SEISMIC PERFORMANCE OF TUNED LIQUID DAMPER IN NOVEL WALL INTERLOCKING BLOCK

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To my beloved family and parents

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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.

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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

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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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