



DEVELOPMENT OF EARTHQUAKE RESISTANT DESIGNS, METHODOLOGIES AND CONSTRUCTION TECHNOLOGIES FOR MASONRY BUILDINGS IN SRI LANKA

By
V.Ratnam

The thesis submitted to the Department of Civil Engineering of the University of Moratuwa in partial fulfillment of the requirements for the Degree of Master of Engineering in Structural Engineering Design.

Research Supervised
By
Dr.C.S. Lewangamage
Senior Lecturer

DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF MORATUWA
SRI LANKA

2009

93904



Abstract

Earthquakes are natural hazards under which disasters are mainly caused by damage to or collapse of buildings and other man-made structures. Earthquake damage depends on many parameters, including intensity, duration and frequency content of ground motion, geological and soil condition, quality of construction, etc. Building design must be such as to ensure that the building has adequate strength, high ductility, and will remain as one unit, even when subjected to very large deformation.

Although Sri Lanka is considered to be located away from a region of high seismic activity, researches have given evidence that there is possibility for seismic hazards in the South Asian region in the near future that can affect structures built in Sri Lanka. The effects of earthquakes are commonly considered for structures designed by engineers while domestic buildings constructed without professional guidance lack the provision for earthquake resistance. Therefore, it would be useful to analyze the behaviour of the masonry structures and take adequate precautions to minimize damage from earthquakes.

Many references have been made in this research to identify various existing masonry construction methods in the world that can be adopted to minimize the effects of earthquakes on residential buildings. Apart from literature survey, two economical methods of earthquake -resistant methods have been proposed using hollow cement stabilized soil interlocking blocks as the masonry element. One method is to use steel as reinforcing material and the second method is to use bamboo as the reinforcing material. In both the options the walls have been designed as load bearing walls for gravity loads and also as shear walls for lateral seismic loads, to safely withstand the effects of earthquakes. The structural system of construction is the same as a shear wall - diaphragm concept, which gives three-dimensional structural integrity for the buildings. Both these methods , especially safeguard the openings, by avoiding cracks around them in the case of seismic loading.



In order to observe the actual performance of the masonry walls under seismic loadings, masonry walls constructed out of hollow cement stabilized soil interlocking blocks both reinforced and un-reinforced with steel reinforcement have been modeled and tested to determine their in-plane cyclic performance. From these experimental studies, the relative performance of each masonry construction system in resisting the in-plane lateral loads under a constant superimposed vertical load was assessed. The reinforced cement stabilized soil interlocking system that was tested showed that the system was more ductile when subjected to cyclic loads than the non reinforced system.

A suitable methodology to verify the seismic resistance of masonry structures has been developed. The methodology is based on a method specified in the Eurocode 6 and the Australian seismic code. The method was applied for the typical house that has been analyzed throughout the paper. A design criteria is presented, with specific attention to the definition of behaviour factors to be used in the analysis and more generally on methods for the seismic performance verification of masonry buildings. Necessary and possible developments of design/assessment procedures and code provisions are presented. A cost comparison of various masonry technologies has been presented and the two proposed earthquake resistance technologies have been found to be very economical.

DECLARATION

I, V.Ratnam, hereby declare that the content of this thesis is the original work carried out by me. Whenever others' work is included in this thesis, it is appropriately acknowledged as a reference.

Signature :*V.Ratnam*.....
Name of the Student :*V.RATNAM*.....
Date :*29/09/2024*.....

Signature :***UOM Verified Signature***.....
Name of the Supervisor :*Dr. C. S. Loesangamga*.....
Date :*29/09/2024*.....

ACKNOWLEDGEMENTS

Firstly, I would like to give a special thanks to my family especially my parents for supporting me to finish this project.

I wish to express my sincere appreciation to my project supervisor, Dr.C.S.Lewangamage for supervising and guiding the preparation of my project from the very beginning till its completion. Without his guidance, advices and encouragement, this project would have not been the same as presented here.

I also wish to thank Prof.M.T.R.Jayasinghe, who always encouraged and supported us through the duration of the research project by organizing a series of discussions about research works.

Besides that, my sincere appreciation also extends to the Academic Staff of Faculty of Civil Engineering, University of Moratuwa, my friends Priyantha and Namal and others who had provided assistance at various occasions

My thanks also go to the minor staff of the Civil Engineering Computer Laboratory, Building Material Laboratory and Structural Testing Laboratory who gave valuable assistance when it was necessary.

V.RATNAM

September, 2009

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	i
	ACKNOWLEDGEMENT	ii
	ABSTRACT	iii
	TABLE OF CONTENTS	iv
	LIST OF FIGURES	ix
	LIST OF TABLES	xiii
1	INTRODUCTION	1
	1.1 Background	2
	1.2 Scope of Study	4
	1.3 Objective	5
	1.4 Methodology	5
	1.5 Main Findings	7
	1.6 Arrangement of the report	8
2	LITERATURE REVIEW	10
	2.1 Effects on buildings due to earthquakes	11
	2.1.1 Inertia Forces in buildings	11
	2.1.2 Effects of deformation in structures	12
	2.1.3 Horizontal and vertical shaking	12
	2.1.4 Flow of inertia forces to foundation	13
	2.2 Damages of buildings due to earthquakes	14
	2.2.1 Non structural damage	14
	2.2.2 Damage and Failure of Bearing Walls as Structural Damage	15
	2.2.3 Causes of Damage in Masonry Buildings	16
	2.3 Various building technologies used around the world for building earthquake resistant masonry buildings	16
	2.3.1 Introduction	16

2.3.2 The Wall Improvement Techniques	17
2.3.2.1 Reinforcing Masonry Walls	18
2.3.2.1.1 Horizontal Reinforcement in walls	19
2.3.2.1.2 Vertical Reinforcement in walls	21
2.3.3 Adobe Masonry	23
2.3.4 Brick Nogged Timber Frame Construction	25
2.3.5 The Rat-trap Bond Technology	26
2.3.5.1 Introduction	26
2.3.5.2 Rat-trap Bond	27
2.3.5.3 The technology and process	27
2.3.5.4 The strength of Rat-trap bond	29
2.3.5.5 For extra stability	30
2.3.5.6 Points for notification	30
2.3.5.7 Advantages and Disadvantages	31
2.3.6 The Form Block System	31
2.3.6.1 Applications	32
2.3.6.2 Form Block Components	32
2.3.6.3 Form Bridge	33
2.3.6.4 Wall Construction	33
2.3.7 Confined Masonry Construction	37
2.3.7.1 About Confined Masonry Construction	37
2.3.7.2 How Confined Masonry is Different from RC Frame Construction	40
2.3.8 Pre-stressed Masonry	41
2.3.9 Tying of walls with steel mesh reinforcement	47
2.3.10 Connections	49
2.3.10.1 Connections of wall to foundation using bamboo, or cane	49
2.3.10.2 Connections of wall to foundation using rebar	49
2.3.10.3 Wall to column connection	50
2.3.10.4 Connections in masonry courses using dowel Bars	50
2.3.10.5 Connections for wall to roof	51



	2.3.11 Effective planning and layouts	52
2.4	Seismic strengthening / retrofitting options and systems for enhancing seismic safety of existing buildings.	57
	2.4.1 Repair of Cracks	57
	2.4.2 Re-pointing	58
	2.4.3 Reinforced Cement Coating	59
	2.4.4 Pre-stressing	60
	2.4.5 Tying walls with steel ties	61
	2.4.6 Strengthening externally with steel strips	61
	2.4.7 Confining by introducing RC Column	63
	2.4.8 Centre Core Technique	63
	2.4.9 Strengthening with Epoxy bonded GFRP sheets	64
3	APPLICATION OF EARTHQUAKE RESISTANT CONSTRUCTION TECHNOLOGIES IN SRI LANKA	65
	3.1 Method 1 – Cement Stabilized Soil Interlocking Blocks	
	Reinforced with steel	66
	3.1.1 Properties of Cement stabilized soil interlocking Blocks	66
	3.1.2 Reinforcing Cement stabilized soil interlocking Blocks	67
	3.2 Method 2 – Cement Stabilized Soil Interlocking Blocks	
	Reinforced with Bamboo	68
	3.2.1 Properties of Bamboo	68
	3.2.2 Reinforcing using Bamboo as reinforcing material	69
4	EXPERIMENTAL APPROACH	70
	4.1 Introduction to In-plane Cyclic test	71
	4.2 Construction Details of Test Walls	72
	4.2.1 Building Materials	72
	4.2.2 Configuration of Panels	73
	4.3 Construction Procedure	74
	4.4 Test Set-up and Instrumentation	74

	4.5 Method of Testing	75
	4.5.1 Review of Structural Seismic Design	75
	4.5.2 Adopted Method of Testing	76
	4.5.3 Planned Loading Cycle	77
	4.5.4 Definitions use in Test Descriptions	77
	4.6 Results	78
5	MODELING OF A DOMESTIC BUILDING WITH PROPOSED EARTHQUAKE RESISTANT TECHNIQUES	81
	5.1 Description of the typical house used for analysis	82
	5.2 Structural Analysis with SAP 2000 for un-reinforced cement stabilized soil interlocking Blocks	84
	5.3 Structural Analysis with SAP 2000 for cement stabilized soil interlocking blocks with steel reinforcement	89
	5.4 Structural Analysis with SAP 2000 for cement stabilized soil interlocking blocks reinforced with bamboo	93
6	CONSTRUCTION METHODOLOGIES OF THE PROPOSED TECHNIQUES	97
	6.1 Option I – Steel reinforced cement stabilized soil interlocking blocks	98
	6.1.1 Cement stabilized soil interlocking blocks	98
	6.1.2 Reinforcing Cement Stabilized Soil Interlocking Blocks	100
	6.2 Option II – Cement stabilized soil interlocking blocks Reinforced with bamboo	102
7	DESIGN METHODOLOGIES AND COST ANALYSIS	105
	7.1 Design Methodology	106
	7.1.1 Calculation of Total weight of the building	107
	7.1.2 Calculation of the fundamental natural frequency of The building	108
	7.1.3 Determination of the Base Shear Force	109

7.1.4	Distribution of Floor shear among the walls	111
7.1.5	Calculation of design resistance and checking with the Design effects	113
7.2	Cost Analysis	118
7.2.1	Introduction	118
7.2.2	Calculations and comparisons	118
8	CONCLUSIONS AND FUTURE RECOMMENDATIONS	122

REFERENCES



University of Moratuwa, Sri Lanka.
Electronic Theses & Dissertations
www.lib.mrt.ac.lk

LIST OF FIGURES

Figure 2.1: Effect of inertia in a building when shaken at its base	11
Figure 2.2: Inertia force and relative motion within building	11
Figure 2.3: Principal directions of building	13
Figure 2.4: Flow of inertia forces through all structural components	13
Figure 2.5: Cracking due to Bending and Shear	15
Figure 2.6: Fall of Roof	15
Figure 2.7: Failure modes for masonry walls subjected to in-plane loads	18
Figure 2.8: Mechanism of action of vertical and horizontal reinforcement of a Masonry wall failing in shear	18
Figure 2.9: Gable band and roof band in a building	20
Figure 2.10: Pulling and bending of bangs	20
Figure 2.11: Cross section of lintel bands	21
Figure 2.12: Horizontal RC bands in masonry building	21
Figure 2.13: Reinforcement in RC band	21
Figure 2.14: Recommended joint details with the vertical reinforcement	22
Figure 2.15: Overall arrangement of reinforcing masonry buildings	23
Figure 2.16: Assembling of crushed canes for the horizontal wall reinforcement	24
Figure 2.17: Assembling of crushed canes for the horizontal wall reinforcement	24
Figure 2.18: Brick Nogged Timber Frame	25
Figure 2.19: Rat Trap Bond	26
Figure 2.20: Positioning off brick courses	27
Figure 2.21: Rattrap bond methods	27
Figure 2.22: Laying of bricks	28
Figure 2.23: L and T Corners in the wall	28

Figure 2.24: At door opening	29
Figure 2.25: At window opening	29
Figure 2.26: Rat trap bonded masonry brick	29
Figure 2.27: T joint with vertical r/f	30
Figure 2.28: L joint with vertical r/f	30
Figure 2.29: 190mm block series	33
Figure 2.30: Form Bridges	33
Figure 2.31: Positioning of Starter Bars	33
Figure 2.32: Base Course	34
Figure 2.33: Installation of Bridges	34
Figure 2.34: Corner and End Detail	35
Figure 2.35: Laying Subsequent Courses	35
Figure 2.36: Horizontal Steel Placement	35
Figure 2.37: Cutting Form Blocks	36
Figure 2.38: Grout Filling	37
Figure 2.39: A typical confined masonry building	38
Figure 2.40: Confined masonry construction in Slovenia, with the walls built using hollow clay tiles	39
Figure 2.41: Confined masonry construction	40
Figure 2.42: Pre-stressed masonry construction	42
Figure 2.43: Clay unit used with tendons	43
Figure 2.44: Effect of offset openings	44
Figure 2.45: Cast-in-place anchor	45
Figure 2.46: Bottom anchor method	46
Figure 2.47: Design detail for new construction	46

Figure 2.48: Tightening of the tendons	47
Figure 2.49: Tying of walls with steel mesh reinforcement	48
Figure 2.50: Tying of walls with steel mesh reinforcement-a detail	48
Figure 2.51: RC bond beam -splicing of rebars at wall corners	49
Figure 2.52: Connections of wall to foundation using rebar	49
Figure 2.53: Wall to column connection	50
Figure 2.54: For the direction of earthquake shaking shown, wall B tends to fail	51
Figure 2.55: Wall B properly connected to wall A: walls A (loaded in strong direction) support walls B (laded in weak direction)	51
Figure 2.56: Timber roof anchorage to bond beam	52
Figure 2.57 Distribution of structural walls in plan	53
Figure 2.58 Examples of regular configuration of masonry buildings	53
Figure 2.59 Irregular masonry buildings should be separated in regular sections	54
Figure 2.60 Wall repaired with reinforced cement coating	59
Figure 2.61 Pre-stressed wall	60
Figure 2.62 Wall tied with steel ties	61
Figure 2.63 Layout of masonry wall strengthened with steel strips	62
Figure 2.64 Placement of new column in a masonry wall	63
Figure 2.65 GFRP laminated wall	64
Figure 3.1 Reinforcing cement stabilized soil interlocking blocks	67
Figure 3.2 : Reinforcing with Bamboo	69
Figure 4.1 Model prior to testing	71
Figure 4.2 Model after the testing	71
Figure 4.3: Configurations of proposed block	72
Figure 4.4: Wall panel without method	73

Figure 4.5: Wall panel with method	73
Figure 4.6: Construction procedure	74
Figure 4.7: Proposed Elevation	74
Figure 4.8: Actual Arrangement	75
Figure 4.9: Response spectra	75
Figure 4.10: Loading cycle Vs Force	77
Figure 4.11: Expected and experimental crack patterns of non-reinforced panel	79
Figure 4.12: Expected and experimental crack patterns of reinforced panel	80
Figure 5.1 Plan of the typical house	82
Figure 5.2 Elevations and Sections of the typical house	83
Figure 5.3: Seismic Response Spectrum	84
Figure 5.4 Stress Distribution of the block model for $E=0.1\text{N/mm}^2$ – X dir	85
Figure 5.5 Stress Distribution of the block model for $E=0.2\text{N/mm}^2$ – X dir	85
Figure 5.6 Stress Distribution of the block model for $E=0.3\text{N/mm}^2$ – X dir	86
Figure 5.7 Stress Distribution of the block model for $E=0.4\text{N/mm}^2$ – X dir	86
Figure 5.8 Stress Distribution of the block model for $E=0.1\text{N/mm}^2$ – Y dir	87
Figure 5.9 Stress Distribution of the block model for $E=0.2\text{N/mm}^2$ – Y dir	87
Figure 5.10 Stress Distribution of the block model for $E=0.3\text{N/mm}^2$ – Y dir	88
Figure 5.11 Stress Distribution of the block model for $E=0.4\text{N/mm}^2$ – Y dir	88
Figure 5.12 Structural Model after reinforcement	89
Figure 5.13 Stress Distribution of steel reinforced model without connectivity – X dir	90
Figure 5.14 Stress Distribution of steel reinforced model without connectivity – Y dir	91
Figure 5.15 Stress Distribution of steel reinforced model with connectivity – X dir	91
Figure 5.16 Stress Distribution of steel reinforced model with connectivity – Y dir	92

Figure 5.17 Structural Model of the Reinforced Structure with Bamboo	93
Figure 5.18 Stress Distribution of bamboo reinforced model without connectivity – X dir	94
Figure 5.19 Stress Distribution of bamboo reinforced model without connectivity – Y dir	94
Figure 5.20 Stress Distribution of bamboo reinforced model with connectivity – X dir	95
Figure 5.21 Stress Distribution of bamboo reinforced model with connectivity – Y dir	95
Figure 6.1 CSSIB Blocks	98
Figure 6.2 Crossbar splitter	103
Figure 6.3 Other splitting methods	103
Figure 6.4 Mechanical splitter	103
Figure 7.1: Flow chart showing the design methodology	106
Figure 7.2: Cost Comparison of Different Wall Types	120
Figure 8.1: Lateral load Vs lateral displacement curves	124
Figure 8.2: Idealized component behaviors from backbone curves	124

LIST OF TABLES

Table 2.1: A comparison between the confined masonry and RC frame Construction	40
Table 2.2: Distance between masonry bearing walls and wall openings	56
Table 4.1: Average test results for reinforced masonry panel	78
Table 4.2: Average test results for non-reinforced masonry panel	78
Table 5.1 Summary of the Analysis Results for various values of E	89
Table 5.2a Maximum Stresses in shells after the analysis (without connectivity)	96
Table 5.2b Maximum Stresses in shells after the analysis (with connectivity)	96
Table 7.1: Cost of the house with Construction of Different Wall Types	120
Table 7.2: Cost per unit area of the house with Construction of Different Wall Types	121

