UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF ELASTOMERIC BEARING UTILIZING STEEL CORE WITH GRANULAR AND POLYMER FILLER SYSTEM FOR STRUCTURES AND BRIDGES

TAN KAR CHUN

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By

TAN KAR CHUN

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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DEDICATION

This work is dedicated to my dearest mother for her unconditional love and support, and Luna for the happiness she brought to our family.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Elastomeric bearing is the most common base isolation system for structure and bridges subjected to vibration and ground motion. To improve the energy dissipation performance of the base isolator, a lead core is implanted to enhance the damping and stiffness of elastomeric bearing. However, the most notable impact from lead-core rubber bearing is the adverse effect brought to human and environment by lead material.

Therefore, in this study, an attempt has been made to innovate an elastomeric bearing equipped with steel core and filler system to improve the performance of bearing while posing minimal impact to human and environment. Two types of filler, namely sand and epoxy were implemented. The steel core was introduced to improve the shear stiffness of filler. The aim of this study is to develop an innovative elastomeric bearing that shows improvement in performance when compared to conventional elastomeric bearing and lead-core rubber bearing.

Numerical models were developed for the proposed device according to prepared design details. Simulation was conducted using finite element method to evaluate the performance of proposed isolation and confirm the initial design details.

Thereafter, the prototypes were manufactured and then experimentally tested under the combination of axial load and lateral displacement to assess the performance of propose base isolation devices.

Effective stiffness and energy dissipation are used as the evaluation parameters, as they are commonly used to define the base isolator spring-dashpot model during structural analysis. The results from numerical analysis were deemed acceptable since the stiffness and damping component derived from it were within the acceptable error tolerance when compared against that derived from experimental result. Based on both numerical and experimental result, the proposed bearing systems were found possessing greater shear stiffness compared to the conventional elastomeric bearing and lead-core rubber bearing.

Upon validation of finite element model, numerical parametric study was conducted based on the developed models. The purpose of this study is to evaluate the effect of material properties and loading conditions on the performance of proposed elastomeric bearing.

Then, application case study was conducted by the mean of finite element analysis by integrating the base isolator into a G+5 building. From the analysis, the base isolators were able to elongate the vibration period of structure and reduces the peak spectral acceleration acting on the structure. They were proven effective in reducing the base shear acting on the structure, and eventually reduce the structural burden when ground motion occurs.

In overall, the implementation of steel core and filler system provides a reliable improvement to the performance of conventional elastomeric bearing. Among the proposed innovations, fully filled sand system is the best for its tremendous improvement in bearing characteristics, as well as convenience during fabrication and maintenance.

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

PEREKAAN GALAS ELASTOMER YANG MENGGUNAKAN SISTEM TERAS KELULI BESERTA ISIAN BUTIRAN DAN POLIMER BAGI STRUKTUR DAN JAMBATAN

Oleh

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Galas elastomer ialah sistem pengasingan asas yang paling biasa untuk struktur dan jambatan yang tertakluk kepada getaran dan gerakan tanah. Untuk meningkatkan prestasi pelesapan tenaga pengasing asas, teras plumbum ditanam untuk meningkatkan redaman dan kekakuan galas elastomer. Walau bagaimanapun, kesan yang paling ketara daripada galas getah teras plumbum ialah kesan buruk yang dibawa kepada manusia dan alam sekitar oleh bahan plumbum.

Oleh itu, dalam kajian ini, percubaan telah dibuat untuk menginovasikan galas elastomer yang dilengkapi dengan teras keluli dan sistem pengisi untuk meningkatkan prestasi galas sambil menimbulkan kesan minimum kepada manusia dan alam sekitar. Dua jenis pengisi iaitu pasir dan epoksi telah dilaksanakan. Teras keluli diperkenalkan untuk meningkatkan kekukuhan ricih pengisi. Matlamat kajian ini adalah untuk membangunkan galas elastomerik inovatif yang menunjukkan peningkatan dalam prestasi jika dibandingkan dengan galas elastomer konvensional dan galas getah teras plumbum.

Model berangka telah dibangunkan untuk peranti yang dicadangkan mengikut butiran reka bentuk yang disediakan. Simulasi telah dijalankan menggunakan kaedah elemen terhingga untuk menilai prestasi pengasingan yang dicadangkan dan mengesahkan butiran reka bentuk awal.

Selepas itu, prototaip telah dihasilkan dan kemudian diuji secara eksperimen di bawah gabungan beban paksi dan anjakan sisi untuk menilai prestasi peranti pengasingan asas yang dicadangkan.

Kekakuan yang berkesan dan pelesapan tenaga digunakan sebagai parameter penilaian, kerana ia biasanya digunakan untuk mentakrifkan model periuk spring-dashpot pengasing asas semasa analisis struktur. Keputusan daripada analisis berangka dianggap boleh diterima kerana komponen kekakuan dan redaman yang diperoleh daripadanya berada dalam toleransi ralat yang boleh diterima jika dibandingkan dengan yang diperoleh daripada keputusan eksperimen. Berdasarkan kedua-dua keputusan berangka dan eksperimen, sistem galas yang dicadangkan didapati mempunyai kekukuhan ricih yang lebih besar berbanding dengan galas elastomer konvensional dan galas getah teras plumbum.

Selepas pengesahan model unsur terhingga, kajian parametrik berangka telah dijalankan berdasarkan model yang dibangunkan. Tujuan kajian ini adalah untuk menilai kesan sifat bahan dan keadaan pembebanan ke atas prestasi galas elastomer yang dicadangkan.

Kemudian, kajian kes aplikasi telah dijalankan dengan purata analisis unsur terhingga dengan menyepadukan pengasing asas ke dalam bangunan G+5. Daripada analisis, pengasing asas dapat memanjangkan tempoh getaran struktur dan mengurangkan pecutan spektrum puncak yang bertindak ke atas struktur. Mereka telah terbukti berkesan dalam mengurangkan ricih asas yang bertindak pada struktur, dan akhirnya mengurangkan beban struktur apabila gerakan tanah berlaku.

Secara keseluruhan, pelaksanaan teras keluli dan sistem pengisi memberikan peningkatan yang boleh dipercayai kepada prestasi galas elastomer konvensional. Antara inovasi yang dicadangkan, sistem pasir terisi penuh adalah yang terbaik untuk peningkatan yang luar biasa dalam ciri galas, serta kemudahan semasa fabrikasi dan penyelenggaraan.

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A	Plan area of elastomeric bearing/ creep parameter (hysteresis parameter)
A_r	Reduced plan area of elastomeric bearing
b	Breadth of elastomeric bearing
BPM	Bonded particle method
BRB	Ball rubber bearing
C	Creep strain exponent (hysteresis parameter)
c	Effective damping
C_d	Deflection amplification factor
CP	Collapse prevention
CR	Chloroprene rubber
C_t	Approximate period parameters
C_u	Coefficient of uniformity
C_{01}, C_{02}, C_{10}, C_{11}, C_{20}, C_{30}	Material constant for hyperelastic models
$C_R^{(A)}$	Initial shear modulus (hysteresis parameter)
DBE	Design-based earthquake
DC	Damage control
D_1,D_2,D_3	Material constant for hyperelastic models
DEM	Discrete element modelling
D_{lim}	Clear vertical distance between top of core and the soffit of top cover plate
d_n	Peak negative displacement
DP	Drucker-Prager plasticity model
$\mathrm{d_p}$	Peak positive displacement

e	Void ratio in sand
E	Modulus of elasticity
E_b	Bulk modulus of rubber
ECRB	Epoxy-core rubber bearing
EDC	Energy dissipation capacity
EGC	Geosynthetic-encased granular column
EPDM	Ethylene-propyl-enediene-rubber
EQC	Equivalent quartz content
F_a	Site coefficient for seismic loading
FBSD	Force-based seismic design
FEM	Finite element method/ finite element model/ finite element modelling
FRP	Fibre reinforcement (polymer)
FRRB	Fibre-reinforced rubber bearing
F_n	Peak negative force
F_p	Peak positive force
F_v	Compression applied on elastomeric bearing/ site coefficient for seismic loading
G	Shear modulus of rubber
GC	Gravel content
G_s	Specific gravity of sand
G_0	Initial shear modulus of rubber
h	Length of elastomeric bearing
H_{core}	Height of steel core
H_{fill}	Height of filler
H_r	Height of elastomeric bearing

HS	Hardening soil
IDDR	Ratio of inelastic displacement to ultimate inelastic displacement capacity
IDR	Inter-storey drift ratio
IO	Immediate occupancy
IRHD	International Rubber Hardness Degrees
I	Seismic importance factor
I_1,I_2	Strain invariant
k	effective stiffness
K_0	Initial bulk modulus of rubber
k_d	Post-yield stiffness
k_{eff}	Effective stiffness of elastomeric bearing
L_{bot}	Length of bottom cover plate
LCRB	Lead-core rubber bearing
LRB	Laminated rubber bearing
LS	Life safety
L_{top}	Length of top cover plate
LVDT	Linear variable differential transformer
m	Effective stress exponent (hysteresis parameter)
M	Mass of filler
MBT	Mercaptobenzothiazole
MBTS	Mercaptobenzothiazole disulfide
MC	Mohr-Coulomb plasticity model
MIIDR	Maximum inelastic inter-storey drift ratio
MTIDR	Maximum transient inter-storey drift ratio

MTL	Moment transfer law
n_r	Number of rubber layers
NR	Natural rubber
n_s	Number of steel shims
OGC	Ordinary granular column
OP	Operational (seismic performance level)
P	Force free perimeter of rubber layer
P_{all}	Allowable pressure exerted on elastomeric bearing
PBSD	Performance-based seismic design
pga	Peak ground acceleration
pgv	Peak ground velocity
PIDR	Permanent inter-storey drift ratio
PNB	Polynorbornene
PRB	Peripherally restrained bearing
P_v	Pressure exerted on elastomeric bearing due to design compression
Q	Yield force of elastomeric bearing
Q_d	Characteristics strength of elastomeric bearing
Q_n	Negative intersection of the hysteresis curve and vertical axis
Q_p	Positive intersection of the hysteresis curve and vertical axis
R	Response modification factor
R^2	Coefficient of determination for the developed linear regression model
S	Shape factor of the elastomeric bearing/ stress scaling factor (hysteresis parameter)

S'	Shape factor of the thickest rubber layer
SBR	Styrene butadiene rubber
SCRB1	Sand-core rubber bearing type 1 (partially filled condition)
SCRB2	Sand-core rubber bearing type 2 (fully filled condition)
S_{DS}	Design spectral acceleration at 0.2s period
S_{D1}	Design spectral acceleration at 1s period
SGM	Sand-gravel mixture
SLS	Serviceability limit state
SMA	Shape memory alloy
SMREIB	Steel mesh reinforced elastomeric isolation bearing
Ss	0.2s spectral acceleration
SSE	Sum of squares error
SSM	Steel slag sand mixture
SSR	Sum of squares due to regression
SST	Sum of squares total
S_1	Primary shape factor of elastomeric bearing/ 1s spectral acceleration
S_2	Secondary shape factor of elastomeric bearing
t	Height of elastomeric bearing
T_{bot}	Thickness of bottom cover plate
TDD	Total design displacement
t_{eff}	Effective thickness of rubber layer
TGC	Transitional gravel content
TIDR	Transient inter-storey drift ratio
T_L	Long-period transition period parameter

TLCRB	Tension-resistant lead-core rubber bearing
t_r	Thickness of elastomer in elastomeric bearing
$t_{r,i}$	Thickness of inner rubber layer in elastomeric bearing
$t_{r,o}$	Thickness of outer rubber layer in elastomeric bearing
t_s	Thickness of steel shims in elastomeric bearing
TRD	Tension-resistant device
T_{top}	Thickness of top cover plate
ULS	Ultimate limit state
V	Volume
W	Weight of building on elastomeric bearing/ stored-energy function/ strain-energy function
W_{bot}	Width of bottom cover plate
W_{lim}	Clear horizontal distance between core and bearing body
WMPF	White monofilament polypropylene fibres
W_r	Width of elastomeric bearing
W_{top}	Width of top cover plate
x	Approximate period parameters
y	Dependent variable in developed linear regression model
$\hat{y}$	Predicted dependent variable using developed linear regression model *Greek*
$\alpha_1, \alpha_2, \alpha_3$	Material constant for Ogden hyperelastic model
γ_{dry}	Dry unit weight of sand
γ_w	Unit weight of water
Δ	Displacement/ error of numerical analysis results from experimental results
ϵ_{max}	Elongation at break

ϵ_{yield}	Yield strain
θ_b	Beam rotation
θ_c	Column rotation
$\lambda_1, \lambda_2, \lambda_3$	Principal stretch
μ_1, μ_2, μ_3	Material constant for Ogden hyperelastic model
ν	Poisson ratio
ξ	Damping ratio
ξ_J	Equivalent viscous damping
σ_{max}	Ultimate stress
σ_y	Yield strength
σ_{yield}	Yield stress
ϕ	Internal friction angle
ϕ_b	Overall diameter of the elastomeric bearing
$\phi_{c,bot}$	Diameter of the section at the bottom of core
$\phi_{c,top}$	Diameter of the section at the top of core
ϕ_{void}	Diameter of void at the centre of bearing body
ψ	Dilatancy angle of sand
Ω	Overstrength factor

CHAPTER 1

INTRODUCTION

1.1 Introduction

Structure tends to respond dynamically to applied lateral forces such as wind, earthquake and tide. When a structure is moving or vibrating, additional stress and strain, mostly in cyclical pattern will be developed in structural elements. These responses will eventually cause deterioration in those elements over long run.

To remedy this unfavourable action, structural enhancement has been researched over past decades. Such enhancement comes in three major forms today: base isolation, passive energy dissipation and active control.

Base isolation system is effective in reducing structural dynamic response, especially when the structure is subjected to ground motion. To do so, the isolator, most commonly elastomeric bearing, must be vertically stiff to sustain the load that comes from the dead weight of structure and occupants' daily activities, yet laterally flexible to reduce the transfer of huge force coming from the ground to superstructure. Meanwhile, elastomeric bearing that equips with high damping material e.g. rubber, will start to dissipate excessive energy and stop the structural vibration.

Commercially, laminated rubber bearing which consists of alternating layers of rubber and reinforcing steel is the most common type of device for its simplicity and low cost. Another widely implemented elastomeric bearing is lead-core rubber bearing. By introducing lead plug as the core of elastomeric bearing, the performance of bearing has been proven more promising than laminated rubber bearing. In research and development, less known alternatives such as fibre-reinforced rubber bearing, enhancement of existing types of bearing, or hybrid system with complementary mechanisms are intensively researched to produce a competitive alternative that performs better and cost less.

1.2 Background and earlier works

Laminated rubber bearing with the purpose of isolating superstructure and substructure was introduced in year 1954. Layers of rubber sheet and reinforcing steel plate provide vertical and horizontal stiffnesses that enable such device to accomplish its task. Prior to that, a bridge isolator was only made of natural rubber, and its function was solely absorbing impact (Markou & Manolis, 2016).

Major leap in elastomeric bearing technology was achieved when lead core was added to existing laminated rubber bearing system and therefore created lead-core rubber bearing (Robinson, 1982). As a result, the shear resistance of bearing device improves, and this drastically improves the energy dissipation capacity of bearing while being compared to laminated rubber bearing. Another advancement was achieved when the idea of replacing reinforcing steel plate in laminated rubber bearing with fibre reinforcement material was conceived. This modification produced an elastomeric bearing that costs less while giving consistent performance.

Factors affecting the performance of these types of elastomeric bearing have been consistently studied. For laminated rubber bearing and fibre-reinforced rubber bearing, global geometry of bearing, which often described by primary and secondary shape factors directly influences the bearing's peak displacement, energy dissipation capacity and failure mode (Montuori et al., 2016, Gauron et al., 2018, Zhou et al., 2018). For lead-core rubber bearing, factor such as diameter of lead core affects the overall performance of bearing (Ahmadipor & Alam, 2017).

Problems related to elastomeric bearing have been identified at material level. For lead-core rubber bearing, the main component is made of toxic heavy metal that brings adverse impact to human health and environment (Gottesfeld et al., 2017, Gałuszka et al., 2018). In the view of mechanical aspect, lead core is susceptible to heating due to rigorous movement, and this affects the overall performance of bearing (Ozdemir & Dicleli, 2012). For laminated rubber bearing and fibre-reinforced rubber bearing, majority of the issues are related to rubber. Stiffening of rubber may help in enhancing the shear resistance of bearing, but it weakens the bearing's ability to isolate structure and dissipate structural vibration (Li et al., 2016). As a result, greater stress will be developed in superstructure. When subjected to high tensile stress, rubber ruptures and this leads to destruction of bearing (Tubaldi et al., 2016). Damaged bearing usually exhibits uncontrollably large displacement when subjected to lateral force and exposes the structure to the risk of unseating failure and collapse (Kim et al., 2006).

1.3 Statement of problem

Most issues related to the mechanical performance of an elastomeric bearing is associated with its constituent material – rubber.

When bearing sustains large shear force, it will undergo large deformation. Such displacement can cause bridge unseating failure and lead to collapse of superstructure. Nonetheless, such situation is not only caused by large shear force and accompanying deformation. When the bearing's lateral stiffness is reduced or lost, the lateral capacity of bearing will be decreased tremendously, and large deformation can easily occur. Moreover, rubber hardens when it is subjected to unusually large strain. The hardening process causes the rubber to lose its flexibility and ability to dissipate vibration. As a result, this causes the bearing to lose its primary function as an isolator.

A notable advancement in elastomeric bearing is the use of lead plug as core, aiming to enhance the lateral stiffness and damping capacity of bearing. However, the use of lead has been proven poses negative impact to human health and environment.

An innovative elastomeric bearing completed with novel mechanisms is required to resolve the issues as outlined above. The lead core enhances the stiffness and damping of elastomeric bearing. To replace the hazardous lead core, proposed mechanism must be able to provide improvements in the same aspect. The proposed system may consist of a stiff material that aims to provide lateral stiffness to the bearing, and high damping material that enhance the energy dissipation of the device. On top of that, rubber deformation needs to be controlled to avoid associated damage. The current technology relies on the component of elastomeric bearing in resisting the displacement applied on it, rather than restraining the deformation of bearing to the allowable magnitude. Therefore, the innovation needs displacement control mechanism to accomplish this.

However, innovation alone is not enough to make an impact in the industry. For the innovation to be widely implemented, comprehensive design guide should be developed and made accessible by the industry. By following the design procedure properly, bearing with consistent performance could be produced. Also, numerical analysis model is required for the engineer to check the adequacy of structural design of the innovative elastomeric bearing under various design criteria, and provide convenience for future research and improvement. Further assessment of the proposed elastomeric bearing is needed through case study, where the elastomeric bearings are implemented to a structure. The numerical analysis model compliments with the case study, where the output of numerical analysis can be used to determine the parameters required to conduct structural analysis.

1.4 Identified gaps

The identified gaps are as follows:

1. Need of novel bearing with displacement control mechanism to restrict rubber deformation and avoid undesired damage & superstructure unseating problem,
2. Need of avoid the use of lead, which is hazardous to human and environment while improving the performance of bearing,
3. Need of numerical analysis model to simulate the behaviour of an elastomeric bearing with the proposed mechanism under various loading condition, and
4. Need of design guide to enable engineer and manufacturer to determine the size of elastomeric bearing with the proposed mechanism based on various design criteria.
5. Need of a case study on a building to identify the effect of implementation of proposed innovative elastomeric bearing.

1.5 Objectives of study

The main objective of this study is as follow:

1. To develop an innovative elastomeric bearing as a replacement of lead-core rubber bearing by utilizing the steel core and granular and polymer filler system with displacement control mechanism.

To achieve this main objective, the following specific objectives need to be fulfilled:

1. To develop manual design process for innovated elastomeric bearing,
2. To evaluate the performance of developed elastomeric bearing in terms of bearing characteristics through conducting experimental test and finite element simulation,
3. To determine the effect of bearing material properties and loading conditions on the performance of proposed elastomeric bearings by the mean of finite element analysis. And
4. To assess the performance of the developed elastomeric bearing through application to a reinforced concrete structure subjected to earthquake excitation.

1.6 Hypothesis of the study

In the present study, the following hypothesis are made:

1. Implementing the steel core and granular and polymer filler system in elastomeric bearing improves the effective stiffness and damping ratio in comparison to the conventional laminated bearing and it can be used as a replacement of lead-core rubber bearing,
2. Utilization of displacement control mechanism in elastomeric bearing restricts the movement of the bearing and prevent any excessive displacement, and
3. Implementation of proposed elastomeric bearing can improve a building's structural response when it is subjected to ground motion, compared to the fixed base condition.

1.7 Scope and limitation of work

The scopes of this research are:

1. Development of an innovative elastomeric bearing by introducing a mechanism that improves the performance of bearing and controls the bearing displacement,
2. Use of material that brings minimal impact to health and the environment, as a replacement of hazardous lead core,
3. Development of innovative elastomeric bearing design guide in accordance with currently implemented code of practice, namely BS5400 and EN 1337,
4. Development of numerical analysis model using finite element method and conduct analysis to determine the hysteresis behaviour of proposed bearings, and derive their bearing characteristics,
5. Conduct numerical parametric study on the innovative elastomeric bearing under various material properties and loading conditions, namely rubber and filler properties, applied displacement, loading pattern, frequency and history,
6. Manufacturing of proposed elastomeric bearing prototypes and a conventional laminated rubber bearing as benchmark,
7. Test of the prototype under the combination of compression and cyclic shear as per the design condition,
8. Verification of numerical analysis based on experimental test result, in terms of hysteresis curve, derived bearing characteristics and spring-dashpot model parameters,
9. Perform numerical analysis on a case study building with and without the proposed innovative elastomeric bearing, as well as lead-core rubber bearing for comparison.

The limitations of this research are:

1. Temperature, which is another factor that can affect the properties of rubber, is not considered,
2. The effect of loading history on innovative elastomeric bearing is not studied experimentally,
3. The function of system in limiting the lateral deformation of bearing when subjected to large force and displacement is not tested experimentally,
4. The response of building implementing the innovative elastomeric bearing, especially the effect of implementation on building drift is not studied experimentally, and
5. Comparison of the device level performance between innovative elastomeric bearing and lead-core rubber bearing experimentally.

1.8 Layout of the thesis

This thesis is divided into 5 chapters. The brief description of each chapter is described as below:

Chapter 1 summarizes the state of development in seismic isolation system and the identified gaps in the field. This chapter also highlights the objectives of study that aims to improve the identified problems.

Chapter 2 presents the review of previous works related to performance based seismic design and seismic isolation system. The advancement and state of development of seismic isolation system are highlighted. Studies on the potential material for innovation and numerical analysis method for bearing are presented in this chapter as well.

Chapter 3 presents the methodology of the study. The methodology is divided into 4 stages: preliminary, model development, experiment and numerical. The methods and considerations that aligned to the objectives of study are highlighted in detail in this chapter.

Chapter 4 presents the result and discussion of the study. The results from each stage are presented and arranged according to the stages as stated in methodology. Discussions of the result are presented as well.

Chapter 5 presents the conclusions of the study. The fulfilment of study objectives is justified in this chapter. Recommendations are made to guide future research related to the proposed innovative elastomeric bearing.

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