Contents

1 INTRODUCTION 1

1.1 MOTIVATION 1
1.2 PROBLEM DEFINITION, LIMITATION AND SOLUTION 1
1.3 OVERVIEW OF THE THESIS 2

2 RISK MANAGEMENT 5

2.1 GENERAL REMARKS 5
2.1.1 Catastrophes 5
2.1.2 Uncertainties 9
2.2 METHODOLOGY FOR MANAGING DISASTER RISK 10
2.2.1 Existing definitions of disaster risk 11
2.2.2 Risk management concept 12
2.2.2.1 Risk identification phase 13
2.2.2.2 Risk assessment phase 13
2.2.2.3 Risk treatment phase 16
2.2.3 Evaluation and integration of most common definitions 17
2.3 MEASURING RISK 18
2.3.1 General remarks 18
2.3.2 Damage parameters 19
2.3.3 Loss parameters 20
2.4 RISK EVALUATION 21
2.5 SUMMARY 23

3 EARTHQUAKES AND STRUCTURAL RESPONSE 25

3.1 GENERAL REMARKS 25
3.2 DESCRIPTION OF EARTHQUAKES 27
3.2.1 Magnitudes and seismic moment 27
3.2.2 Amplitude parameters 28
3.2.3 Duration 28
3.2.4 Intensity 29
3.2.4.1 Time domain 29
3.2.4.2 Damage intensity scales 30
3.2.5 Frequency content parameters 32
3.3 EARTHQUAKE RECORDS 32
3.4 STRUCTURAL DYNAMIC 33
3.4.1 Single-degree-of-freedom system 33
3.4.2 Damping 34
3.5 CORRELATION BETWEEN STRONG MOTION PARAMETERS AND STRUCTURAL DAMAGE 35
3.6 PROBABILITY OF EARTHQUAKE LOADING 36
3.6.1 General remarks 36
3.6.2 Probability assessment for an endangered region and ground motion estimation 39
3.7 REQUIREMENTS ON THE SEISMIC PERFORMANCE OF STRUCTURES 42
3.7.1 General remarks 42
3.7.2 Shear capacity 44
3.7.3 Ductility 44
3.7.4 Conclusion 44
3.8 SUMMARY 45

4 MASONRY 47

4.1 UNREINFORCED MASONRY 47

4.1.1 Mechanical properties of masonry 47
4.1.1.1 Material behaviour of units and mortar 47
4.1.1.2 Compression behaviour of masonry 48
4.1.1.3 Tension behaviour of masonry 49
4.1.1.4 Shear behaviour of masonry 49
4.1.2 Support conditions of masonry walls 52
4.1.3 Failure mechanisms of horizontal in-plane loaded masonry walls 52
4.1.4 Influencing parameters on failure mechanisms 55
4.1.4.1 Vertical load level, slenderness and support conditions 55
4.1.4.2 Material parameters of masonry 56
4.1.5 Experimental tests of shear walls 57
4.1.5.1 Eindhoven 57
4.2 VERTICAL PRESTRESSED MASONRY 58
4.2.1 Means to apply vertical prestressing in practice 58
4.2.2 Function of prestressing 60
4.2.2.1 Shear behaviour 60
4.2.2.2 Bending behaviour 61
4.2.2.3 Stability 62
4.2.2.4 Cracking 63
4.2.3 Comparison of historical and modern masonry regarding a reasonable application of vertical prestressing 63
4.2.4 Experimental tests of prestressed shear walls 65
4.2.4.1 Dortmund 65
4.2.4.2 iBMB tests of Braunschweig 66
4.2.5 Wall-tendon interaction 70
4.2.6 Examples of application 71
4.2.6.1 Salvation Army Citadel 71
4.2.6.2 Kindergarten Zurich 73
4.2.6.3 Factory Regensdorf 74
4.2.6.4 Hall 8 iBMB 75
4.2.6.5 EMPA-building in Dübendorf 77
4.2.6.6 The bell tower in Trignano 78
4.3 NUMERICAL MODELLING 79
4.3.1 Modelling strategies for masonry 79
4.3.2 Basics of plastic theory 80
4.3.3 Material models 82
4.3.3.1 Interface material model of Delft 82
4.3.3.2 Material model of Lagomarsino and Gambarotta 83
4.3.3.3 Material model of Schlegel 87
4.3.3.4 Discussion of the models for a reasonable application 90
4.3.4 Damage parameters 90
4.3.4.1 Storey drift 90
4.3.4.2 Mortar damage 91
4.3.4.3 Unit damage 91
4.3.4.4 Plastic strains 91
4.3.4.5 Plastic activity 92
4.3.4.6 Stresses 92
4.3.5 Numerical modelling of prestressed masonry 93
4.3.5.1 Means to model vertical prestressing 93
4.3.5.2 Reasons to model tendons 93
4.4 SUMMARY 93

5 IMPACT OF PRESTRESSING ON THE DYNAMIC BEHAVIOUR 95
5.1 EXPERIMENTAL RESULTS 96
5.1.1 Static shear wall tests 96
5.1.2 Static cyclic shear wall tests 98
5.1.3 Dynamic shear wall tests 98
5.1.4 Dynamic tests of prestressed beams 98
5.2 RESULTS OF A NON-LINEAR SIMULATIONS 99
5.3 SUMMARY 99
6 NUMERICAL INVESTIGATION OF NON-PRESTRESSED AND PRESTRESSED MASONRY STRUCTURES 101
6.1 EXPERIMENTAL TESTS OF STATIC LOADED SHEAR WALLS 101
6.2 CASE STUDIES 104
6.2.1 Results of a non-linear static case study 104
6.2.1.1 Basics of the case study 104
6.2.1.2 Model 105
6.2.1.3 Impact on change of prestressing forces in the tendon 106
6.2.1.4 Restoring forces due to tendons 108
6.2.1.5 Rotation of the top 110
6.2.1.6 Shear capacity 111
6.2.1.7 Ductility 113
6.2.1.8 Summary of unexpected and important results 114
6.2.2 Results of a non-linear dynamic case study 115
6.2.2.1 Basics of the case study 115
6.2.2.2 Results 115
6.3 SIMULATION OF THE EXPERIMENTAL TESTS OF PRESTRESSED WALLS 119
6.3.1 Static and static cyclic loading 119
6.3.2 Earthquake simulation with and without prestressing 132
6.3.2.1 Wall 1 132
6.3.2.2 Wall 3 137
6.3.3 Probabilistic earthquake simulation with and without prestressing 142
6.3.3.1 Wall 1 143
6.3.3.2 Wall 3 147
6.4 SIMULATION OF HALL 8 IBMB 155
6.4.1 Simulation of the existing state 156
6.4.2 Simulation without prestressing 158
6.5 SUMMARY 159
7 FURTHER MEASURES TO ATTAIN A GOOD SEISMIC PERFORMANCE 161
7.1 DISCUSSION OF FURTHER MEASURES 161
7.1.1 Microscopic level - Reasonable material parameter selection for masonry 161
7.1.2 Macroscopic level - Reasonable parameter selection for walls 161
7.1.2.1 Wall geometry 162
7.1.2.2 Vertical load level 162
7.1.2.3 Elastomer bearing 162
7.1.2.4 Miscellaneous ideas 162
7.2 SIMULATION OF FURTHER MEASURES 163
7.2.1 Division in slender walls as non-prestressed and prestressed version 163
7.2.2 Unit type, masonry bond and unit size 168
8 APPLICATION OF THE RISK MANAGEMENT METHODOLOGY TO EVALUATE DIFFERENT MEASURES 171

8.1 HAZARD ANALYSIS 171
8.2 DAMAGE ASSESSMENT 171
8.3 RISK CALCULATION 173
8.4 RISK REDUCTION - COMPARISON OF PRESTRESSED AND NON-PRESTRESSED WALLS 176
8.5 OPTIMISATION 176
8.6 IMPACT OF PRESTRESSING ON THE LOSS 177

9 SYNOPSIS 179

9.1 SUMMARY 179
9.2 CONCLUSION 181
9.3 OUTLOOK 181

APPENDIX A: RISK MANAGEMENT GLOSSARY 183

APPENDIX B: DATA OF ARTIFICIAL GENERATED EARTHQUAKE FOR PROBABILISTIC ANALYSES 187

APPENDIX C: DATA OF ARTIFICIAL GENERATED STRONG MOTION EARTHQUAKE 195

APPENDIX D: ROTATION OF THE WALL FOR SC 2 IN DEPENDENCY ON TENDON POSITION AND SLENDERNESS 199

APPENDIX E: PROBABILISTIC RESULTS FOR WALL 1 AND WALL 3 201

APPENDIX F: DESCRIPTION OF THE NORTHRIDGE EARTHQUAKE 211

APPENDIX G: RISK ESTIMATION 213

APPENDIX H: MATERIAL PARAMETERS 219

APPENDIX I: SUGGESTIONS FOR THE PRACTICAL APPLICATION OF PRESTRESSING ON MASONRY 223

LIST OF ABBREVIATIONS 225

REFERENCES 233