SEISMIC PERFORMANCE OF TUNED LIQUID DAMPER IN NOVEL WALL INTERLOCKING BLOCK

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

JULY 2016

To my beloved family and parents

ACKNOWLEDGEMENT

Having nearly unable to complete Doctorate research because of personal commitments, but after which by putting in countless determination, perseverance and discipline, I have managed to complete it. I would like to convey that the research would not have been completed without the assistance and support of those who guided me in the course of my Doctorate research, be it from Professors to industries, or, from undergraduate students to family members. In preparing this thesis, I come across with many people, they have contributed towards my understandings and thoughts. In particular, I wish to express my sincere appreciation to my supervisor, Professor Dr. Azlan Adnan, for his encouragement, support, guidance, critics and friendship. Without his continuous support, this thesis would not have been completed. In addition to valuable advices provided from Professor Dr. Kenny Kwok of University Western Sydney, who has been very encouraging and has always become a role model figure for all his students.

I would like to acknowledge the student financial contributions from the Ministry of Science, Technology and Innovation, apart from the University Teknologi Malaysia through the Engineering Seismology and Earthquake Engineering Research (e-SEER) group and the technicians’ assistance in making the research successful.

My sincere appreciation goes to all my colleagues and friends who have provided assistances in various occasions in my life. Their views, tips and helps have been very useful indeed. Unfortunately, it would not be possible to list all of them in this limited space.

Lastly but not the least, I am grateful to my family members, in particular, my parents, for their loves, cares, supports, understandings and daily encouragements. In addition to my new family member, the dedication has to go to my daughter, Sze Ting (Alicia), she has given me strength and purpose in my life. I would like to note that when everything seemed far from reaching the completion of the thesis, while maintaining works requirements and the family needs, the God has given me the will of the family power to continue on and complete my PhD’s journey.

ABSTRACT

Building structural vibrations are generally regarded to be a serviceability problem, mainly affecting the architectural façade, and occupant comfort. However, in extreme cases such as earthquakes, it may lead to structural collapse. The excessive building vibrations are sometimes seen due to the resonant effect. In this study, the following blocks were proposed and investigated: Tuned Liquid Damper block (i-Block), Friction Damper block (B-Block) and vertical supporting block (V-Block). The newly developed non-loadbearing cement interlocking-block masonry was incorporated with damping characteristics. The laboratory study has identified Young's modulus of 3.3 N/m^2 and Poisson's ratio of 0.278 to be most optimum for dry-mix concrete. Meanwhile, based on various robustness tests, the i-Block was found to possess the most suitable mechanical properties for interlocking block damper. Geometrical aspects of the i-Block were fixed at internal dimensions of 190 mm (length) x 60 mm (width) x 90 mm (height) with varying water depth, d_w in the range of 0 mm to 80 mm. In the dynamics tests, resonant Transmissibility's ratio plot approaches were used to compare the control sample with different d_w. The responses of sine-sweep resonant test have shown the increasing damping values which were compared by simulation and empirical calculation. It was found that natural frequencies, f_n obtained from the test were considerably matching the numerical simulation and empirical calculation. Interestingly, a small portion of water at 5 mm d_w was sufficient to increase the damping ratio of the overall performances. In the seismic simulation, the Northridge, El Centro and Loma Prieta ground motion were numerically simulated by Ansys software. The peak ground base shears to displacement hysteresis on structural responses have been reduced by 19%, 26% and 35% for Northridge, El Centro and Loma Prieta's earthquakes respectively. Meanwhile, effective performances were observed at the top floor level in relation to the mass of lower water contents to overall structure mass ratio requirement. Therefore, i-Block can be used to provide damping and reduce responses to building from earthquake disasters.

ABSTRAK

Getaran pada struktur bangunan biasanya dikaitkan dengan masalah had kebolehkhidmatan bangunan, terutamanya pada facade arkitek, dan keselesaan penghuni. Namun, dalam kejadian-kejadian yang esktrem, ia mungkin menyebabkan keruntuhan bangunan. Kejadian getaran bangunan yang berlebihan ini adalah disebabkan oleh kesan resonans. Dalam kajian ini, batu-batu blok saling kunci yang dikaji terdiri daripada *blok meredam jenis cecair tertala-TLD* (i-Blok), *blok meredam jenis geseran* (B-Blok) dan *blok menyokong menegak* (V-Blok). Perkembangan baru batu blok simen saling kunci tanpa keupayaan sokongan secara struktur telah digabungkan dengan pelbagai peredam. Keputusan kajian mendapati sifat-sifat bahan modulus Young pada 3.3 N/m^2 dan nisbah Poisson pada 0.278 adalah sesuai untuk konkrit campuran kering. Sementara itu, berdasarkan kepada sifat-sifat mekanik daripada ujian-ujian keteguhan, i-Blok dikenalpasti sebagai blok peredam saling kunci yang paling sesuai. Dari segi geometrinya, dimensi dalaman ditetapkan pada 190 mm (panjang) x 60 mm (lebar) x 90 mm (tinggi) dan kedalaman air, d_w dalam julat 0 mm hingga 80 mm. Dalam ujian-ujian dinamik, plot-plot Nisbah Kebolehpindahan resonan telah digunakan untuk menbandingkan sampel kawalan dengan setiap kedalaman air tersebut. Keputusan pada ujian resonan *sine-sweep* menunjukan peningkatan pada nilai-nilai redaman yang dibandingan dengan bacaan nilai simulasi dan pengiraan empirikalnya. Selain itu, pertambahan kecil air dengan kedalaman 5 mm memadai untuk menaikan nisbah redaman secara keseluruhan. Dalam simulasi seismik, pergerakan tanah gempa bumi daripada Northridge, El Centro dan Loma Prieta telah disimulasikan menggunakan perisian komputer Ansys. Pergerakan gempa bumi daripada keputusan histerisis ricih tapak kepada pesongan ke atas struktur berkurang sebanyak 19%, 26% dan 35% bagi gempa bumi Northridge, El Centro dan Loma Prieta. Di samping itu, prestasi yang lebih baik didapati berlaku di aras tingkat atas, ia berhubung dengan nisbah jisim kandungan air yang rendah berbanding dengan jisim keseluruhan struktur bangunan tersebut. Oleh itu, i-Blok didapati dapat memberikan peredaman dan pengurangan tindak balas daripada bencana gempa bumi.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xii
	LIST OF FIGURES	xiv
	LIST OF ABBREVIATIONS	xix
	LIST OF SYMBOLS	xxi
	LIST OF APPENDICES	xxv
1	**INTRODUCTION**	**1**
	1.1 General	1
	1.2 Background and Problem Statement	2
	1.3 Objectives	3
	1.4 Scope and Limitation of Study	4
	1.5 Significant of Study	5
	1.6 Outline of Thesis	5
2	**LITERATURE REVIEW**	**8**
	2.1 Introduction	8
	2.1.1 Structural Retrofitting Systems	10
	2.1.2 Masonry block	13
	2.1.3 Masonry Block Interlocking System	15
	2.2 Dry-cast Nonloadbearing Concrete Blocks	16
	2.3 Tuned Liquid Damper	17

2.3.1 Principle of Tuned Liquid Damper 18
2.3.2 Current Application and Problem of Tuned Liquid Damper 20
2.4 Mathematical background 23
2.5 Numerical Simulation 26
2.6 International Seismic Design Requirement 28
2.7 Search of Other Wall Interlocking Block Dampers 30
2.8 Passive Damper As Wall Interlocking Block Damper 31
2.9 Dynamic Simulation of Unrestrained Interlocking Tuned Liquid Damper Blocks 33
2.9.1 Random Excitation by the Probability Density Function Prediction Method 34
2.9.2 Seismic Simulation on Masonry Blocks 35
2.10 Research Gap 38

3 METHODOLOGY 40
3.1 Introduction 40
3.2 Type of Block Dampers 42
3.2.1 i-Block 43
3.2.2 V-Block and B-Block 44
3.3 Material Properties 45
3.3.1 Fine Aggregate 47
3.3.2 Cube test 49
3.3.3 Prism 51
3.3.4 Cylinder 52
3.3.5 Young’s Modulus Determination 54
3.4 Specimen Preparation 56
3.4.1 Capping 59
3.4.2 Loaded Area 60
3.4.1 Dimension 61
3.5 Dynamic Experimental Test 62
3.6 Numerical Modelling 63

3.7 Concluding Remarks 64

4 DEVELOPMENT OF NEW INNOVATIVE INTERLOCKING BLOCK WITH VIBRATION RESISTANCE 66
4.1 Introduction 66
  4.1.1 Methodology 67
4.2 Experimental Studies on Individual Blocks 69
  4.2.1 Specimen Preparation 69
    4.2.1.1 i-Block 70
    4.2.1.2 V-Block 71
    4.2.1.3 B-Block 72
  4.2.2 Results and Discussions 73
4.3 Experimental Studies on Column Blocks 77
  4.3.1 Specimen Preparation 77
  4.3.2 Results and Discussions 77
4.4 Nonlinear Static Modelling of Masonry Unit 81
  4.4.1 Results and Discussions 83
    4.4.1.1 Failure Mode of V-Block 84
    4.4.1.2 Failure Mode of B-Block 88
    4.4.1.3 Failure Mode of i-Block 92
4.5 Shear Interlocking Test Preparation 95
  4.5.1 Results and Discussions 96
4.6 Block Passive Energy Dissipation 97
4.7 Concluding Remarks 99

5 DYNAMIC SIMULATION OF UNRESTRAINED INTERLOCKING TUNED LIQUID DAMPER BLOCKS 102
5.1 Introduction 102
5.2 Tuned Liquid Damper Calculation 102
5.3 Methodology 104
  4.3.1 Material Properties 105

5.3.2 Experimental Test 106
5.3.3 Numerical Modelling 106
5.4 Results and Discussion 110
5.4.1 Experimental Consideration 110
5.4.2 Numerical Analysis of TLD Blocks 111
5.4.3 Forced Excitation Response Function 113
5.4.4 Comparison to Numerical Analysis and Test Results 116
5.4.5 Damping Considerations 120
5.5 Concluding Remarks 125

6 SEISMIC SIMULATION FOR PEAK GROUND EXCITATION ON NEW TUNED LIQUID DAMPER INTERLOCKING BLOCKS RESPONSES 128
6.1 Introduction 128
6.2 Methodology 129
6.2.1 Experimental Testing 131
6.2.2 Numerical Modelling 132
6.3 Results and Discussions 133
6.3.1 Induced Acceleration and Natural Frequency under constant amplitudes and varying frequency 133
6.3.2 Damping ratios characteristics 134
6.3.3 Overturning Moment Induced Based Shear 138
6.3.4 Structural Damping Ratio to Different Structure Level 140
6.3.5 Experimental Transmissibility Results on the Structure and TLD Blocks 141
6.3.6 Comparison of Responses between the Control Sample with Various TLD Depth by Analytical Approach 143
6.3.7 El Centro, Northridge, and Loma Prieta Time History Analysis with Seismic

Excitation 144

6.3.7.1 Peak Ground Acceleration 148

6.3.7.2 Peak Ground Displacement 150

6.3.7.3 Base Shear 151

6.4 Concluding Remarks 153

7 CONCLUSION AND RECOMMENDATION 155

7.1 Introduction 155

7.2 Conclusions 155

7.3 Demerit of i-Block 158

7.4 Recommendations 159

REFERENCES 161

Appendices A – K 177-228

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Structural protection systems	8
2.2	Passive Energy Dissipation for vibration mitigation for vibration mitigation structures by Tuned Liquid Dampers (TLDs) (Chaiviriyawong and Prachaseree, 2010)	17
3.1	Summary of material properties	47
3.2	Fineness modulus with weight of retained fine aggregate	48
3.3	The percentages of moisture contents in natural sand	49
3.4	Proposed trial mix of cube compressive strength	50
3.5	Modulus of rapture for the concrete blocks in the 28 days cast	52
3.6	Splitting tensile test for the concrete blocks in 28 days cured	53
3.7	Topping mix design	60
3.8	Dimension checking	61
3.9	Thickness correction factor for masonry compressive strength	62
4.1	Seer i-Block individual compression strength	71
4.2	V-Block individual compression strength	72
4.3	B-Block individual compression strength	73
4.4	Summary of compression tests to simulation samples and displacement in lateral and vertical directions	74
4.5	Density material properties rolling average to compressive strength	80

4.6 Material mixture #4 cement brick physical properties 81

5.1 Block with different depth of water in comparison to calculated, simulated (1st Mode) and tested natural frequency (1st Mode) 111

5.2 Numerical simulations and tests results verification summary 119

6.1 Table indicating the characteristics of the TLD blocks to the heights of the structural frequency* 135

6.2 Table Critical damping ratio obtained from sinesweep half-power bandwidth 138

6.3 Combined block to structure displacement at various responses at test and numerical simulation 144

6.4 Summary of the peak displacement, acceleration and base shear responses under Northridge, El Centro and Loma Prieta Earthquake. The results show the numerical excitation with and without TLD blocks 153

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Seismic application of Passive Energy Dissipation (PED) in North America (Soong & Spencer Jr, 2002)	9
2.2	Schematic passive energy damper: (a) Conventional Structure, (b) Structure with Passive Energy Dissipation (PED), (c) Structure with Active Control, (d) Structure with Hybrid Control, and (e) Structure with Semi Active Control (Soong & Spencer Jr, 2002)	12
2.3	Schematic of Tuned Liquid Damper family (Nanda, 2010)	18
2.4	The equivalent TMD model of the TLD	23
2.5	Rectangular and circular TLD configuration	25
2.6	Performance of the ground motion to building performance levels by NEHRP Seismic Use Groups (NEHRP, 2000)	29
3.1	Overall flow chart of methodology in determining dynamics performance of tuned liquid damper in wall interlocking block	41
3.2	i-Block layout from the front and back view	44
3.3	V-Block with vertical element at the middle of the block	44
3.4	B-Block with diagonals embracing in two directions	45
3.5	Material grading of retained sand versus sieve size for natural aggregate in sample 1, 2 and 3	49

3.6 The placement of Young’s modulus and Poisson’s ratio a) TINIUS OLSEN Super “L” Universal Testing Machine with 3MN capacity and b) close-up strain measuring arrangement 55
3.7 Typical stress-strain curves of dry-mixed concrete 56
3.8 Test model setup in site and elevation view on the shake table 63
3.9 2D block simulation for i-Block was first modelled and meshed 64
4.1 Schematic flow chart 67
4.2 Compression tests on individual block for (a) i-Block, (b) B-Block and (c) V-Block were analysed for compression testing 69
4.3 Seer i Block dimension measurement 70
4.4 V Block dimension measurement 71
4.5 B-Block dimension measurement 72
4.6 Series of group testing on the i-Block 77
4.7 Block stacking test samples on i-Block: normal, failure mode 1 and mode 2 78
4.8 2D blocks simulation of (a) V-Block, (b) B-Block and (c) i-Block was first modelled for further analysis 82
4.9 Figure crack propagation on one of test samples of i-Block 84
4.10 V-Block y-direction displacement – half, before failure, after failure 85
4.11 V-Block y-direction stress – half, before failure, after failure 86
4.12 Physical failure mode of four numbers of V-Blocks 87
4.13 B-Block y-direction stress – half, before failure, after failure 89
4.14 B-Block y-direction stress – half, before failure, after failure 90
4.15 Physical failure mode of four numbers of B-Blocks 91

4.16 i-Block y-direction stress – half, before failure, after failure 93

4.17 i-Block y-direction stress – half, before failure, after failure 94

4.18 Physical experimental results of four numbers of i-Blocks 95

4.19 Push-over shear tests on i-Block groove and tongue locking area 96

4.20 Block shear interlocking test samples on (a) i-Block in 90 phase angle orientation, (b) failure mode 1, and (c) failure mode 2 97

4.21 (a) Preliminary experiment with harmonic excitation and (b) damped structural response in acceleration 99

5.1 Chapter 5 Schematic flow chart for dynamic determination summary 104

5.2 Block at (a) no TLD, at (b) increment of TLD to (l) full capacity at air flow valve or overflow outlet of the surface opening level 108

5.3 Comparison of TLD natural frequency in (a) simulation and testing, and (b) empirical calculation and testing verification plots 110

5.4 Typical simulation verification to test at first mode frequency of 1.058 Hz of 60 mm depth of block 112

5.5 Verification of displacement transmissibility, u_t/u_g to frequency ratio, ω/ω_n with block at various depth of (a) 0 mm, (b) 5 mm, (c) 10 mm, (d) 15 mm, (e) 20 mm, (f) 25 mm, (g) 30 mm, (h) 40 mm, (i) 50 mm, (j) 60 mm, (k) 70 mm, and (l) 80 mm, respectively. Continuous line indicated the simulation, while dot line indicated the test; in sine-sweep responses 118

5.6 Pseudo absolute displacement of various combinations to equivalent damping parameters in absent of damping block in numerical model. 124

5.7	Critical damping ratio sudden increment to the overall structural performance by using TLD retrofitting system as soon as 5 mm water was added to the system	125
6.1	Schematic flow chart of seismic simulation	130
6.2	Sine-sweep excitation with ground motion displacement, u_g of 2 mm in steady-state time history as in (a) 0.95 Hz, (b) 1.05 Hz, and (c) 1.15 Hz	134
6.3	Transmissibility of (a) 0 mm and (b) 5 mm observed one degree of freedom observed	135
6.4 (a) & (b)	Two degree of freedom responses observed from the vibration analysis	136
6.5	Critical Damping Ratio to block water depth at overall structural performance	137
6.6	(a) Stiffness Damping Constant, and (b) Mass Damping Constant to block water depth to block water depth at overall structural performance	138
6.7	Maximum overturning moment to the structure in sinesweep excitation at control blocks to the overall average M_o, and Δd of 5 mm and 60 mm	139
6.8	Test structure damping ratio according to different depth, d_w of TLD block at Top, Middle and bottom level of test structure	140
6.9	Comparison of test resonant responses of Pseudo absolute transmissibility acceleration, a_t/a_g at the topmost level to sine-sweep excitation on 0 mm to various to (a) 5 mm (b), 10 mm (c) 15 mm, (d) 20 mm, (e) 25 mm, (f) 30 mm, (g) 40 mm, (h) 50 mm, (i) 60 mm, (j) 70 mm, (k) 80 mm, and (l) 80 mm depth TLD	143
6.10	Time history ground acceleration based on (a) El Centro, (b) Northridge, and (c) Loma Prieta with minimum time step of 0.1 seconds for structure and TLD blocks excitation	145

6.11 (a) Northridge, (b) El Centro and (b) Loma Prieta hysteretic responses to base shear versus displacement 148
6.12 Structure and TLD blocks peak acceleration initial responses based on Northridge, El Centro and Loma Prieta time history 149
6.13 Structure and TLD blocks peak displacement initial responses based on Northridge, El Centro and Loma Prieta time history 150
6.14 Structure and TLD blocks base shear according to the initial responses of peak acceleration and displacement based on Northridge, El Centro and Loma Prieta time history 152

LIST OF ABBREVATIONS

TLD - Tuned Liquid Damper
TMD - Tuned Mass Damper
FD - Friction Damper
VD - Viscous Damper
URM - Unreinforced Masonry
PGA - Peak Ground Acceleration
2D - Two Dimension
UBC - Uniform Building Code
PED - Passive Energy Dissipation
SDOF - Single-Degree-Of Freedom
ACI - American Concrete Institute
C - Circular Sloshing
RU - Rectangular - Unidirectional
MTLD - Multiple Tuned Liquid Damper
TLMD - Tuned Liquid Mass Damper
TLCD - Tuned Liquid Column Damper
FFT - Fast Fourier Transform
PSD - Power Spectral Density
LCBD - Liquid Column Ball Damper
ATLD - Annular Tuned Liquid Dampers
CLCD - Circular Liquid Column Damper
LCVA - Liquid Column Vibration Absorbers
ICC - International Code Council
IBC - International Building Code
SBC - Standard Building Code
BOCA - Building Officials and Code Administrators, Inc.
NEHRP - National Earthquake Hazards Reduction Program

NSD	-	Nonlinear Stiffness and Damping
SBC	-	Slotted Bolted Connection
FM	-	Fineness Modulus
ASTM	-	American Society for Testing and Materials
BS	-	British Standard
LVDT	-	Linear Variable Differential Transducers
MS	-	Malaysian Standard
R&D	-	Research and Development
OPC	-	Ordinary Portland Cement
MDOF	-	Multi-Degree-Of-Freedom
KLIA	-	Kuala Lumpur International Airport
PEER	-	Pacific Earthquake Engineering Research Centre
MBS	-	Maximum Base Shear

LIST OF SYMBOLS

g - Gravity= 9.81m/s^2

f_n - Natural/Fundamental Frequency

m_w - Mass of Water

m_d - Mass of Damper

F_w - Forced Resistance of Water

k_d - Stiffness with Damping

F_d - Damping Force

c_d - Critical Damping

F_d - Forced Resistance of damper

f_w - Sloshing Motion

L - Length of Tank

D - Diameter of Tank

h_0 - Undisturbed Water Depth

F_h - Hydrodynamic Force

ρ - Water Density

b - Tank Width

h_l - Left Water Surface Elevations

h_r - Right Water Surface Elevations

f'_c - Compressive Strength

R - Modulus of Rapture

P - Applied Load

d - Average Depth for Modulus of Rupture

b - Average Width for Modulus of Rupture

l - Length of Splitting Tensile Strength Cylinder

d - Diameter of Splitting Tensile Strength Cylinder

T - Splitting Tensile Strength

f_{cu} - Compression Strength of Cube

t_{p1} - Thickness of block #1 check in accordance to BS 6073
t_{p2} - Thickness of block #2 check in accordance to BS 6073
t_{p3} - Thickness of block #3 check in accordance to BS 6073
h_p - Height of block in accordance to BS 6073
f_m - Compressive Strength of Masonry
f_{mt} - Compressive Strength after Adjustment
P_{min} - Stress at Minimum Test
P_{max} - Stress at Maximum Test
S_{max} - Lateral Displacement, mm
S_{min} - Vertical Displacement
x - Degrees of Freedom in the translations of nodal x direction
y - Degrees of Freedom in the translations of nodal y direction
d_w - i-Block Water Depth
u_t - Top Displacement
u_g - Ground Displacement
ω - Forced Excitation Natural Frequency
ω_n - Angular Natural frequency
f_{UBC} - Uniformed Building Code rule of thumb for building natural frequency
α - Mass-weighted Proportional Damping Coefficient
β_i - Stiffness Hysteresis for Solid Proportional Damping Coefficient
M - Mass Proportional Matrix Forms
K - Stiffness Proportional Matrix Forms
C - Damping Proportional Matrix Forms
ξ - Critical Damping
E - Modulus of Elasticity
H - Height of Structure
L - Length of Structure
I - Moment Inertial
w_s - Structural Mass
w_b - TLD Block Unit Mass
w_f - Frequency Calibrated Additional Mass

w_c - Unit Mass of TLD Block Container
W - Total Mass
T - Structure Period
$\ddot{x}$ - Acceleration
θ - Phase Angle
A_0 - Amplitude
f_1 - Frequency band 1 when $f_{res}/\sqrt{2}$
f_2 - Frequency band 2 when $f_{res}/\sqrt{2}$
f_{res} - Frequency at Resonance
x_n - Modal Amplitude
$\emptyset_n$ - Mode Shape Vector
K_n - Modal Stiffness
β_n - Frequency Ratio
u_i, - Displacement at i DOF in n mode
u_j - Displacement at j DOF in n mode
f_i - Force Amplitude in DOF of i
m_d - Absorber Mass (water), kg
M - Generalized Mass of Primary Structure, kg
f_w - Fundamental Natural Frequency of the water, Hz
f_s - Fundamental Natural Frequency of the structure, Hz
h_0 - Water Depth, m
g - Gravity Acceleration, m/s^2
L - Length of Tank, m
D - Diameter of Tank, m
c_d - Equivalent Viscous Damping of damper, N.s/m
c_s - Equivalent Viscous Damping of structure, N.s/m
w_s - Structural Weight, kg
μ - Mass Ratio
β - Tuning Ratio of natural frequency of damper to structure
ϕ - Normalized Modal Deflection
ω_δ - Damped Angular Natural Frequency of damper, Hz
ω_σ - Natural Frequency of structure, Hz

ξ - Damping Ratio

ξ_δ - Absorber Damping Ratio

ξ_σ - Structural Damping Ratio

V - Base Shear

M_0 - Overturning Moment

Δd - Water Depth

m_c - Container Weight

m_s - Required Structural Weight

T_{TLD} - Tuned Liquid Damper Natural Period

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Technical Description	177
B	Tuned Liquid Damper Block (i-Block) Versions	180
C	Manufacturing Process	183
D	Endurances of Tuned Liquid Damper (i-Block)	187
E	Shake Table Test on Symmetrical Structure with Tuned Liquid Damper Under Random Excitation by Probability Density Function Solution	188
E(A)	Model Configurations Approximation Chart	209
E(B)	Equivalent Damping System	209
E(C)	Random Vibration Model	210
F	Harmonic Vibration Model	211
G	Controller to Shake Table Calibration Chart	212
H	i-Block Design (30% height)	217
I	i-Block Design (70% height)	218
J	Northridge Earthquake, El Centro, & Loma Prieta results	219
K	Macro files coding	228

CHAPTER 1

INTRODUCTION

1.1 General

Undesirable vibrations of lightly damped flexible modern structures have created concern in the structural engineering community. Although these vibrations are related to serviceability problems, such as occupant comfort and cladding integrity, rather than affecting the primary load-bearing capacity, the economic considerations are also significant. The most promising solution to mitigating these vibrations is through the use of artificial damping devices.

In previous years, one type of passive damping system, called the tuned liquid damper (TLD) has been successfully employed in practice, e.g., Tamura *et al.* (1988); Fujii *et al.*(1990); Wakahara *et al.* (1992) and Fediw *et al.* (1995). Although this type of device has many advantages, the mechanism by which it dissipates energy related to undesirable vibrations is not completely understood, nor has it been thoroughly investigated.

In spite of Computational Fluid Dynamics at its infancy, numerical simulation has gained popularity with researchers. In present day, the latest research could be obtained from Chang *et al.* (2010), Samanta & Banerji (2010), Li *et al.* (2012), and Kaneko & Ishikawa (2015), to name a few. The development of the Tuned Liquid damper has been effectively described and analytically tested on the effect of hydraulic resistance produced by installed tank on the performance of the examined TLDs.

The primary objective of this study is to experimentally and numerically investigate the behaviour of tuned liquid dampers in order to identify the underlying physical phenomenon of the liquid sloshing behaviour that has contributed to the damping characteristics of the Tuned Liquid Damper Block. A new interlocking block has been developed which incorporated the knowledge and technology with design emphasis on the development of vibration resistance.

1.2 Background and Problem Statement

Despite several successful applications as well as numerical and experimental investigations of the TLD behaviour, there currently exist limitations which restrict the designer's ability to effectively employ the TLD as a damping device. These limitations include, but are not limited to, the following:

1. Masonry system has been used in existing construction materials for a long time but the consideration for alternative block has been limited. The masonry system provides shelter and safety for human to live in, however, under the action of one or combination of wind or earthquake, building can be very sensitive to natural excitations. These excitations may cause the building to experience

structural failure. Passive damping masonry as an alternative for existing expensive damping required to be proposed and studied as the internal wall.

2. It was commonly accepted that Unreinforced Masonry (URM) structures are the most vulnerable during earthquake by Li *et al.* (2001), but excessive building responses to the overall structure have been identified to be detrimental during the resonant effect. Passive block damper dynamic properties in its optimum level and damping consideration required attention.

3. The question arises to most practitioners why bother earthquake masonry block? It has been noted global earthquake El Centro, Northridge, and Loma Prietra happened and immediately changed the engineering evolution. The impending natural issue required immediate call for reviewing on the block dampers which has always been the main part of the construction materials. Meanwhile, in Malaysia, Kuala Lumpur is subjected to 0.12g Peak Ground Acceleration (PGA) time history in the latest study of Hamid and Mohamad (2013), yet earthquake analysis has not been an important design consideration to be incorporated in the building analysis. Study is required on passive blocks to enhance awareness so developing nation can understand the impending natural issue.

1.3 Objectives

In this study, we seek to investigate new masonry blocks with inherent damping characteristics that could withstand earthquakes. The objectives as below:

1. To propose new interlocking masonry blocks. Three types of blocks to be considered and incorporated with passive energy damping schemes. The blocks

to be numerically and experimentally tested to determine the material properties and its structural robustness.

2. To conduct testing and numerical simulation for the dynamics properties and damping consideration of the TLD blocks (i-Blocks), in order to compare the resonant responses of the TLD blocks in various depths for its increased damping solution.

3. To conduct multiple seismic simulations by combining the structure and TLD blocks (i-Blocks), in order to compare El Centro, Northridge, and Loma Prietra time history for its reduction in the performances.

1.4 Scope and Limitation

The scope of the thesis is listed below:

1. Two masonry blocks will be identified from site existing blocks, while one new block will be proposed and designed according to the damper requirements as Tuned Liquid Damper requires water tight container and a chamber in the proposed block.

2. Each of the blocks is to incorporate different damping system. Tuned Liquid Damper shall be incorporated in i-Block, while frictional and vertical bracing damping system for B-Block and V-Block respectively.

3. The i-Block characteristics were limited to internal dimensions of 190 mm (length) x 60 mm (width) x 90 mm (height) and the internal dimension of the Tuned Liquid Damper (TLD) cast in a concrete masonry unit to be subjected to a wide range of water depth from 5 mm to 80 mm.

4. Performance of TLD random excitation in the experiments was carried out in single directional configuration.

1.5 Significance of Study

Accelerated mortarless masonry constructions with distinctive features have been developed and used in different countries. However, many of the existing masonry system have not been able to withstand dynamic excitation. The new development of the non-load bearing cement interlocking-block masonry system (i-Block) incorporated damping characteristics. The innovation of the block is the Tuned Liquid Damper (TLD), based on the force excitation against the balancing act of the initial forces.

1.6 Outline of Thesis

In this thesis, a review of background information for this study has been presented. Following this review, an outline of the organization of this dissertation is provided as below:

Chapter 2 is the compilations of previous study on the successful applications of Tuned Liquid Dampers (TLDs) to civil engineering structures. It briefs on the general choices the structural engineer has in applying the damper in the building. Apart of the Tuned Liquid Damper and others, the study implied bricks and blocks as an option to masonry block dampers that this study has been undertaking. Thus, direction of the literature review also reported on the influence of the superior properties of the bricks has for building, civil engineering work, and landscape design.

Chapter 3 described the methodology on the work flow of the tests and simulation. Blocks were proposed in the study with consideration to the material properties. The methods used for dynamics experimental tests were described and justified. Followed by numerical modelling, the elemental formulation was briefed in respect for it being entitled to simulations. Further clarifications were detailed in subsequent chapters which deemed fit and paramount to be assigned in each chapter.

Chapter 4 presents study of the first objective on developing a new construction material as an alternative for expensive dampers. It explained on the robustness and characteristics of the vertical-supported block (V-Block); braced-supported block (B-Block) and block with liquid damper (i-Block). By experimental tests and numerical modelling, it was intended to investigate if the liquid damper can significantly enhance the overall performance of the block.

Chapter 5 described the second objective on the examination of the individual block on free vibration and harmonic characteristics to consider for the resonant effect of the building subjected to a wide range of water depth. It described about the successful applications of Tuned Liquid Dampers (TLDs) to masonry block. Further study of the combined structural model and TLD blocks test as a system has been compared with the experimental works and numerical simulations results. It was to investigate if the new innovative block with tuned liquid can significantly increase the damping characteristics.

In Chapter 6, numerical simulation scheme only has been used to model the interaction of a TLD in single degree-of-freedom structure with earthquake ground motions. The seismic excitation of the Northridge, El Centro and Loma Prieta ground motion were used. Each level of lower, middle and upper floor was evaluated. The last objective was to observe the structure and block seismic behaviour combined responses. Therefore, the proposed new masonry blocks suitability can be adopted to save building from earthquake disasters.

The last Chapter 7 concluded the Block study by summarizing the overall results and suggestions. Together with a new development of the block subjected to the disadvantages in its application. Finally, the future development and its recommendations of the block shall also be discussed to make sure the block to be as inclusive as possible as new seismic performance Tuned Liquid Damper interlocking block.

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