DEVELOPMENT OF HYBRID RUBBER-CONCRETE ISOLATION SLAB SYSTEM FOR 3D VIBRATIONS

By

FAYYADH NAHAL KAMIL FAYYADH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Nowadays, by utilizing structures with various machines and application of structures for operation of variety of trains, trucks or rotary mechanical machineries, the structural components are subjected to multi-directional vibrations as vertical and horizontal cyclic oscillations. The slabs are the main structural components which the dynamic loads, due to vibration generator machines, are imposed to it, and then the load is transferring to the foundation through the girders and columns. Recently, application of the rubber bearings as base isolator systems to dissipate imposed dynamic loads to the structure is frequently considered by design engineers. However, in order to implement the base isolation, it is required to construct each level of building as separated story which highly leads to reduce the lateral strength and stiffness of structure. Moreover, rotary machines induce 3D vibrations and the floating slab system, which implements rubber bearings with compression damping properties, is effective only for damping vertical vibrations rather than horizontal vibrations. Additionally, Regulation No.5 of the Malaysian Regulations for Factories and Machinery (1983) highlighted that any vibrating machinery should not be installed in floors higher than the ground level unless such floor is designed to support the load so imposed thereon. Therefore, the present research aimed to propose a hybrid rubber-concrete isolation slab system (HRCISS) by developing a floating slab system with implementing of high damping rubber in the intermediate layer of concrete slabs. The proposed HRCISS is composed of two upper and lower concrete slab panels with an intermediate layer of square-plan HDR bearings. The initial design details of HRCISS are developed and the performance of the system in reducing the vibrations in both horizontal and vertical directions and the applicability to diminish 3D vibrations is investigated through finite element simulation.

After finalizing the design, two prototypes for HRCISS have been manufactured and tested separately, each specimen at a time, under horizontal and vertical cyclic loads by using dynamic actuators in order to evaluate the performance of system and validate the numerical simulation. In order to assess the efficiency of the hybrid system in damping

3D vibrations, it is applied in a half-scale 3-story, 1-bay building and the capability of the system to protect the building from interior vibrations, i.e. machine vibrations as well as its ability to protect the machines from exterior vibrations, such as earthquakes, have been evaluated. The results have shown the effectiveness of the HRCISS in reducing deformations when compared to the conventional 3-story building. Furthermore, utilizing structure with the hybrid system appeared more effective in minimizing lateral drifts and inter-story drifts when it’s installed in lower levels with average 87.33% and 75.8% drop in lateral drift and inter-story drift with respect to the conventional buildings, as well as the remarkable reduction in deflection of the structural slab with 11.1% reduction. The similar results achieved when the 3-story building is imposed to ground motion at the base level as the HRCISS seemed more efficient in reducing the lateral drifts when it’s equipped in the first story, working as a TMD system. Also, the floating slab displaced in less amplitudes in comparison to the structural slab beneath for all the three components of the earthquake, indicating the rubber functioning as a BI system.

It can be concluded that the HDR bearings in the HRCISS are influential in controlling 3D vibrations and protecting the structural building from interiorly and exteriorly induced vibrations and hence, the capability to widen the application of vibrating machines in higher stories.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN SISTEM PAPAK PENGASINGAN GETAH-KONKRIT HIBRID UNTUK GETARAN 3D

Oleh

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Kini, melalui penggunaan struktur dengan pelbagai jentera dan aplikasi struktur bagi operasi pelbagai jenis tren, truk atau jentera mekanikal berputar, komponen struktural tertakluk kepada getaran multiarah sebagai ayunan siklik menegak dan mendatar. Papak merupakan komponen struktural utama di mana beban dinamik, akibat mesin generator getaran, yang dikenakan ke atasnya, dan kemudian beban tersebut diubah kepada asas melalui galang dan kolum. Kebelakangan ini, aplikasi bering getah sebagai sistem isolator asas bagi menghilankan beban dinamik yang dikenakan kepada struktur tersebut kerap diambil kira oleh jurutera reka bentuk. Walau bagaimanapun, bagi melaksanakan isolasi asas tersebut, adalah perlu untuk mengkonstruksi setiap aras bangunan sebagai tingkat berasingan yang amat membawa kepada pengurangan kekuatan lateral dan kekakuan struktur. Tambahan pula, jentera berputar mencetuskan getaran 3D dan sistem papak terapung, yang mengimplementasi bering getah dengan sifat peredam mampat, adalah efektif hanya bagi getaran menegak peredam dan bukannya getaran mendatar. Di samping itu, Peraturan No.5 Peraturan bagi Kilang dan Jentera Malaysia (1983) menegaskan bahawa sebarang jentera yang bergetar tidak seharusnya dipasang di lantai yang lebih tinggi daripada aras bumi kecuali lantai tersebut telah direka bentuk bagi menyokong beban yang dikenakan dan sebagainya. Oleh sebab itu, penyelidikan ini bertujuan untuk mengesyorkan sistem papak isolasi getah konkrit hibrid (HRCISS) dengan membangunkan sistem papak terapung dengan pengimplementasian getah peredam yang tinggi pada lapisan papak konkrit pertengahn. HRCISS yang disyorkan terdiri daripada dua panel papak atas dan bawah dengan lapisan papak HDR plan segiempat sama pertengahan. Reka bentuk mendalam awal bagi HRCISS yang disyorkan telah dibangunkan dan prestasi sistem yang disyorkan dalam pengurangan getaran pada kedua-dua arah mendatar dan menegak dan keterterapan bagi menghapuskan getaran 3D telah diselidiki melalui simulasi elemen finit. Selepas memuktamadkan reka bentuk tersebut, dua prototaip bagi HRCISS telah dihasilkan dan diuji secara berasingan, setiap spesimen pada satu masa, di bawah beban siklik mendatar dan menegak menggunakan penggerak dinamik bagi menilai prestasi sistem yang

disyorkan dan bagi mengesahkan simulasi numerikal.

Bagi menilai kecekapan sistem hibrid pada getaran 3D peredam, ia diaplikasikan dalam 3 tingkat separuh skala, bangunan 1 petak dan keupayaan sistem yang disyorkan untuk melindungi bangunan daripada getaran dalaman, iaitu getaran jentera di samping kebolehannya untuk melindungi daripada getaran luaran, seperti gempa bumi, telah dinilai. Dapatan menunjukkan bahawa keberkesanan HRCISS dalam pengurangan kecelaan ketika dibandingkan dengan bangunan 3 tingkat konvensional. Di samping itu, menggunakan struktur dengan sistem hibrid didapati lebih efektif dalam meminimumkan hanyut lateral dan hanyut antara tingkat ketika ianya dipasang di aras bawah dengan penurunan rata-rata 87.33% dan 75.8% pada hanyut lateral dan hanyut antara tingkat, di samping pengurangan yang ketara dalam pesongan papak structural dengan pengurangan 11.1%.Dapatan yang serupa juga dikesan ketika bangunan 3 tingkat dikenakan gerakan bumi pada aras asas disebabkan HRCISS didapati lebih efisien dalam mengurangi hanyut lateral ketika ia dilaraskan dalam tingkat pertama, bekerja sebagai sistem TMD. Di samping itu, papak terapung yang disesar dalam amplitud yang rendah berbanding dengan papak struktural di bawah semua tiga komponen gempa bumi, memperlihatkan pemfungsian getah sebagai sistem BI.

Kesimpulannya, bering HDR dalam HRCISS adalah efektif dalam mengawal getaran 3D dan melindungi bangunan struktural daripada getaran terarah secara interior dan eksterior dan oleh itu, keupayaan untuk memperluas pengaplikasian getaran jentera pada tingkat yang lebih tinggi.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

3S1B	3-story 1-bay building
3S1BC1	1st story machine-equipped 3-story 1-bay conventional building
3S1BC2	2nd story machine-equipped 3-story 1-bay conventional building
3S1BC3	3rd story machine-equipped 3-story 1-bay conventional building
3S1BH1	1st story machine-equipped 3-story 1-bay hybrid building
3S1BH2	2nd story machine-equipped 3-story 1-bay hybrid building
3S1BH3	3rd story machine-equipped 3-story 1-bay hybrid building
3S1B-30	3-story 1-bay building with HRCISS of 30mm-height HDR bearings
3S1B-45	3-story 1-bay building with HRCISS of 45mm-height HDR bearings
3S1B-60	3-story 1-bay building with HRCISS of 60mm-height HDR bearings
3S1B-75	3-story 1-bay building with HRCISS of 75mm-height HDR bearings
3S1B-90	3-story 1-bay building with HRCISS of 90mm-height HDR bearings
3S1B-30-1	3-story 1-bay building with 30mm-HDR HRCISS-equipped 1st story
3S1B-45-1	3-story 1-bay building with 45mm-HDR HRCISS-equipped 1st story
3S1B-60-1	3-story 1-bay building with 60mm-HDR HRCISS-equipped 1st story
3S1B-75-1	3-story 1-bay building with 75mm-HDR HRCISS-equipped 1st story
3S1B-90-1	3-story 1-bay building with 90mm-HDR HRCISS-equipped 1st story
3S1B-30-2	3-story 1-bay building with 30mm-HDR HRCISS-equipped 2nd story

3S1B-45-2	3-story 1-bay building with 45mm-HDR HRCISS-equipped 2^{nd} story
3S1B-60-2	3-story 1-bay building with 60mm-HDR HRCISS-equipped 2^{nd} story
3S1B-75-2	3-story 1-bay building with 75mm-HDR HRCISS-equipped 2^{nd} story
3S1B-90-2	3-story 1-bay building with 90mm-HDR HRCISS-equipped 2^{nd} story
3S1B-30-3	3-story 1-bay building with 30mm-HDR HRCISS-equipped 3^{rd} story
3S1B-45-3	3-story 1-bay building with 45mm-HDR HRCISS-equipped 3^{rd} story
3S1B-60-3	3-story 1-bay building with 60mm-HDR HRCISS-equipped 3^{rd} story
3S1B-75-3	3-story 1-bay building with 75mm-HDR HRCISS-equipped 3^{rd} story
3S1B-90-3	3-story 1-bay building with 90mm-HDR HRCISS-equipped 3^{rd} story
AASHTO	The American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
BI	Base Isolation
BS	British Standards
DR	Drift Ratio
EC	Eurocode
E_W	East West
FE	Finite Element
FEM	Finite Element Method

FIS	Floor Isolation System
FPS	Friction Pendulum System
FST	Floating-Slab Track
HC	Horizontally Cyclic-Loaded HRCISS Specimen
HDR	High Damping Rubber
HDRB	High Damping Rubber Bearing
HRCISS	Hybrid Rubber-Concrete Isolation Slab System
IHRB	Isolated High-Rise Building
ISD	Inter-Story Drift
JRA	Japan Road Association
LRB	Lead Rubber Bearing
LSD	Lateral Story Drift
LVEM	Laminated Visco-Elastic Materials
MVIMD	Multi-Dimensional Vibration Isolation and Mitigation Device
MT	Mass Timber
NPP	Nuclear Power Plants
NRB	Natural Rubber Bearing
N_S	North South
RC	Reinforced Concrete
RTCS	ratio of tensile to compressive stiffness
TMD	Tuned Mass Damper
VC	Vertically Cyclic-Loaded HRCISS specimen
VE	Visco Elastic
VR	Gravity Shear Ratio

U_D	Up and Down

CHAPTER 1

INTRODUCTION

1.1 Definition

Isolation is one of the most preferred systems that are commonly used to eliminate vibrations on structural elements in various constructions. The concept of the isolation process is providing flexible devices that add up to the flexibility of the whole system, decoupling two main parts of the construction by dissipating the energy and mitigating vibrations transfer from one part to the other. This discontinuity, caused by the isolation bearings, reduces the demand of dynamic loads rather than increasing the system's resistance.

In an isolation system, the essential features are flexibility and energy dissipation capacity, as the formal is capable of increasing the fundamental period of the system by shifting it out of the dominant period of the effective dynamic loadings while the latter is responsible for increasing the damping and hence, reducing the deformations in the system.

1.2 Background

In general, vibrations that affect the buildings can either be in horizontal or vertical directions according to the source of the vibration. Examples on horizontal vibration are earthquakes, wind, waves and machinery equipment. Vertical vibrations on the other hand, are generated from several sources of loading, i. e. traffic vehicles, movement of individuals, machinery motion and vertical component of ground motion. The effects of these cyclic loads on buildings and their structural membranes have been well investigated over decades. For example, slab panels which are the horizontal diaphragms of the buildings that are supported on columns, beams or walls and transfer loads in the building through the vertical membranes, have been widely studied under lateral and vertical loadings and the performance has been assessed based on the damage occurring in the slab-column/ slab-wall connections (Smadi et al., 2008, Almeida et al., 2016, Emitiaz et al., 2017, Abdul Hamid and Masrom, 2012, Foglar and Göringe, 2015 and Daud et al., 2015). However, these connections are weak under large cyclic vibrations (Rha et al., 2014) and thus there has been a need to dissipate such vibrations and eliminate their effects on the structure in order to prevent possible deterioration, especially in the vertical diaphragms that are weak against lateral vibrations. Many solutions to reduce these vibrations have been used, most commonly, base-isolation, mid-story isolation and TMD systems in terms of lateral vibrations.

Base-isolation system is effective in decoupling structures from the ground motion during earthquakes by providing sufficient flexibility to the structure via the use of isolators in the base layer, disconnecting the superstructure from the substructure beneath. These isolators provide damping which dissipate lateral vibrations transmitting from ground to the superstructure through the isolator materials (Fan F-G et al., 1990, Ramkrisna et al., 2006, Gaibaulung and Subramanian, 2016, Karabork and Turan, 2011 and Gowardhan and Deosarkar, 2015). The other approach of isolation against horizontal movements is the mid-story isolation system in the multi-story buildings. It's gaining popularity rather than the base-isolation system for being more feasible and architecturally attractive, especially in high populated regions with buildings close to each other which do not offer much space in the base level, thus favoring the mid-story system (Su and Ahmadi, 1992, Huang et al., 2008, Ryan and Earl, 2010, Wu et al., 2019). While, tuned mass damper (TMD) system is the use of an isolated body structure functioning as a tuned mass to damp vibrations, most notably under wind loads, that keep the building stiff unlike base and mid-story isolation which make the building flexible to resist ground motions (Warburton 1982, Villaverde et al., 2005, Melkumyan, 2014, Angelis De et al., 2012, Chey et al., 2013 and Fabrizio et al., 2017).

On the other hand, in terms of vertical vibrations, various methods have been studied and tested in the past to diminish such vibrations, including the separation of the structural membranes from the effective vibrating objects using isolators that are inserted below the vibrating structures and above the structure beneath which is directly bonded to the rest of the building that needs to be protected from damage. Of the many ways of isolation against vertical vibration, floating floors, floating-slab track are the most preferred tools. Their concept is to lift slab panels that are attached directly to the moving body from the floor slab beneath by providing resilient layer between the two slabs which works as dissipation tool to eliminate the vibrations and mitigate energy generated from the vibrating objects and prevent them from passing to the substructure and buildings near the vibration region in order to protect the surrounding constructions from deterioration due to the affecting vibration that its period might coincide with the natural period of the buildings nearby which can cause them to collapse (Xu et al., 2015, He et al., 2018, Jin et al., 2017, Kim et al., 2018, Hui and Ng, 2007 and Mukherjee, 2017).

The two mentioned systems are used separately, each system for specific type of vibrations. However, in most cases, induced vibrations may have influence on buildings in all directions. Various approaches have been utilized and the one that is most feasible and commonly implemented is the 3D isolation system which employs multiple isolation systems to perform in combination under lateral and vertical motions. For the cases of isolation under lateral or vertical vibrations, the most commonly utilized devices are made of rubber materials, which are hyperelastic materials showing some viscoelastic characteristics that provide sufficient flexibility to decouple structural elements and dissipate vibrations that are generated due to the dynamic forces acting on the structure as well as mitigating the potential of these vibrations to cause damage. A favorable material and commonly used over the years in isolation against horizontal cyclic loads, especially under seismic motion, are lead rubber bearings LRB and high damping rubber bearings HDB (Naeim and Kelly, 1999; Yoshida et al., 2004; Bhuiyan, 2009; Hwang, 2002; Yoshida et al., 2004; Grant et al., 2004; Bhuiyan et al., 2009; and Castellano et al., 2015).

Whereas, various types of rubber bearings have been in mounting use for the vertical isolation. However, in case of three-dimensional isolation, a combined system of isolators is in use, namely, dampers for vertical isolation and rubber bearings for horizontal isolation (Wong et al., 2013, Suhara et al., 2008, Okamura et al., 2005, Zhou et al., 2016, Shun and Lin, 2008, Takahashi et al., 2008, Xu et al., 2019, Kitayama et al., 2017).

1.3 Problem Statement

Isolation of a whole building against applied dynamic loads can be highly expensive. The modified approach of isolation is proposed to be used as an alternative technique in order to protect the structure from such loads of a specific installed equipment (i.e. machinery) that might induce vibrations to the structural element (slab panel), beneath, in both vertical and horizontal directions. The rubber isolators, such as high damping rubber (HDR) bearings are functioning mostly for lateral vibration as in case of seismic and wind motion and have been rarely utilized for vertical vibration control despite showing a sufficient degree of isolation.

On the other hand, rubber pads in floating slab systems are utilized specifically for isolating vertical vibrations, and the resilient layer used in such systems, which implements types that differ from damping rubber, is efficient in acoustic insulation rather than vibration isolation. In addition, many vehicles and rotary machines induce vibrations in both directions on the structural membranes in which they're installed to or nearby. This can generate vibrations with high frequencies that can be damaging to the structure which will decrease the life span of the building and may cause discomfort to the individuals within the building, and must be diminished at the machine base by decreasing the transmissibility value. For this reason, advanced and complex instruments are used for isolation of multidirectional vibrations which comprise more than one isolation system to eliminate deformations, and their application is highly costing, time consuming and complicated in manufacturing and installment.

By considering of discussed issues related to the ordinary isolation systems for horizontal, vertical (machine-induced) and combined 3D (seismic) vibrations, there's a need to implement an effective system to minimize the number of required systems for isolation to a single system with proper potential to dissipate vibration energy and diminish vibrations in the three directions as well as the capability to be equipped in existing constructions with reasonable cost and easy installation. The high damping rubber is selected as the isolation material since it offers low stiffness in the horizontal direction and a higher stiffness in the vertical direction to carry the machine's weight.

1.4 Research Questions and Hypothesis

The current research aims to answer the question:

1- Since HDR proved its ability to diminish horizontal ground motion, is it able to exploit this property in order to eliminate machine-induced horizontal vibrations?

2- Could modified HDR bearings become a more efficient replacement to ordinary rubber bearings in damping vertical vibrations of machinery and seismic sources?

3- Are the HDR bearings sufficient in higher levels of a multistory building rather than the rigid floor of the ground level?

4- The hypothesis of this study, based on the research background and questions, can be formulated as:

By applying High Damping Rubber bearings in a floating slab system, they have the potential to eliminate deformations in the horizontal and vertical directions, caused by interior and exterior vibrations from machinery and ground motion, respectively. In addition, the varying thickness of the rubber layer could affect the performance of the floating slab system in a multistory building to reduce displacements on the structural slab as well as the ability to protect certain installed machines from vibrations in more than one direction.

1.5 Research Objectives

1- To design a single isolation system of hybrid rubber-concrete slab panels for controlling horizontal and vertical vibrations.

2- To investigate the dynamic response of the proposed hybrid rubber-concrete isolation slab system under horizontal and vertical cyclic displacements through FEM and to verify the design by manufacturing the prototype and conducting experimental tests using dynamic actuators.

3- To evaluate the deformation reduction capability of the hybrid rubber-concrete isolation slab system in the horizontal and vertical directions, with varying shape factors, in a multistory structure subjected to interior machine vibrations and seismic excitations through finite element study.

1.6 Scope of Study and Limitations

For the scope of the current study, RC slab panels have been considered and square-sectioned bearings of high damping rubber (HDR) were implemented for the isolation layer. FEM and experimental tests have been conducted, only cyclic loading was used using the experimental testing, whereas cyclic and seismic loadings have been applied on the research specimens throughout the study. Multistory buildings of RC flat slabs and columns have been studied to investigate the cyclic and seismic loadings, as well as to investigate the shape factor effect.

Moreover, shape factors of no more than 2 and no less than 0, have been utilized. Furthermore, interior vibrations were represented by horizontal cyclic and vertical half-cyclic displacement-controlled loadings, while exterior vibrations were represented by 3D components of El Centro 1940 Earthquake with 10 seconds duration. Whereas, limitations for this research are: the laboratory horizontal actuator can only push and pull below 100 mm horizontally. Hence, the horizontal cyclic displacement protocol should be designed for less than 100 mm amplitude for experimental testing and verification. On the other hand, the vertical actuator movement in limited to maximum of 50 mm and is restricted from upward movement, which means it only pushes downwards and release up to the zero point. Thus, the vertical displacement protocol is a half-cyclic protocol that’s designed for a maximum amplitude below 50 mm.

The dimensions of structural (lower) slab of the research isolation system prototype are limited by the strong floor bolts of the experimental laboratory which are aligned 500 mm apart, longitudinally and transversely. This leads to multiples of 500 mm for the lower slab dimensions of 1500 mm x 1500 mm, and the 100 mm height is due to the elevation of the actuator which is connected to the floor. Whereas, the floating (upper) slab dimensions are limited to 800 mm x 800 mm x 100 mm to avoid contacting with the strong floor bolts of 150 mm height, due to the lateral motion when the specimen is subjected to the horizontal actuator movement.

The horizontal and vertical cyclic tests are not conducted simultaneously due to the difficulty in linking the two orthogonal actuators into one specimen at the same point. This leads to the conduction of each test separately and the need to implement two identical specimens. The study focuses only on harmonic loads rather than impact loads despite the applicability of the latter. Also, in this study, ageing factor isn’t considered, and natural type of rubber is studied. In addition, higher velocities and different load frequencies were not considered throughout the research. Application of the HRCISS in a multistory building is conducted through FEM only, since these buildings require horizontal and vertical actuators of larger scales.

1.7 Thesis Content

This research work will be divided into several sections. In first section, and introduction to the general isolation systems used against both lateral and vertical vibrations is displayed with background and review of the most recent methods implemented for each type of vibration in addition to demonstrating the advantages and disadvantages of the common isolators as well as highlighting the gaps of the past research works with illustration of the possible benefits of the new proposed system. Afterwards, stating the problems and questions of this research and the objectives related to solving these problems. In the second chapter, a literature of the most related work, to this research, over the past years is reviewed assuring the existence of the gaps that this research work attempts to cover and highlighting the issues that need to be solved. In the third chapter, the methods in which the new hybrid rubber-concrete isolation slab system are explained. Model design in both numerical and experimental work will be discussed and the dimensions and material properties used in the model as well as the ways of connecting parts of the model are displayed. In addition, the setup and test protocol will be illustrated as well as. Furthermore, the design of a 3-story, 1-bay building will be presented with the equipment of the HRCISS in different story elevations and different shape factor values.

In chapter 4, the results for both numerical and experimental tests will be shown in these and discussed and comparisons between the two types of the results will be explained. Then, the FEM results of the HRCISS application in the multistory flat slab building will be demonstrated and the controlled deformation with the use of HRCISS will be compared with conventional buildings. Additionally, the shape factor effect will also be discussed by comparing the different outcomes in terms of damping, stiffness, and deformation, for five shape factor values.

Lastly, conclusions will be driven in chapter 5, based on all the data obtained and explained in previous chapters and recommendations for future works will be given at the end of the chapter.

1.8 Summary

In the beginning, vibrations and their control methods have been introduced with a brief presentation of their background studied. Then, a statement of the problem, based on the gap found in the literature, was made and the objectives were determined. The scope of the study with its limitations have also been displayed, in order to detect the criteria for the design of the proposed hybrid rubber-concrete isolation slab system for the current research.

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