UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF RECTANGULAR RUBBER ISOLATORS FOR A TUNNEL-FORM STRUCTURE SUBJECTED TO SEISMIC EXCITATIONS

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By

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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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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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April 2021

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Faculty : Engineering

The tunnel-form building system is gaining popularity due to its characteristics in time saving in construction. However, the tunnel-form structure is more vulnerable against lateral loads because of its large weight to stiffness ratio, which can potentially intensify the forces induced to the structure during seismic events. To improve this vulnerability during earthquake hazards, seismic base isolation systems can be incorporated into the tunnel-form structure. Among others, rubber isolators have been adopted extensively as effective base isolation systems for various building and bridge structures around the world. However, the most common shapes used for base isolators are circular and square, as the anisotropic isolation system has typically been designed by employing symmetrical-shaped seismic isolators. While, these configurations are not applicable for the tunnel-form building system, since the distribution of the loads corresponding to the shear wall does not provide a uniform support condition along the walls. Therefore, an attempt was made in this study to develop rectangular rubber isolators with couple cores that are applicable for tunnel-form structures. A rectangular isolator with dual lead cores instead of a single core is proposed to enhance the efficiency of the isolator along the direction of the wall in terms of lateral shear resistance and energy absorption capacity. Previous studies had revealed the poisoning effects of lead material exposure on the environment and human health. Thus, to avoid adverse effects caused by exposure to lead material, a rectangular isolator with dual rubber cores instead of lead cores was developed. In this study, the rubber cores in a rectangular isolator are confined with a single layer of CFRP wrap and stainless steel tube to improve the lateral shear behavior and damping ratio of the isolators. For the sake of comparison, a rectangular rubber isolator without cores is also considered in this study. Five full-scale rectangular isolators are manufactured and experimentally tested under a vertical compressive load and horizontal displacements to derive and evaluate their hysteresis response. Finite element models for the 5 mentioned large-

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scale isolators are developed, and their performance under cyclic loads is investigated. The experimental and numerical results were then compared and they showed a good agreement. Based on the experimental testing and simulation results, the CFRP and stainless-steel tube confinement were found effective in improving the behavior of rectangular isolators with rubber cores in terms of damping ratio and energy dissipation capacity.

Furthermore, the proposed rectangular isolators are implemented into a 5-story tunnel-form structure, and nonlinear dynamic analyses were conducted for different structural performance levels. The seismic performance of the fixed base and base-isolated buildings is investigated by performing the Incremental Dynamic Analysis (IDA) using a suite of 10 pairs of earthquake ground motion records. Also, the fragility curves were created based upon the results of incremental dynamic analysis as it is one of the effective methods of conducting nonlinear dynamic analyses to gather data to estimate the fragility curves. In all models, the results showed that the probabilities of exceeding the Immediate Occupancy (I.O) performance level for coupling beams under both DBE and MCE hazard levels are less than 10 and 20%, respectively. This way, under both DBE and MCE hazard scenarios, these values for the walls are about 3 and less than 6%, respectively. It can be concluded that the tunnel-form structure can practically satisfy the Immediate Occupancy (I.O) performance level by implementing the proposed rectangular isolator systems even under severe seismic excitations.

Finally, the finite element parametric study based on the validated finite element models is conducted on 12 rectangular rubber isolators with one, two, and four square lead and rubber cores subjected to lateral cyclic loads. As in the case of prototype samples, the square rubber cores are confined with CFRP and steel layers which play a vital role, as concluded earlier, in improving the damping parameter of the proposed rectangular isolators. The numerical parametric study results showed a slight increase in the damping ratio with increasing the number of rubber cores. The results also indicated no remarkable difference between isolators tested along the length and those tested along the width. This shows that the response of the isolator does not depend on its shape rather than it is dependent on the amount and number of lead/rubber cores.

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

PEMBANGUNAN ISOLATOR GETAH SEGI EMPAT TEPAT BAGI STRUKTUR BENTUK TEROWONG DI BAWAH PENGUJAAN SEISMOS

Oleh

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Sistem bangunan berbentuk terowong semakin popular kerana ciri-ciri penjimatan masa dalam pembinaan. Walau bagaimanapun, struktur terowong lebih rentan terhadap beban lateral kerana nisbah berat dan kekakuannya yang besar, yang berpotensi dapat meningkatkan kekuatan yang disebabkan struktur pada kejadian seismik. Untuk memperbaiki kerentanan ini semasa bahaya gempa, sistem pengasingan pangkalan seismik dapat dimasukkan ke dalam struktur terowong dari. Antara lain, isolator getah telah diadopsi secara meluas sebagai sistem pengasingan asas yang berkesan untuk pelbagai struktur bangunan dan jambatan di seluruh dunia. Walau bagaimanapun, bentuk yang paling umum digunakan untuk pengasing asas adalah berbentuk bulat dan persegi, kerana sistem pengasingan anisotropik biasanya dirancang dengan menggunakan pengasing seismik berbentuk simetris. Walaupun, konfigurasi ini tidak berlaku untuk sistem bangunan bentuk terowong, kerana pengedaran beban yang sesuai dengan dinding ricih tidak memberikan keadaan sokongan yang seragam di sepanjang dinding. Oleh itu, percubaan dibuat dalam kajian ini untuk mengembangkan isolator getah segi empat dengan pasangan inti yang dapat digunakan untuk struktur bentuk terowong. Isolator segi empat tepat dengan dua teras utama dan bukannya satu teras dicadangkan untuk meningkatkan kecekapan pengasing sepanjang arah dinding dari segi ketahanan ricih lateral dan keupayaan penyerapan tenaga. Kajian terdahulu telah menunjukkan kesan keracunan pendedahan bahan plumbum terhadap persekitaran dan kesihatan manusia. Oleh itu, untuk mengelakkan kesan buruk yang disebabkan oleh pendedahan kepada bahan plumbum, sebuah isolator segi empat tepat dengan teras getah berganda dan bukannya teras plumbum dikembangkan. Dalam kajian ini, inti getah dalam isolator segi empat dibatasi dengan lapisan tunggal CFRP wrap dan tiub keluli tahan karat untuk memperbaiki tingkah laku ricih lateral dan nisbah redaman isolator. Sebagai perbandingan, pengasing getah segi empat tanpa teras juga dipertimbangkan dalam kajian ini. Lima pengasing segi empat tepat berskala

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penuh dihasilkan dan diuji secara eksperimen di bawah beban mampatan menegak dan anjakan mendatar untuk mendapatkan dan menilai tindak balas histeresisnya. Model elemen hingga untuk 5 isolator berskala besar yang disebutkan telah dikembangkan, dan prestasi mereka di bawah beban siklik diselidiki. Hasil eksperimen dan berangka kemudian dibandingkan dan mereka menunjukkan persetujuan yang baik. Berdasarkan hasil ujian dan simulasi eksperimen, CFRP dan pengikat tiub tahan karat didapati berkesan dalam meningkatkan tingkah laku pengasing segi empat tepat dengan teras getah dari segi nisbah redaman dan kapasiti pelesapan tenaga.

Selanjutnya, isolator segi empat tepat yang dicadangkan diimplementasikan ke dalam struktur terowong 5 tingkat, dan analisis dinamik nonlinier dilakukan untuk tahap prestasi struktur yang berbeza. Prestasi seismik bangunan tetap dan terpencil pangkalan disiasat dengan melakukan Analisis Dinamik Tambahan (IDA) menggunakan rangkaian 10 pasang rekod gerakan tanah gempa. Juga, lengkungan kerapuhan dibuat berdasarkan hasil analisis dinamik tambahan kerana ia adalah salah satu kaedah berkesan untuk melakukan analisis dinamik nonlinier untuk mengumpulkan data untuk menganggarkan keluk kerapuhan. Dalam semua model, hasilnya menunjukkan bahawa kebarangkalian melebihi tahap prestasi Penghunian Segera (I.O) untuk gandingan gandingan di bawah tahap bahaya DBE dan MCE masing-masing kurang dari 10 dan 20%. Dengan cara ini, di bawah senario bahaya DBE dan MCE, nilai-nilai untuk dinding masing-masing sekitar 3 dan kurang dari 6%. Dapat disimpulkan bahawa struktur bentuk terowong secara praktikal dapat memenuhi tahap prestasi Penghunian Segera (I.O) dengan menerapkan sistem isolator segi empat tepat yang dicadangkan walaupun dalam keadaan gegaran seismik yang teruk.

Akhirnya, kajian parametrik elemen hingga berdasarkan model elemen terhingga yang disahkan dilakukan pada 12 isolator getah segi empat dengan teras timah dan getah satu, dua, dan empat persegi yang dikenakan beban siklik lateral. Seperti dalam contoh prototaip, inti getah persegi dibatasi dengan lapisan CFRP dan keluli yang memainkan peranan penting, seperti yang disimpulkan sebelumnya, dalam meningkatkan parameter redaman isolator segi empat tepat yang dicadangkan. Hasil kajian parametrik berangka menunjukkan sedikit peningkatan nisbah redaman dengan peningkatan bilangan teras getah. Hasilnya juga menunjukkan tidak ada perbezaan yang luar biasa antara isolator yang diuji sepanjang dan yang diuji sepanjang lebarnya. Ini menunjukkan bahawa tindak balas pengasing tidak bergantung pada bentuknya daripada bergantung pada jumlah dan bilangan teras plumbum / getah.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

A	Cross-Sectional Area
ACI	American Concrete Institute
a_g	Ground Acceleration
A_i	Area of Isolator
A_l	Area of Lead Core
A_{lead}	Cross-Sectional Area of Lead Core
A_r	Area of Rubber Core
A_{rubber}	Cross-Sectional Area of Rubber Core
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
ATC	Applied Technology Council
ATC3-06	Amended Tentative Provisions for The Development of Seismic Regulations for Buildings
BS8110	British Design Code
C.P	Collapse Prevention
CFRP	Carbon Fiber Reinforced Polymer
CIDB	Construction Industry Development Board
CIMP	Construction Industry Master Plan
D	Lateral Displacement
D.L	Dead Load
DBE	Design Basis Earthquake
D_i	Diameter of Isolator
D_{lead}	Diameter of Lead Core

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DM	Damage Measure
DOF	Degree of Freedom
D_{rubber}	Diameter of Rubber Core
DS	Damage State
Dy	Yield Displacement
E	Elastic Modulus of Steel
E_c	Rubber Compression Modulus
EC8	Eurocode Design
EI	Bending Stiffness
FEA	Finite Element Analysis
FEM	Finite Element Modeling
FEMA	Federal Emergency Management Agency
F_Y	Yield Strength of Lead/Rubber Material
G	Rubber Shear Modulus
h	Total Height of Isolator
H_{lead}	Height of Lead Core
H_{rubber}	Height of Rubber Core
H_w	Height of Shear Wall Segment
I	Importance Factor
I.O	Immediate Occupancy
I_1	First Invariant of The Strain Deviator
IBS	Industrialized Building System
IDA	Incremental Dynamic Analysis
IDR	Interstory Drift Ratio

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IM	Intensity Measure
$IRHD$	International Rubber Hardness Degrees
J_{el}	Volume of Elastic Strain
K	Stiffness
k	Rubber Bulk Modulus
K_1	Elastic Stiffness
K_2	Post-Yield Stiffness
K_{eff}	Effective Stiffness
K_H	Horizontal Stiffness
$K_{h,eff}$	Horizontal Effective Stiffness
$KLIA$	Kuala Lumpur International Airport
K_r	Total Rubber Stiffness
K_V	Vertical Stiffness
$L.L$	Live Load
$L.S$	Life Safety
L_l	Length of Loading Steel Plate
L_r	Length of Rubber Pad
L_s	Length of Sealing Steel Plate
LS	Limit State
L_{sh}	Length of Steel Shim Plate
L_w	Length of Shear Wall Segment
M	Coefficient of Translational Effective Mass Factor
MCE	Maximum Considered Earthquake
$MGDM$	Mineral and Geosciences Department of Malaysia

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MGDM	Mineral and Geosciences Department of Malaysia
MMI	Modified Mercalli Intensity
N_{lead}	Number of Lead Cores
NPP	Nuclear Power Plant
n_r	Number of Rubber Layers
N_{rubber}	Number of Rubber Cores
n_{sh}	Number of Steel Shim Layers
NZ310	New Zealand Design Code
PEER	Pacific Earthquake Engineering Research Center
PGA	Peak Ground Acceleration
PLC	Programmable Logic Controller
Q	Characteristic Strength
Q_G	Gravity Load
R	Distance to The Closest Fault Rupture
RC	Reinforced Concrete
R_i	Lateral Force Coefficient
RP	Reference Point
S	Shape Factor
SDOF	Single Degree of Freedom
SR	Slip Rate
SSI	Soil-Structure Interaction
T	Effective Period
t_{CFRP}	Thickness of CFRP Sheet
T_D	Design Basis Earthquake (DBE) Time Period

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t_l	Single Loading Steel Plate Thickness
T_M	Maximum Considered Earthquake (MCE) Time Period
T_r	Total Rubber Thickness
t_r	Single Rubber Thickness
t_s	Single Sealing Steel Plate Thickness
t_{sh}	Single Steel Shim Thickness
t_{steel}	Thickness of Stainless Steel Layer
UBC97	Uniform Building Code 97
USGS	United States Geological Survey
W	Density of The Strain Energy
W_d	Area of Hysteresis Loop
WHO	World Health Organization
W_l	Width of Loading Steel Plate
W_r	Width of Rubber Pad
W_s	Width of Sealing Steel Plate
W_s	Restored Energy
W_{sh}	Width of Steel Shim Plate
Y	Realized Condition of Ground Motion
Z	Seismic Zone Factor
β_{eff}	Effective Damping
γ	Rubber Shear Strain
Δ	Drift
ε_{Eng}	Engineering Strain of Steel
ε_{true}	True Strain of Steel

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ζ_{eq}	Equivalent Viscous Damping
θ	Chord Rotation
μ	Ductility
v	Poisson's Ratio
σ_{Eng}	Engineering Stress of Steel
σ_{true}	True Stress of Steel
Φ	Diameter of Rubber Pad
Φ_D	Diagonal Steel Reinforcement
Φ_H	Horizontal Steel Reinforcement
Φ_{HT}	Horizontal Transverse Steel Reinforcement
Φ_L	Longitudinal Steel Reinforcement
Φ_V	Vertical Steel Reinforcement
Φ_{VT}	Vertical Transverse Steel Reinforcement
ω	Natural Frequency
ξ	Damping Ratio

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In most living areas, an earthquake as a devastating event affects its habitants, so the primary objective of earthquake scientists and researchers was to minimize the earthquake irreversible damage. The use of nonlinear dynamic analyses was expanded by passing the time and switching points of view from strength-based plotting to performance-based plotting. The performance-based design is the modern approach that was commonly used in the latest instructions and regulations (ASCE 41-13, 2013; ATC-40, 1996; FEMA 273, 1997; FEMA 350, 2000; FEMA 356, 2000; FEMA P695, 2009). During seismic excitations, some tensions are generated in structures that advance the structural components toward yield and collapse (Providakis, 2008). The first stage in the seismic improvement of existing structures is the seismic vulnerability analysis. The vulnerabilities and deficiencies of structures are defined based on the evaluation methods carried out on them. Primarily, several limitations are existed in selecting the enhancement methods of structures that impact the adopted approach. One of the most economical and efficient strategies is to separate the foundation from the superstructure to prevent the damage caused by the earthquake, which decreases the energy generated by the earthquake without affecting the structure's stability. The seismic performance-based design is the modern design approach used for evaluating the performance of structures through conducting the Incremental Dynamic Analysis (IDA) which includes scaling ground motion records to cover the entire domain of structure response, from elasticity to yielding, and then global dynamic instability (Mansouri et al., 2017).

In high seismicity areas, seismic base isolator systems are frequently used to ensure the seismic protection of essential facilities. Earthquake experts have developed and installed various seismic base isolation systems (Kim et al., 2019). Among others, seismic rubber isolators have been adopted extensively as isolation systems for various building and bridge structures worldwide. Although it is not possible to control the earthquake itself, its actual impact on the building can be controlled by mitigating the effects of the foundation's movement on the superstructure by employing base isolators. Through installing seismic isolators between the foundation and superstructure, the isolation system offers improved stability and energy dissipation capacity. Although the use of conventional seismic isolator systems may be familiar in various countries around the world, rectangular rubber isolators have rarely been investigated for shear wall structures (Al-Kutti & Islam, 2019; Ismail et al., 2010; Islam & Al-Kutti, 2018; Ounis & Ounis, 2013; Saha et al., 2015). The design of base-isolated structures is primarily based on the assumption that

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when subjected to seismic excitations, the structure will effectively respond elastically. It is predicted that the damage caused by seismic forces will be concentrated in the isolators that are designed to be easily replaceable. As their design is aligned with the concepts of resilience, i.e., rapid restoration and low-damage, isolated structures are resilient. The use of steel shim layers alternating with rubber layers provides improved vertical stiffness to preserve the structure's self-weight and the isolator’s lateral flexibility (Kalfas et al., 2017).

The Industrialized Building System (IBS) is the construction process that most of its structural components such as walls, slabs, beams, columns, and staircases are pre-prepared in the factory and assembled on the site in a short amount of time with high-quality construction. This system is effective in projects that provide repetitive formation opportunities with today's refinements. Because of its industrialized modular construction method, the more repetitive steps there are, the greater the benefits. The system is especially suitable for multi-unit housing, student housing, military housing, hotels, single-family homes, townhouses, and prisons (Qasem, 2016). The tunnel-form building system is classified under the IBS which consists of shear walls and flat slabs. There are two primary functions of shear walls: carrying vertical loads (load-bearing walls) and resisting lateral loads such as wind and seismic loads. During the construction process of the tunnel-form structural system, cast-in-situ concrete is poured into two inverted L-shape steel formworks to simultaneously build the shear walls and flat slabs in a daily cycle. For every 24 hours, the formwork is transferred to another building level. Upon finishing each story level, the construction process is repeated on the next floor and as a result, the residential units can be built up quickly. For this purpose, the tunnel-form system is a unique alternative to repetitive plans for erecting medium to high-rise buildings. In this innovative system, precast components don’t exist in which the structural members such as shear walls and slabs are poured in place having almost the same thickness. This leads to minimize the number of joints and result in a symmetrical configuration in vertical and horizontal plan views of a monolithic structure, as well as to provide high seismic resistance.

Malaysia is located close to the most seismically active region known as the earthquakes zone and volcanic eruption encircling the pacific ring of fire. However, Malaysia is deemed a low seismic zone under a far-field earthquake from Sumatra and near-field earthquakes from Bukit Tinggi to Kuala Lumpur fault lines (Hamid et al., 2014). The majority of existing reinforced concrete (RC) buildings in Malaysia have been designed based on the British BS8110 code to sustain gravity loads, notional lateral loads, and wind loads, which has no specific provision for seismic loads (Qasem, 2016). Nevertheless, due to the regularly felt ground tremors from earthquake events in the neighboring countries and earthquakes of local origins that occurred in Malaysia, RC buildings may be at risk under a repetitive low cycle of failure that leads to significant damage of these buildings. For instance, the reinforced concrete school building in Sabah has experienced partial damages under an earthquake with a magnitude of 4.3 scale Richter. These damages indicate that

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a structure's overall performance could not sustain under a low magnitude of seismic excitation. If an unexpected earthquake occurs within 300 km of the epicenter of Malaysia, a significant collapse of these structures can happen (Hamid et al., 2014). Figure 1.1 shows the seismic activities surrounding the east and west of Malaysia (Syahrum, 2007).

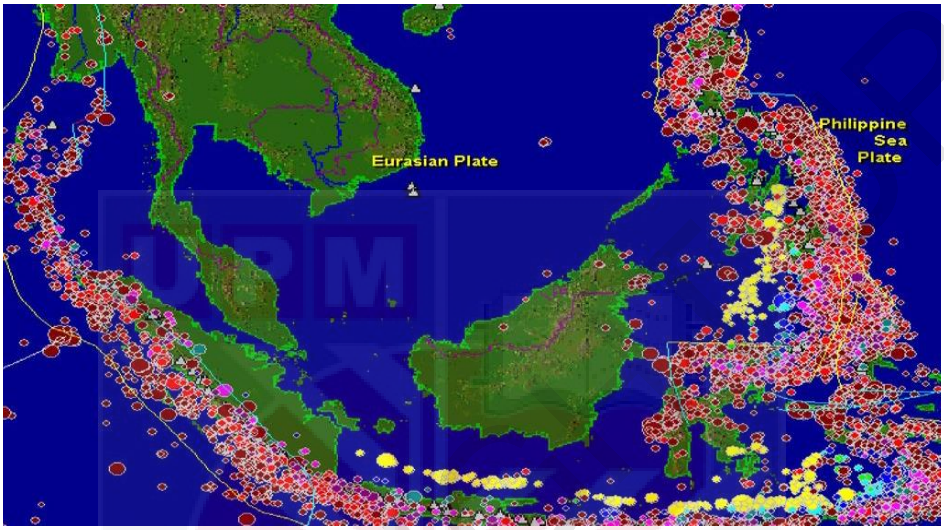

Figure 1.1: Sea seismic activities surrounding Malaysia
(Source: Syahrum, 2007)

1.2 Research Hypothesis

Energy dissipation covers any component used to reduce the movement of structures under dynamic excitation (e.g., wind, earthquakes). From the literature review, it is further observed that the majority of conventional lead rubber bearing isolators available in the market have a single lead core which is not sufficient for shear wall structures due to its great weight and stiffness. Therefore, increasing the number and amount of lead cores is crucial to achieving the high damping performance of the proposed rectangular rubber isolators along the wall direction of the tunnel-form building system. Although there are limited studies on rectangular isolators for shear wall structures, proper experimental tests and physical and material modeling of rectangular rubber isolators are not seen. On the other hand, the previous research studies proved the poisoning effects of lead material exposure on the environment and human health. Therefore, to avoid any harmful effects caused by the lead material, a rectangular isolator with rubber cores instead of lead cores will be developed. The literature review revealed that the rubber cores in the conventional base isolators are unconfined which resulted in a low viscous damping ratio and unable to withstand the great weight and stiffness of tunnel-form structures under seismic activity and vibration. Thus, the rubber cores will

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be confined with a single layer of CFRP wrap and stainless steel tube to increase the damping ratio of the isolation system via dissipating more energy and vibrations induced to the building. This study aims to develop a new type of seismic base isolator that uses a combination of lead or rubber cores to improve energy dissipation. Full-scale experimental testing will be conducted. A numerical model will be developed to investigate the device considering lateral cyclic loading. Scenarios involving different types of plugs will be considered; the stiffness and damping of the devices will be discussed. In the second half of the study, nonlinear time history analysis will be performed on a base-isolated tunnel-form building with the bearings mentioned above. The structure's response will be evaluated based on base shear, drift, and damage of the concrete structural elements. An incremental dynamic analysis will be performed, and fragility curves will be generated.

1.3 Brief Review of Earlier Works

Seismic rubber isolators are common types of seismic isolation systems. Numerous studies have been investigated under seismic excitation for mechanical simulation of these isolators. Cho et al. (2016) conducted comparative research on various models of rubber hyperelastic materials. The analysis is performed on lead rubber isolators with different rubber material properties. The study revealed that the Ogden model captures the material with fewer errors than other hyperelastic models. Ahmadipour and Alam (2017) presented the mechanical properties of a square lead rubber isolator with a sensitivity analysis. The research compared the isolators' horizontal and vertical stiffness to various lead types, lead radius, and rubber layers. Their findings revealed that the radius of the lead core was the most influential parameter among the three variables above in effecting the quality of the lead rubber isolator. The degradation of vertical stiffness of laminated rubber isolators was performed under lateral shear loading by Yang et al. (2017). The analysis results revealed that the ratio of vertical stiffness is calculated only by the section proportion of the lateral deformation to the inertia radius, and is not affected by the section shape, direction of loading (compressive or tensile), and isolator size. Kalfas et al. (2017) and Kalfas and Mitoulis (2017) used finite element methods to examine the response of laminated rubber isolators under the effect of different axial loads. The study results indicated that increasing axial compressive load caused a remarkable decrease in the isolator stiffness. Their results indicated that the isolator demonstrates a fluctuate behavior when considering the combination of shear strain, axial loading, and rotation. Zeynali et al. (2018) carried out an experimental and numerical investigation on the use of lead rubber dampers in the chevron braced frame. They concluded that the isolator with a larger diameter of the lead core has a greater capacity for energy dissipation. Kumar and Whittaker (2018) proposed a mathematical model capable of providing the best estimate of the isolator's response under extreme load. Xiang et al. (2018) conducted a shake table test of a highway bridge by enabling laminated rubber isolators to be slid with and without restraining equipment. Gauron et al. (2018) used experimental results to test the shear failure and lateral stability limit states of rubber bridge isolators. The

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study findings demonstrated that the limited operating conditions seem to be virtually impossible, and why the majority of isolators do not show any damage before failure cannot be determined experimentally. Rahnavard and Thomas (2019) performed a theoretical study on the mechanical properties of elastomeric base isolators with various rubber cores under combined tensile and compressive loading effects. Their study showed that rubber isolators with different radially distributed circular rubber cores overcome those with a single central rubber core. In a more recent study, Rahnavard et al. (2020) performed a numerical investigation on the static and dynamic lateral stability of circular and square rubber isolators with different rubber cores. They concluded that using single and multiple rubber cores increases the lateral stability of the isolators due to the high critical axial forces.

The innovative construction industry is gaining popularity in the structural engineering community and progressing increasingly towards more effective structural systems and technologies to minimize expenses, construction time, and human resources, as well as to improve the durability and stability of buildings during severe loading excitations such as intense earthquakes. However, the novel tunnel-form building systems may deliver many advantages in this regard, such as professional planning capacity, shortening the construction time, and ultimately contributing to a rapid return on assets (Mohsenian et al., 2019). All the vertical load-bearing members of this unique system are composed of walls and slabs classified as lateral and vertical load-bearing components, which are cast in each story simultaneously. Since the walls and slabs are built simultaneously in each level, using a cold joint to maintain an integrated performance of the structure throughout an earthquake event is unnecessary (Tavafoghi & Eshghi, 2008). Although such structural systems are extensively being used in densely populated urban areas and industrial projects, relatively few studies in this field have been performed. There is absolutely no specification or standard that describes this novel system as a different load-bearing structural system. An analysis of the code-based relationships for determining the fundamental vibration period found that the values obtained from the empirical relationships were either notably underestimated or overestimated; this inconsistency between the actual and empirical results demonstrated a deficiency in predicting the seismic demands (Mohsenian et al., 2019).

Balkaya and Kalkan (2003) and Balkaya and Kalkan (2004) suggested some mathematical relationships to measure the fundamental vibration periods of 2 and 5-story tunnel-form building structures with a varying number of stories and plans through performing a variety of pushover analyses. Correspondingly, the 3D membrane behavior was observed to be a dominant force function in such buildings. Finally, for both shorter and taller buildings, response modification factors equal to 5 and 4 have been suggested. Yuksel and Kalkan (2007) and Kalkan and Yüksel (2008) examined the 3D behavior of intersection walls by conducting several tests on samples containing minimum reinforcement percentage for the small longitudinal reinforcement ratio. Using computer-aided design software, the analysis results showed that increasing longitudinal

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reinforcement bars in the corners of the walls would have a desirable effect on their response and could vary the brittle fracture failure even in small reinforcement ratios. Tavafoghi and Eshghi (2008) performed different studies on tunnel-form building structures and their findings revealed that the fundamental period of vibration has depended on the building's height in both directions. Thus, the number of walls, as well as the aspect ratio, were having a negligible impact on the building's fundamental vibration period. Besides, Aval et al. (2018) assessed the seismic performance of the tunnel-form building that was subject to both near-field and far-field ground motion records using the effects of forward directivity. Based on the results, it has been indicated that forward directivity can affect the modes of failure of a tall tunnel-form building structure and minimize the design reliability. Recently, Mohsenian et al. (2019) evaluated the seismic performance of tunnel-form building structures, considering the soil-structure interaction effect. Depending on their numerical findings, the effects of SSI on the structural response such as story displacement, story shear force, and position of damage initiation became more significant with an increase in building heights and earthquake intensities.

1.4 Problem Statement

The problem statement of this study which derived through reviewing of the literature is summarized as follow:

1- Currently, the most common isolators are available in a circular or square shape which is not applicable for the tunnel-form buildings as isolation systems, since the distribution of the shear wall loads (gravity loads) does not create a uniform support condition along the walls.
2- The majority of conventional isolators have a single lead core which is insufficient for a tunnel-form structure due to its great weight and stiffness. Therefore, increasing the number and amount of lead core is essential to enhance the efficiency of the rectangular isolators along the wall direction of the tunnel-form system.
3- Pervious research studies and international organizations are suggested to eliminate lead material due to its harmful effects on the environment and human health. Thus, an alternative material instead of the lead material is required to implement.
4- The literature revealed that the rubber cores in the seismic isolators are unconfined, which resulted in a low energy absorption capacity. Therefore, confining the rubber cores with CFRP/steel layers is crucial since it acts as a full bounded jacketing to provide a remarkable lateral shear capacity and damping ratio for the rectangular isolators.

1.5 Objectives of The Study

The primary objectives of this research work can be summarized as follow:

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1- To increase the viscous damping ratio of the rectangular rubber isolators for a tunnel-form structure subjected to seismic events.
2- To experimentally investigate five full-scale rectangular rubber isolators with double lead and rubber cores under combined vertical and horizontal loads.
3- To numerically propose rectangular rubber isolators with different square lead and rubber cores based on the validated finite element models.
4- To apply the developed rectangular rubber isolators into 5-story base-isolated tunnel-form structures and compare the results with the seismic performance of the fixed base structure.

1.6 Scopes of The Study

The primary scopes of this study are summarized as follow:

1- The energy dissipation capacity of the rectangular isolators was increased by increasing the amount of the lead cores and confining the rubber cores with a CFRP sheet and stainless steel tube.
2- The proposed design for the rectangular rubber isolators was evaluated through finite element simulations and experimental tests under combined vertical compressive and shear loadings.
3- The finite element parametric study was conducted based on the validated models in order to propose rectangular isolators with a variety of square lead and rubber cores.
4- The Incremental Dynamic Analysis (IDA) was performed and the fragility curves were generated in order to assess the seismic performance of the base-isolated buildings.

1.7 Thesis Outlines

Chapter One presents the introduction and general philosophy of the study. The problem statement and objectives of the present study are also illustrated in this chapter. **Chapter Two** reviews the previous research works related to the base isolation devices and their applications in the buildings. The seismic performance of the tunnel-form structures, including earlier researches in this field, is also presented. The experimental and numerical procedures of the proposed rectangular isolators are described in **Chapter Three** along with a brief explanation of the material properties and specifications used in this study. Experimental and numerical results are summarized and discussed in **Chapter Four**. The finite element parametric study based on the validated models is also conducted and its results are examined in this chapter. **Chapter Five** draws attention to embody the study's conclusions and additional recommendations intended for future research works.

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