
4.4.4 Calculation of Adjusted Collapse Margin Ratio ........ 118

4.4.5 Development of Collapse Fragility Curves ............ 118

4.5 Collapse Performance of Study Frames ............ 119

4.5.1 Structural Performance Factors ............ 119

4.5.2 IDA Results ............ 120

4.5.3 Collapse Margin Ratio ............ 121

4.5.4 Collapse Fragility Curves ............ 123

4.6 Summary ............ 124

**CHAPTER 5 ............ 127**

5.1 Overview ............ 127

5.2 Design of Strengthened Frames ............ 128

5.2.1 Determination of BRB sizes ............ 128

5.2.2 Computation of design base shear of strengthened frame ............ 130

5.2.3 Design of strengthened frames ............ 132

5.2.4 Numerical modelling ............ 134

5.3 Linear Modal Analysis ............ 135

5.4 Nonlinear Static Analysis ............ 138

5.4.1 Lateral strength ............ 138

5.4.2 Pushover curves ............ 139

5.4.3 Hinge mechanisms ............ 139

5.5 Nonlinear Time-history Analysis ............ 141

5.5.1 Hinge mechanisms ............ 141

5.5.2 Floor displacement-time response ............ 145

5.5.3 Inter-story drift response ............ 147

5.5.4 Residual drift response ............ 149

5.6 Summary ............ 149

**CHAPTER 6** .......... **151**

6.1 Overview .......... 151

6.2 Description of Test Frame .......... 152

6.2.1 Material properties .......... 155

6.2.2 Preparation of test frame .......... 156

6.2.2.1 Chiselling of damage concrete .......... 157

6.2.2.2 Epoxy primer and Micro-concreting .......... 158

6.2.2.3 Epoxy injection (Grouting) .......... 159

6.2.2.4 Carbon fibre wrapping .......... 161

6.3 Test Set-up .......... 162

6.3.1 Servo-hydraulic Actuator .......... 162

6.3.2 Load-transferring systems and lateral supports .......... 163

6.3.3 Instrumentation and Sensors .......... 167

6.4 Test Program .......... 168

6.4.1 Forced-vibration Test .......... 168

6.4.2 Displacement-controlled cyclic test .......... 169

6.5 Summary .......... 173

**CHAPTER 7** .......... **175**

7.1 Overview .......... 175

7.2 Experimental Program .......... 175

7.2.1 Loading protocol .......... 176

7.3 Test Results .......... 177

7.3.1 Overall behaviour .......... 178

7.3.2 Hysteretic response .......... 180

7.3.3 Lateral stiffness degradation .......... 182

7.3.4 State of strain on specimen ....................................................................183

7.3.5 Energy dissipation capacity ....................................................................184

7.4 Summary....................................................................................................186

**CHAPTER 8**..........................................................................................................**187**

8.1 Summary....................................................................................................187

8.1.1 Seismic performance of RC frames with and without infills.................188

8.1.2 Collapse performance assessment of RC frames ...................................188

8.1.3 Seismic performance of BRB strengthened RC frames..........................189

8.1.4 Experimental study on FRP rehabilitated damaged RC frame ..............189

8.1.5 Slow-cyclic testing of FRP rehabilitated RC frame...............................189

8.2 Conclusions................................................................................................190

8.2.1 Seismic performance of RC frames with and without infills.................190

8.2.2 Collapse performance assessment of RC frames ...................................191

8.2.3 Seismic performance of BRB strengthened RC frames..........................192

8.2.4 Experimental study on FRP rehabilitated damaged RC frame ..............192

8.3 Recommendations for the Future Work .....................................................193

**APPENDIX A**.......................................................................................................**195**

A.1 General .......................................................................................................195

**REFERENCES**......................................................................................................**207**

**ANNEXURE**..........................................................................................................**235**

# LIST OF FIGURES


| ***Description*** | ***Page no.*** |
|---|---|
| Figure 1.1: Observed failure of RC buildings in (a) 2001 Bhuj Earthquake (Jain et al., 2011), and (b) 2011 Sikkim Earthquake | 3 |
| Figure 2.1: Example of a lognormal distribution of the estimated damage factor for an Intensity showing the mean low (ML), mean best (MB), and mean high (MH) estimates of the damage factor (adapted from McCormack and Rad (1997)) | 16 |
| Figure 2.2: Vulnerability curves by for moment-resisting frames using PSI in which D1 to D5 relate to damage states in the MSK scale (Spence et al., 1992) | 19 |
| Figure 2.3: Typical fragility curves for (a) low and (b) medium rise buildings (Singhal and Kiremidjian, 1996)) | 25 |
| Figure 2.4: Vulnerability functions to relate damage factor (*d*) and peak ground acceleration (PGA) for different values of vulnerability index {*Iv*} [adapted from Guagenti and Petrini et al., 1989] | 26 |
| Figure 2.5: Flowchart to describe the components of the calculation of analytical vulnerability curves and damage probability matrices (adapted from Dumova-Jovanoska, 2004) | 31 |
| Figure 2.6: Simulated (thick line) and observed (thin line) vulnerability functions for MSK intensity VII (Barbat et al., 1996) | 33 |
| Figure 2.7: Collapse mechanisms of frames (Cosenza et al., 2005) | 34 |
| Figure 2.8: Estimation of damage from ground shaking in HAZUS (FEMA, 1999) | 36 |
| Figure 2.9: Simplified model for an equivalent SDOF system | 37 |
| Figure 2.10: Seismic strengthening strategy for existing RC building (Sugano, 1981) | 38 |

Figure 2.11: Retrofitting of columns and slabs of RC frame using steel braces (Masri and Goel, 1996) 40

Figure 2.12: (a) Sectional details and (b) hysteretic response of typical BRBs (Merritt et al., 2003) 42

Figure 2.13: Cross-section of typical BRBs (Tsai and Lai, 2002) 43

Figure 2.14: Lateral load-transfer in RC frame with masonry walls (a) frame action and (b) predominant truss action (Murty and Jain 2000) 52

Figure 2.15: (a) Effective width of compression strut and (b) detailing of three struts 54

Figure 2.16: Sliding-shear failure of masonry panels 55

Figure 2.17: Compression failure of masonry walls 57

Figure 2.18: Diagonal tension failure of masonry infill panel 58

Figure 2.19: Micro-modelling of infill walls (a) simplified and (b) detailed (Asteris *et al.*, 2013) 60

Figure 2.20: Various macro-models used for masonry infills (Crisafulli et al. 2000) 61

Figure 3.1: Building plan, elevation of bare, open ground story, and fully-infilled frame, and section sizes of beams and columns of 4-story frame 68

Figure 3.2: Frame elevations and section sizes of beams and columns of 8-story frame 69

Figure 3.3: Frame elevations and section dimensions of beams and columns of 20-story frames 71

Figure 3.4: Reinforcement detailing in beams and columns of the study frames (*Values in the parenthesis represent reinforcement area in* $cm^2$) 72

Figure 3.5: Numerical models of 4-, 8-, and 20-story frames: (a) BF, (b) OGS, (c) FIF 76

Figure 3.6: (a) Effective width of compression strut and (b) details of three strut model 77

Figure 3.7: Plastic hinges adopted in this study: (a) Axial load- bending moment (*P-M*) hinge, (b) Moment-curvature (*M-ϕ*) hinge, (c) Shear force-displacement hinge, (d) Axial force-displacement (compression) hinge 78

Figure 3.8: Location of plastic hinges in beams and columns of the 4-story frame 79

Figure 3.9: Acceleration-time histories of the selected ground motions 82

Figure 3.10: Response spectra of selected ground motions along with average spectra (a) Unscaled mean spectra and target design spectrum, (b, c, d) Scaled response spectra for 4-story, 8-story and 20-story bare frames 82

Figure 3.11: Comparison of mode shapes of 4-story, 8-story and 20-story frames at bare, open ground story, and filly-infilled stages 87

Figure 3.12: Comparison of capacity curves of study frames (a) 4-story, (b) 8-story and (c) 20 story 89

Figure 3.13: Hinge mechanisms of the study frames noted in pushover analyses (*Note*: Colour codes **B**, **C**, **D**, and **E** represent Yielding (Y), Peak (U), Ultimate (C), and Residual strength/deformation points; **IO**, **LS**, and **CP** denote Immediate Occupancy, Life safety, Collapse prevention states; **F, S,** and **A** represent Flexure, Shear and Axial hinges) 91

Figure 3.14: Roof displacements vs. time response of the 4-story frames 93

Figure 3.15: Roof displacements vs. time response of the 8-story frames 94

Figure 3.16: Roof displacements vs. time response of the 20-story frames 95

Figure 3.17: Hinge mechanisms of 4-story frames under the selected ground motions 97

Figure 3.18: Hinge mechanisms of 8-story frames under the selected ground motions 99

Figure 3.19: Hinge mechanisms of 20-story frames under the selected ground motions 103

Figure 3.20: Comparison of (a) ISDR and (b) RDR response of 20-story frames 105

Figure 4.1: Response spectra of the unscaled ground motions considered in this study 112

Figure 4.2: Normalized ground motions scaled to match the period-based spectral acceleration for 4-story, 8-story and 20-story study frames 112

Figure 4.3: Idealized nonlinear static pushover curve 114

Figure 4.4: Results of incremental dynamic analysis of bare and open ground story frames of 4-story, 8-story and 20-story structures 122

Figure 4.5: Comparison of collapse fragility curves of 4-story, 8-story and 20-story study frames 124

Figure 5.1: (a) BRBs installed in chevron configuration in open ground story of a frame, (b) Axial forces in BRBs under the action of lateral loading 129

Figure 5.2: (a) A typical BRB with different segments, (b) Axial force-displacement hysteretic response of a BRB (Merritt et al., 2003), (c) Idealized backbone curve of axial force-displacement response (Sahoo and Chao, 2010) 130

Figure 5.3: Deformed configurations of (a) frame and (b) BRBs under lateral loading 132

Figure 5.4: Arrangement of BRBs in ground stories of 4-story, 8-story, and 20-story strengthened frames 133

Figure 5.5: Modelling of BRBs in computer software adopted in this study 135

Figure 5.6: Fundamental mode shapes of (a) 4-story and (b) 8-story frames 136

Figure 5.7: Mode shapes of 20-story frame: (a) 1$^{st}$ mode, (b) 2$^{nd}$ mode, (c) 3$^{rd}$ mode 137

Figure 5.8: Comparison of capacity curves of strengthened frames 139

Figure 5.9: Comparison of hinge mechanism of strengthened frames (a) 4-story, (b) 8-story, (c) 20-story 140

Figure 5.10: Observed hinge mechanism of 4-story strengthened frame under the selected seven ground motions 142

Figure 5.11: Hinge mechanism of 8-story strengthened frame under the selected seven ground motions 143

Figure 5.12: Hinge mechanism of 20-story strengthened frame under the selected seven ground motions 145

Figure 5.13: Roof displacements vs. time response of the 4-story frame 146

Figure 5.14: Roof displacements vs. time response of the 8-story frames 147

Figure 5.15: Roof displacements vs. time response of the 20-story frames 148

Figure 5.16: Comparison of inter story drift (IDR) response of strengthened OGS frames (a) 4-story , (b) 8-story and (c) 20-story 148

Figure 5.17: Comparison of residual drift response (RDR) of strengthened frames (a) 4-story, (b) 8-story, (c) 20-story 149

Figure 6.1: Detailed dimensions and elevation view of the test frame 153

Figure 6.2: Dimension and detailing of (a) Retrofitted ground column (b) Upper column (c) End section of beam and (d) Mid-section of beam of test specimen 153

Figure 6.3: Reinforcement detailing of test frame (a) Slab, and (b) Test frame 154

Figure 6.4: Cube test of micro concrete 156

Figure 6.5: Step-wise chiselling process for retrofitting of columns 157

Figure 6.6: Preparation of specimen for micro concrete (a, b) epoxy primer, (c) formwork installation and (d) finished surface 159

Figure 6.7: Nipples installation and epoxy injection on column and beam 160

Figure 6.8: Sequence of FRP wrapping on test specimen 161

Figure 6.9: Lateral support and load-transfer systems, (a) Top view and (b) Side view 164

Figure 6.10: Attachment of test frame with the laboratory strong floor, (a) Top view and (b) Front view 165

Figure 6.11: Test specimen showing the gravity loading at each slab level 165

Figure 6.12: Photograph showing the test specimen with test set-up 166

Figure 6.13: Position of actuator, LVDT and strain gauges 167

Figure 6.14: Forced-vibration test results of frames (a) Mass of various components and (b) Natural frequency of specimen 169

Figure 6.15: Procedure for the evaluation of stiffness matrix for the test frame 170

Figure 6.16: Lateral load vs. displacement response of displacement-controlled cyclic tests of specimens, (a) bottom response and (b) top response 171

Figure 6.17: State of strain in (a) bottom columns (b) top columns and (c) both beams 172

Figure 7.1: Test frame and set-up prior to the slow-cyclic testing 176

Figure 7.2: Imposed displacement history on test specimen 177

Figure 7.3: Sequence of damages in ground story columns of the test frame 179

Figure 7.4: Damages in masonry infill panel and first floor beam level 180

Figure 7.5: Frame mechanism along with crack propagation on test frame during displacement control test 181

Figure 7.6: (a) Hysteretic response and (b) backbone curve of lateral load-displacement response of the retrofitted frame 181

Figure 7.7: Lateral stiffness degradation of test specimens under cyclic load 183

Figure 7.8: State of strain in various locations of test frame (a) ground columns (b) upper columns and (c) both beams 184

Figure 7.9: (a) Energy dissipation and (b) Equivalent viscous damping of test specimens 185

# LIST OF TABLES


| ***Description*** | ***Page no.*** |
|---|---|
| Table 2.1: Relationship between earthquake magnitude and MMI scale | 12 |
| Table 2.2: Damage Probability Matrix Proposed by Whitman et al. (1973) | 15 |
| Table 2.3: Example of a Damage Model for Vulnerability Class C in EMS-98 scale | 17 |
| Table 2.4: Definition of damage state and damage category | 21 |
| Table 3.1: Section properties and shear strengths of beams of study frames | 74 |
| Table 3.2: Section properties and shear strengths of columns of study frames | 75 |
| Table 3.3: Earthquake data and site information of selected ground motion | 81 |
| Table 3.4: Comparison of fundamental periods of study frames | 84 |
| Table 3.5: Peak lateral load carrying capacities of the study frames | 89 |
| Table 4.1: Details of ground motions selected from collapse analysis | 109 |
| Table 4.2: Recorded and normalized ground motion parameters | 111 |
| Table 4.3: Structural performance factors of the study frames | 120 |
| Table 4.4: Comparison of collapse margin ratios of study frames | 122 |
| Table 5.1: Design area of BRB core segments in the strengthened frames | 134 |
| Table 5.2: Axial yield and ultimate strengths of BRB of strengthened frames | 134 |
| Table 5.3: Comparison of time periods of strengthened and unstrengthened frames | 136 |
| Table 5.4: Peak lateral load capacity of strengthened frames | 138 |
| Table 6.1: Compressive strength of micro-concrete | 155 |
| Table 6.2: Properties FRP sheet | 156 |

Table 7.1: Computation of energy dissipation, stiffness degradation and equivalent damping potential of test specimen 185

# LIST OF SYMBOLS

| | |
|---|---|
| $\alpha$ | RMS of strong-motion acceleration. |
| $\alpha_s$ | Reinforcement bond-slip coefficient. |
| $\beta$ | compression strength adjustment factor. |
| $\beta_c$ | Capacity curve variability. |
| $\beta_{ds}$ | The total variability. |
| $\beta_{DR}$ | Design requirements-related collapse uncertainty. |
| $\beta_{eq}$ | Equivalent viscous damping. |
| $\beta_{M(ds)}$ | Damage state variability. |
| $\beta_{MDL}$ | Modelling-related collapse uncertainty. |
| $\beta_{RTR}$ | Record to record variability. |
| $\beta_{TD}$ | Test data-related collapse uncertainty. |
| $\beta_{TOT}$ | Total system collapse uncertainty. |
| $\Delta^+, \Delta^-$ | Peak displacements in positive and negative directions of hysteretic loops. |
| $\Delta_{BRB}$ | Axial displacement of BRBs. |
| $\Delta_u$ | Ultimate displacement. |
| $\Delta_{uD}$ | Deflection of column in single curvature. |
| $\Delta_{us}$ | Deflection of column in single curvature. |
| $\Delta_{ut}$ | Ultimate roof displacement. |
| $\Delta_y$ | Yield displacement. |
| $\Delta_{Y,eff}$ | Effective yield roof drift displacement. |
| $\varepsilon_{co}$ | Ultimate unconfined strain. |

| | |
|---|---|
| $\varepsilon_{cu}$ | Ultimate strain of FRP section. |
| $(\varepsilon_{cu})_{ex}$ | Ultimate compressive strain of existing column |
| $(\varepsilon_{cu})_{up}$ | Ultimate compressive strain of upgraded column. |
| $\theta$ | Angle between the infill height and infill length (radians). |
| $\theta_u$ | Ultimate rotation of structural elements. |
| $\lambda_h$ | Dimensionless parameter with reference to equivalent strut. |
| $\lambda_p$ | Normalized plastic hinge length. |
| $\mu_m$ | Column displacement ductility. |
| $\mu_T$ | Period-based ductility for a given index archetype model. |
| $(\mu_\Delta)_{up}$ | Target displacement ductility. |
| $(\mu_\Delta)_{ex}$ | Displacement ductility of existing column. |
| $(\mu_\phi)_m$ | Curvature ductility factor. |
| $(\mu_\phi)_{up}$ | Target curvature ductility. |
| $\sigma_0$ | RMS acceleration |
| $\sigma_{yBRB}$ | Material yield stress. |
| $\tau_c$ | Shear strength of concrete. |
| $\phi$ | Curvature. |
| $\varphi$ | Normal commutative distribution function. |
| $\varphi_{1,x}$ | Ordinate of the fundamental mode at level $x$. |
| $\phi_n$ | Eigen vectors (mode shapes). |
| $\varphi_u$ | Ultimate curvature. |
| $\varphi_y$ | Yield curvature. |
| $(\Phi_y)_{ex}$ | Yield curvature of existing column. |
| $(\Phi_y)_m$ | Yield curvature of the section. |
| $(\Phi_y)_{up}$ | Yield curvature of upgraded column. |

| | |
|---|---|
| $(\Phi_u)_m$ | Ultimate curvature of the section. |
| $\omega_n$ | Eigen value matrix (natural frequencies). |
| $\Omega$ | Ratio of the maximum base shear resistance, $V_{max}$ to the design base shear, $V$. |
| $a(t)$ | Ground motion acceleration at time $t$. |
| $A_{BRB}$ | Core cross-sectional area. |
| $A_{sl}$ | Area of longitudinal reinforcement. |
| $A_{st}$ | Area of longitudinal steel. |
| $A_w$ | Total effective area of walls in the first story of the building. |
| $B$ | Width of the cross section. |
| $(c_u)_{ex}$ | Neutral axis depth of the existing column |
| $(c_u)_{up}$ | Neutral axis depth of the upgraded column. |
| $C_0$ | Fundamental mode (SDOF) displacement to roof displacement. |
| $C_{b,i}$ | Base shear coefficient. |
| $C_\phi$ | Column curvature coefficient. |
| $CDR(DS)$ | Central Damage Ratio corresponding to damage state $DS$. |
| $d$ | Effective depth of the section. |
| $d_b$ | Diameter of reinforcement bars. |
| $d_{bl}$ | Bar diameter |
| $d_m$ | Diagonal length of infill panel. |
| $D$ | Depth of the cross section. |
| $E_c$ | Modulus of elasticity of concrete. |
| $E_{loop}$ | Energy dissipated per hysteretic loops at a particular drift cycle. |
| $E_m$ | Modulus of elasticity of masonry. |

| | |
|---|---|
| $E_o$ | Basic structural performance. |
| $EI$ | Flexural rigidity. |
| $f_{cc}$ | Ultimate strength of FRP section. |
| $f_{ck}$ | Characteristic compressive strength of concrete. |
| $f_{co}$ | Ultimate unconfined stress. |
| $f_l$ | Confining pressure. |
| $f_{S_a\|MMI}$ | Conditional probability density function of spectral acceleration at specified $MMI$. |
| $f_y$ | Yield strength of reinforcement steel. |
| $f_{ye}$ | Expected yield strength. |
| $F_x$ | Vertical distribution of the lateral force at each story $x$. |
| $G$ | Ground index to account for ground-building interaction. |
| $h$ | Column height. |
| $H_n$ | Height of the building. |
| $I_\Delta$ | Target displacement upgrading index. |
| $I_c$ | Moment of inertia of the column. |
| $I_c$ | Neutral axis upgrading index. |
| $I_s$ | Seismic performance index of a building. |
| $I_{so}$ | Seismic judgement index |
| $I_v$ | Global vulnerability index of building. |
| $I_\phi$ | Curvature upgrading index. |
| $K$ | Stiffness matrix. |
| $K'_{BRB}$ | Lateral stiffness contribution of BRBs. |
| $K_f$ | Lateral stiffness of single story. |
| $K_i$ | Qualification coefficients of buildings in accordance with quality conditions. |

| | |
|---|---|
| $l$ | Length of member. |
| $l_p$ | Length of plastic hinge. |
| $L_c$ | Length of column in double curvature. |
| $L_p$ | Length of plastic hinge. |
| $L_s$ | Shear span. |
| $L_v$ | Length of column in double curvature. |
| $m_x$ | Mass at level $x$. |
| $M$ | Mass matrix. |
| $MDR$ | Mean Damage Ratio |
| $\bar{M}_{ex}$ | Moment capacity ratio of the column for an upgraded column. |
| $\bar{M}_{\mathrm{m}}$ | Moment capacity ratio of the column for an existing column. |
| $M_w$ | Richter moment magnitude |
| $N(DS,I)$ | Number of buildings which are in damage state $DS$ among $N(I)$ buildings. |
| $p_t$ | Percentage of longitudinal steel. |
| $P(DS,I)$ | Probability of a particular damage state $DS$ to occur when structure is subjected to an earthquake of intensity $I$. |
| $P[D \geq d_i \mid Y = y_k]$ | Probability of reaching or exceeding damage state $d_i$ given that ground motion is $Y_k$. |
| $P[ds/S_d]$ | Probability of attaining or exceeding a given damage state. |
| $P_{D\mid MMI,S_a}[d\mid MMI,S_a]$ | Probability of reaching or exceeding given damage state at specified $MMI$ and spectral acceleration $S_a$. |
| $P_{D\mid MMI}[d\mid MMI]$ | Probability of reaching or exceeding given damage state at specified $MMI$. |
| $P_{cy}$ | Design yield axial forces of BRBs in compression. |

| | |
|---|---|
| $P_{ij}$ | Conditional probability of obtaining damage level $j$ due to ground motion intensity $i$. |
| $P_{ty}$ | Design yield axial force of BRBs in tension. |
| $r$ | Radius of angular edge. |
| $R_y$ | Material over strength factor. |
| $S$ | Spacing of transverse reinforcement. |
| $S_{CT}$ | Median collapse level. |
| $S_D$ | Sub-index concerning the structural design of the building. |
| $S_{MT}$ | Maximum considered earthquake ground motion intensity. |
| $S_{d,ds}$ | Median spectral displacement for the damage state. |
| $V$ | Total shear strength of member section. |
| $V_{BRB}$ | Design Story shear. |
| $V_{b,i}$ | Base shear. |
| $V_{max}$ | Maximum base shear capacity. |
| $V_{nc}$ | Shear strength of concrete. |
| $V_{ns}$ | Shear strength of steel. |
| $w$ | Effective width of diagonal compression strut. |
| $W$ | Seismic weight. |
| $W_i$ | Weights to calculate global vulnerability index to account for relative importance. |
| $t_{inf}$ | Thickness of infill panel. |
| $T$ | Strong-motion duration. |
| $U$ | Usage index concerned with the function of the building. |
| $Z$ | Zone index. |