## **ACKNOWLEGEMENTS**

I am grateful to the Department of Civil Engineering, University of Moratuwa for granting me an opportunity to follow the M.Eng. Degree on Structural Engineering Design. I am particularly indebted to Prof. M.T.R.Jayasinghe, who has guided and inspired me to undertake this study.

I wish to thank Secondary Education Modernization Project of the Ministry of Education for their generous sponsorship. Also I would like to acknowledge my debt to School Works Division of the Ministry of Education for granting study leave to follow this course without which this work would not have been possible.



## **CONTENTS**

| Abstracts   | I   |
|---|-----|
| Acknowledgements  | II  |
| List of Figures   | V   |
| List of Tables  | VII |
| Chapter 1-Introduction  |     |
| 1. 1 General  | 01  |
| 1.2 Objectives  | 02  |
| 1.3 Methodology   | 03  |
| 1.4 Main Findings   | 03  |
| 1.5 Arrangement of the Report                                   | 04  |
| Chapter 2-Literature Review                                     |     |
| 2.1 Introduction  | 06  |
| 2.2 Nature of Earthquakes to Affect Sri Lanka                   | 07  |
| 2.2.1 Different Types of Earthquakes heses & Dissertations      | 07  |
| 2.2.2 Seismicity Around Sri Lanka                               | 07  |
| 2.2.3 Types of Reinforced Concrete Structures Used in Sri Lanka | 10  |
| 2.3 Earthquake Design Techniques                                | 11  |
| 2.3.1 International Building Code(IBC,2006) Method              | 13  |
| 2.3.2 National Building Code of Canada Method                   | 14  |
| 2.3.3 Building Code of Japan(2000) Method                       | 16  |
| 2.3.4 Australian Standard AS1170.4,1993 Method                  | 17  |
| 2.4 Behavior of Reinforced Concrete Structures in Earthquakes   | 18  |
| 2.4.1 Factors Affecting Earthquake Performance of Reinforced    | 18  |
| Concrete Structures   |     |
| 2.4.2 Ductility Capacity  | 24  |
| 2.4.2.1 Ductility   | 24  |
| 2.4.2.2 Design Elastic Strength                                 | 25  |
| 2.4.2.3 Structural Response Modification                        | 26  |
| 2.4.2.3 Moment Resisting Frames                                 | 28  |

| 2.4.3 Strength and Ductility of Materials  | 29  |
|--|-----|
| 2.4.3.1 Reinforcement  | 29  |
| 2.4.3.2 Concrete behaviour   | 30  |
| 2.4.4 Dynamic Behaviour of Multi-Story Frames                                    | 31  |
| 2.4.5 Failure of Frames  | 33  |
| Chapter 3-Existing School Building   |     |
| 3.1 General  | 45  |
| 3.2 The Typical Details  | 46  |
| 3.3 Reinforcement Details  | 47  |
| 3.4 Cost for Existing Building   | 48  |
| 3.5 Problems Identified  | 49  |
| 3.6 Summary  | 50  |
| <b>Chapter 4-Improvements For School Buildings</b>                               |     |
| 4.1 General  | 55  |
| 4.2 The General Arrangement  4.2 The General Arrangement  Theses & Dissertations | 55  |
| 4.3 Structural Details www.lib.mrt.ac.lk   | 57  |
| 4.4 Investigation of Performance Under Seismic Effects                           | 58  |
| 4.4.1 Determination of Failure Modes   | 58  |
| 4.4.2 Determination of Seismic Forces by Static Analysis                         | 62  |
| 4.4.3 Vertical Distribution of the Base Shear Force                              | 67  |
| 4.4.4 Response Spectrum Analysis   | 70  |
| 4.4.5 Determination of Member Forces by Structural Analysis                      | 73  |
| 4.4.6 Interpretation of Structural Analysis Results                              | 77  |
| Chapter 5-Cost Implication   |     |
| 5.1 General  | 107 |
| 5.2 Cost Analysis of Structural Elements   | 107 |
| Chapter 6-Conclusion   | 109 |
| References   | 111 |

## LIST OF FIGURES

| Fig No | •    |   | Page No |
|--------|------|---|---------|
| Figure | 1.1  | : Devastated school buildings due to Sichuan Earthquake             | 05      |
| Figure | 2.1  | : Plate Boundaries in the World Map                                 | 35      |
| Figure | 2.2  | : Seismicity around SriLanka  | 35      |
| Figure | 2.3  | : Performance based design flow diagram                             | 36      |
| Figure | 2.4  | : Structure Plan Irregularities (AS 1170.4, 1993)                   | 37      |
| Figure | 2.5  | : Structure Vertical Irregularities                                 | 38      |
| Figure | 2.6  | : Typical Failure mechanisms of masonry infilled frames             | 39      |
| Figure | 2.7  | : Illustration of ductile behavior during cyclic horizontal loading | 39      |
| Figure | 2.8  | : Behaviour of a elastic-perfectly plastic SDOF system              | 39,40   |
| Figure | 2.9  | : Full range structural response                                    | 40      |
| Figure | 2.10 | : Typical stress-strain curves for reinforcing steel                | 41      |
| Figure | 2.11 | : Confinement of compressed concrete by reinforcements              | 41,42   |
| Figure | 2.12 | : Typical compressive stress-strain curves for confined and         |         |
|        |      | unconfined concrete   | 42      |
| Figure | 2.13 | : Typical moment-curvature relationship of concrete                 | 43      |
| Figure | 2.14 | : Moment-curvature relations for a heavily loaded                   |         |
|        |      | column with different quantities of transverse confining            |         |
|        |      | reinforcement   | 43      |
| Figure | 2.15 | : Design spectrum giving acceleration as a function of              |         |
|        |      | damping and period of vibration for a single degree of              |         |
|        |      | freedom linear oscillator responding elastically to some            |         |
|        |      | earthquake ground motions   | 44      |
| Figure | 2.16 | : Some mechanisms of post-elastic deformation of moment             |         |
|        |      | resisting frames and structural walls during severe                 |         |
|        |      | seismic loading   | 44      |
| Figure | 3.1  | : Architectural details of existing classroom building              | 51,52   |
| Figure | 3.2  | : Details of footings   | 53      |
| Figure | 3 3  | · Schedule of columns   | 53      |

| Figure | 3.4  | : Details of Beams  | 53,54   |
|--------|------|---|---------|
| Figure | 3.5  | : Reinforcements details of slab  | 54      |
| Figure | 4.1  | : Plan view of modified building  | 99      |
| Figure | 4.2  | : Architectural details of new building   | 99,100  |
| Figure | 4.3  | : Structural Details of Columns   | 100,101 |
| Figure | 4.4  | : Structural details of beams   | 101     |
| Figure | 4.5  | : Details of slab   | 102     |
| Figure | 4.6  | : 2-D Frames identified in existing building for seismic  |         |
|        |      | analysis  | 102     |
| Figure | 4.7  | : 2-D Frames identified in new building for seismic analysis  | 103     |
| Figure | 4.8  | : Response spectra of several records indicating sharp peaks  |         |
|        |      | and valleys   | 103     |
| Figure | 4.9  | : Design spectrum given in AS1170.4   | 104     |
| Figure | 4.10 | : Study specific response spectra   | 104     |
| Figure | 4.11 | : Basic geometrical view(SAP 2000) of new building  | 105     |
| Figure | 4.12 | : Maximum top drift in X-X direction  | 105     |
| Figure | 4.13 | : Maximum top drift in Y-Y direction foratuwa, Sri Lanka.  Electronic Theses & Dissertations  www.lib.mrt.ac.lk | 106     |

, V

vi

## LIST OF TABLES

|       | Table | No   | Page No                   |
|-------|-------|--|---------------------------|
| Table | 2.1 : | Seismic Events close to SriLanka   | 08                        |
| Table | 2.2 : | Formulae to calculate the fundamental natural frequency of a   |                           |
|       |       | building   | 12                        |
| Table | 3.1 : | Available nonstructural elements and facility equipments   | 47                        |
| Table | 4.1 : | Failure modes and capacities of beams  | 61                        |
| Table | 4.2 : | Failure modes and capacities of columns  | 62                        |
| Table | 4.3 : | Distribution of Horizontal Seismic Base Shear Force among  |                           |
|       |       | 2-D Frames (X-X Direction) of Existing Building  | 66                        |
| Table | 4.4 : | Distribution of Horizontal Seismic Base Shear Force among  |                           |
|       |       | 2-D Frames (Y-Y Direction) of Existing Building  | 67                        |
|       |       | Vertical Distribution of Seismic Forces of Frame A-A in X-X Direction  Electronic Theses & Dissertation  Vertical Distribution of Seismic Forces of Frame B-B in X-X | nka.<br>ons <sup>68</sup> |
|       |       | Direction  | 68                        |
| Table | 4.6 : | Vertical Distribution of Seismic Forces of Frame 1-1 in Y-Y  | <i>3</i> 70               |
|       |       | Direction  | 69                        |
| Table | 4.7 : | Vertical Distribution of Seismic Forces of Frame 2-2 in Y-Y  |                           |
|       |       | Direction  | 69                        |
| Table | 4.8 : | Vertical Distribution of Seismic Forces of Frame 3-3 in Y-Y  |                           |
|       |       | Direction  | 69                        |
| Table | 4.9 : | Vertical Distribution of Seismic Forces of Frame 4-4 in Y-Y  |                           |
|       |       | Direction  | 69                        |
| Table | 4.10: | Fundamental Periods  | 77                        |
| Table | 4.11: | Bending Moments and Shear Forces of Beam B3 at   |                           |
|       |       | First Floor of Frame A-A   | 79                        |
| Table | 4.12: | Bending Moments and Shear Forces of Beam B3 at   |                           |
|       |       | Second Floor of Frame A-A  | 80                        |

| Table | 4.13: Bending Moments and Shear Forces of Beam B3 at      |             |
|-------|---|-------------|
|       | First Floor of Frame B-B                                  | 81          |
| Table | 4.14: Bending Moments and Shear Forces of Beam B3 at      |             |
|       | Second Floor of Frame B-B                                 | 82          |
| Table | 4.15: Bending Moments and Shear Forces of Columns of      |             |
|       | Frame A-A   | 83          |
| Table | 4.16: Bending Moments and Shear Forces of Columns of      |             |
|       | Frame B-B   | 84          |
| Table | 4.17: Bending Moments and Shear Forces of Beam B1,B2      |             |
|       | and Columns of Frame 1-1                                  | 85          |
| Table | 4.18: Bending Moments and Shear Forces of Beam B1,B2      |             |
|       | and Columns of Frame 2-2                                  | 85          |
| Table | 4.19: Bending Moments and Shear Forces of Beam B1,B2      |             |
|       | and Columns of Frame 3-3                                  | 86          |
| Table | 4.20: Bending Moments and Shear Forces of Beam B1,B2      |             |
|       | and Columns of Frame 4-4 of Moratuwa, Sri Lanka.          | 86          |
| Table | 4.21: Summary of yielding points and shear crack on beams |             |
|       | and columns(Existing Building)                            | 87          |
| Table | 4.22: Summary of yielding points and shear crack on beams | <i>j</i> 24 |
|       | and columns(Modified Building)                            | 88          |
| Table | 4.23: Bending Moments and Shear Forces of Beam B2         |             |
|       | at First Floor of Frame A-A                               | 101         |
| Table | 4.24: Bending Moments and Shear Forces of Beam B2         |             |
|       | at Second Floor of Frame A-A                              | 90          |
| Table | 4.25: Bending Moments and Shear Forces of Beam B2         |             |
|       | at First Floor of Frame B-B                               | 90          |
| Table | 4.26: Bending Moments and Shear Forces of Beam B2         |             |
|       | at Second Floor of Frame B-B                              | 91          |
| Table | 4.27: Bending Moments and Shear Forces of Beam B2         |             |
|       | at First Floor of Frame C-C                               | 91          |
| Table | 4.28: Bending Moments and Shear Forces of Beam B2         |             |
|       | at Second Floor of Frame C-C                              | 92          |

| Table | 4.29: Bending Moments and Shear Forces of Columns                   |     |
|-------|---|-----|
|       | of Frame A-A  | 93  |
| Table | 4.30: Bending Moments and Shear Forces of Columns                   |     |
|       | AB  | 93  |
| Table | 4.31: Bending Moments and Shear Forces of Columns                   |     |
|       | of Frame C-C  | 94  |
| Table | 4.32: Bending Moments and Shear Forces of Beam B1                   |     |
|       | and Columns of Frame 1-1  | 95  |
| Table | 4.33: Bending Moments and Shear Forces of Beam B1                   |     |
|       | and Columns of Frame 2-2  | 95  |
| Table | 4.34: Bending Moments and Shear Forces of Beam B1                   |     |
|       | and Columns of Frame 3-3  | 96  |
| Table | 4.35: Bending Moments and Shear Forces of Beam B1                   |     |
|       | and Columns of Frame 4-4  | 96  |
| Table | 4.36: Comparison of max. top drift in direction X-X                 | 97  |
| Table | 4.37: Comparison of max. top drift in direction Y-Y uwa. Sri Lanka. | 97  |
| Table | 5.1 : Comparison of construction cost of structural elements        | 108 |
| Table | 5.2 : Comparison of total construction cost                         | 108 |

37.