A NEW VISCOELASTIC DAMPER FOR SEISMIC PROTECTION OF STEEL BUILDING FRAME

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This thesis is dedicated to the memory of my father who supported me a lot and passed away during my PhD studies. He is always in my heart and I miss him every day. I know that he would be very proud to see me complete my doctoral degree. I also would like to dedicate the thesis to my beloved mother and wonderful wife for their endless love, faith, support, and encouragement. I also dedicate this work to my brother and my wife's parents who have walked alongside me during doctoral degree.

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ABSTRACT

Viscoelastic dampers (VEDs) are widely used to protect structures against earthquake. Conventional VEDs are generally installed within a diagonal brace configuration which provides a stiff structural system and reduces their effectiveness. In addition, the aforementioned configuration is not suitable for retrofitting purpose and violates architectural requirements. In this study, a new type of viscoelastic damper is proposed in order to improve the seismic performance of steel structures and to overcome the drawbacks of the conventional VEDs. In order to evaluate the performance of the proposed VED, dynamic responses of a 3-story scaled down steel frame equipped with the proposed VED were obtained experimentally and numerically under harmonic excitations. In this stage, ABAQUS software was used to establish a detailed finite element analysis. The results obtained were compared with a frame equipped with the conventional VED as well as a moment resisting frame and braced frames. The effects of the size of viscoelastic layer on its dynamic characteristics were also investigated. In addition, a nonlinear time history analysis of a 10-story full scale steel frame was performed using SAP2000 software to demonstrate the effectiveness of the proposed VED for tall buildings. The results of this study showed that the frames equipped with dampers performed better than the braced frames in terms of reduction in the maximum displacement, acceleration and base shear responses of the 3-story moment resisting frame. Compared to the conventional VED, the proposed VED was more effective in reducing displacements, while it was slightly less effective in reduction of accelerations and base shears. It was also found that smaller thickness of the viscoelastic layer decreased displacement responses, however, it increased acceleration and base shear responses. The larger cross-section area of the viscoelastic layer resulted in smaller displacement responses, but larger acceleration and base shear responses. Thus, analysis of the 10-story frame showed that the effectiveness of VEDs for reducing maximum displacement and acceleration responses were strongly dependent on the characteristics of earthquake records. The proposed VED was more effective in reducing responses of the lower floors. Based on the results obtained, the maximum base shear response of the frame equipped with the conventional VED was smaller than the frame equipped with the proposed VED and larger than the bare frame regardless of the characteristics of earthquake records. The results showed that the viscoelastic dampers have more advantage in preventing the formation of plastic hinges in the frames even under severe earthquake. In addition, compared to the conventional VED, the proposed VED resulted in less damage to the structural members due to less plastic hinge formation. Therefore, the implementation of the proposed VED can overcome the deficiency of the VED in seismic protection of structures.

ABSTRAK

Peredam visco-elastik (VED) digunakan secara meluas untuk melindungi struktur terhadap gempa bumi. VED konvensional umumnya dipasang di antara konfigurasi perembat pepenjuru yang menghasilkan sistem struktur yang kukuh dan mengurangkan keberkesanannya. Di samping itu, konfigurasi ini adalah tidak sesuai untuk tujuan pengubahsuaian dan boleh melanggar keperluan seni bina. Dalam kajian ini, peredam visco-elastik jenis terbaru dicadangkan bagi meningkatkan prestasi seismik struktur keluli dan mengatasi kelemahan VED konvensional. Bagi menilai prestasi VED yang dicadangkan, gerak balas dinamik bagi kerangka keluli 3 tingkat yang dilengkapi dengan VED yang dicadangkan telah diperolehi daripada eksperimen dan kiraan berangka di bawah pengujaan harmonik. Pada tahap ini, perisian ABAQUS telah digunakan untuk menjalankan analisis unsur terhingga secara terperinci. Hasil yang diperoleh dibandingkan dengan kerangka yang dilengkapi dengan VED konvensional sepertimana kerangka penahan momen dan kerangka dirembat. Kesan saiz bagi lapisan visco-elastik terhadap ciri-ciri dinamik turut disiasat. Di samping itu, analisis sejarah masa tak linear bagi kerangka keluli 10 tingkat berskala penuh dijalankan menggunakan perisian SAP2000 bagi menunjukkan keberkesanan VED yang dicadangkan untuk bangunan tinggi. Dapatan kajian menunjukkan bahawa kerangka yang dilengkapi dengan peredam adalah lebih baik berbanding kerangka dirembat dari segi pengurangan anjakan maksimum, pecutan dan gerak balas ricih asas untuk kerangka penahan momen tiga tingkat. Berbanding dengan VED konvensional, VED yang dicadangkan adalah lebih berkesan dalam mengurangkan anjakan, namun ia kurang berkesan dalam pengurangan pecutan dan ricih asas. Kajian juga menunjukkan ketebalan yang lebih kecil bagi lapisan visco-elastik mengurangkan gerak balas anjakan, walau bagaimanapun, ia boleh meningkatkan pecutan dan gerak balas ricih asas. Keluasan keratan lintang yang lebih besar bagi lapisan visco-elastik boleh menghasilkan gerak balas anjakan yang lebih kecil, namun pecutan dan gerak balas asas ricih adalah lebih besar. Oleh itu, analisis kerangka 10 tingkat menunjukkan bahawa keberkesanan VED dalam pengurangan anjakan maksimum dan gerak balas pecutan adalah amat bergantung kepada ciri-ciri rekod gempa bumi. VED yang dicadangkan adalah lebih berkesan dalam pengurangan gerak balas bagi tingkat bangunan yang lebih rendah. Berdasarkan keputusan yang diperolehi, gerak balas ricih asas maksimum bagi kerangka yang dilengkapi dengan VED konvensional adalah lebih kecil berbanding kerangka dilengkapi dengan VED yang dicadangkan dan lebih besar berbanding kerangka penahan momen tanpa mengambil kira ciri-ciri rekod gempa bumi. Keputusan juga menunjukkan bahawa peredam visco-elastik mempunyai kebaikan dalam menghalang pembentukan engsel plastik dalam kerangka walaupun di bawah gempa bumi yang teruk. Di samping itu, berbanding dengan VED konvensional, VED yang dicadangkan boleh mengurangkan kerosakan kepada anggota struktur disebabkan pembentukan engsel plastik yang lebih sedikit. Oleh itu, pelaksanaan VED yang dicadangkan dapat mengatasi kekurangan VED konvensional dalam perlindungan seismik struktur.

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LIST OF ABBREVIATIONS

VE	-	Viscoelastic
MDs	-	Metallic Dampers
FDs	-	Friction Dampers
VEDs	-	Viscoelastic Dampers
VED	-	Viscoelastic Damper
VFDs	-	Viscous Fluid Dampers
TMDs	-	Tuned Mass Dampers
TLDs	-	Tuned Liquid Dampers
ADAS	-	Added Damping and Stiffness
BRB	-	Buckling-Restrained Brace
H-BRB	-	Hybrid-Buckling-Restrained Brace
VF	-	Viscous Fluid
PTMD	-	Pounding Tuned Mass Damper
TLCD	-	Tuned Liquid Column Damper
VPD	-	Visco-Plastic Damper
VCD	-	Viscoelastic Coupling Damper
MRPRA	-	Malaysian Rubber Producers' Research Association
UHDNR	-	Ultra-High Damping Natural Rubber
TBD	-	Toggle-Braced-Damper
RC	-	Reinforced Concrete
HMD	-	Hybrid Mass Damper
SMM	-	Standard Maxwell Model
SKM	-	Standard Kelvin Model
FDM	-	Fractional Derivatives Model
MPL	-	Modified Power Law

GEB	-	Global Energy Bound
LVDT	-	Linear Variable Differential Transformer
FE	-	Finite Element
PGA	-	Peak Ground Acceleration
AISC	-	American Institute of Steel Construction
FEMA	-	Federal Emergency Management Agency
ASTM	-	American Society for Testing and Materials
CVED	-	Conventional Viscoelastic Damper
PVED	-	Proposed Viscoelastic Damper

LIST OF SYMBOLS

T_g	-	Glass transition temperature
δ	-	Phase angle
Δt	-	Time interval
N	-	Number of time steps
G'	-	Shear storage modulus
G''	-	Shear loss modulus
η	-	Loss factor
u_{max}	-	Maximum displacement
T	-	Ambient temperature
f	-	Excitation frequency
e	-	Natural logarithm
K_d	-	Damper stiffness
K	-	Spring stiffness
C	-	Dashpot damping
E	-	Young's modulus
υ	-	Poisson's ratio
R	-	Response reduction ratio
g	-	Gravity
$\eta_{(damper\text{-}brace)}$	-	Viscoelastic damper assembly loss factor
K_{brace}	-	Brace stiffness
K_{damper}	-	Viscoelastic damper stiffness
η_{damper}	-	Viscoelastic damper loss factor
$K_{(damper\text{-}brace)}$	-	Viscoelastic damper assembly stiffness
ξ	-	Required damping ratio
K_i	-	ith story stiffness

n	-	Number of viscoelastic layer
A	-	Area of viscoelastic layer
h	-	Thickness of viscoelastic layer
θ	-	Angle of viscoelastic damper
ε	-	True strain
σ	-	True stress
ε	-	Nominal strain
σ_0	-	Nominal stress
E*	-	Complex Young's modulus
E′	-	Shear Young's modulus
A/V	-	Peak ground acceleration to velocity
W	-	Energy dissipation per cycle
F_1	-	Force at maximum displacement
F_2	-	Force at zero displacement
u_i	-	Displacement amplitude of the peak at time i
$u_{(i+nj)}$	-	Displacement amplitude of the peak n periods away

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CHAPTER 1

INTRODUCTION

1.1 Background

An earthquake is the perceptible shaking of the surface of the Earth, resulted by the sudden release of energy in the Earth's crust that creates seismic waves. They are among the most feared natural hazards which cause devastating consequences every year due to destruction of buildings and other structures. For example, the Bam (Iran) earthquake of magnitude 6.6, happened on Dec. 26, 2003, led to enormous loss of life and property. More than 27000 people died, eighty-five to ninety percent of buildings and infrastructures were either damaged or destroyed, and left an estimated 100000 people homeless. Even more recently, the April 2015 Nepal earthquake killed more than 8800 people and injured more than 23000. Hundreds of thousands of people were made homeless with entire villages flattened. It also destroyed century-old buildings at the UNESCO World Heritage sites.

Seismic events usually caused damages in structures that have not been properly designed for earthquake or are constructed prior to the formulation of seismic design guidelines. The seismic performances of these buildings are often unsatisfactory. They often have inadequate lateral strength, stiffness and inadequate ductility. Figure 1.1 shows some of the structural failure around the world due to earthquake. Widespread damage from the 1929 Murchison and 1931 Hawke's Bay earthquakes had a profound effect on public perceptions of the hazard posed by earthquakes. Attention was focused on weaknesses in building construction, especially poor building standards and lack of any provision for earthquake-resistant design. This led to formulation of seismic design guidelines which was incorporated into the building codes. The current building codes (i.e., ASCE, Eurocode 8) recommend that earthquake loading must be considered in design in addition to the gravity load for constructing a structure in a seismically active zone. In addition, the buildings constructed prior the current seismic design codes also require retrofitting or upgrading to be protected from earthquakes.

New Zealand earthquake (2011)

Iran earthquake (Bam 2003)

Nepal earthquake (2015)

Japan earthquake (2011)

Figure 1.1 Structural failure around the world due to earthquake [1, 2]

Nowadays, due to construction of tall and super tall buildings demand for safe and economical seismic design has increased. Therefore, protecting structures together with their occupants and contents from destructive natural hazards such as earthquakes have become a constant challenging task for civil engineers. In general, there are two fundamental approaches in seismic design of building structures; to increase structural capacity (conventional approach) or to decrease seismic demand (innovative approach). Conventional seismic design relies on strategies that increase the strength, stiffness and ductility of a building to control earthquake induced motions. According to the conventional approach, structures should not collapse under a major earthquake, even if the building itself is severely damaged. Therefore, conventional seismic design is not appropriate for structures such as hospital and fire station which must remain functional after earthquake to continue their serviceability. Moreover, this approach does not provide an appropriate safety margin for the design of tall building structures.

To overcome the shortcomings inherent in the philosophy of the conventional seismic design, a number of innovative approaches have been introduced in recent years [3, 4]. These approaches rely on dissipating the seismic energy through improving dynamic characteristics of structures. Therefore, vibration induced by dynamic loads is controlled and the amount of seismic force transmitted to the structure is reduced. The modern approach of seismic design can be classified into two groups including systems that increase the natural period of the structures and those that increase their damping ratio. The latter aims to increase the damping level of structure and reduce their seismic demand by adding some supplemental devices known as dampers. Usage of supplemental damping devices for dissipating seismic induced energy of buildings has gained increasing interest in the past few decades. Variety of energy dissipation systems have been developed and investigated while new types of dampers is under development. Example of typical energy dissipating devices are shown in Figure 1.2. These control system devices can act in passive, active and semi-active method or a combination of them. Active and semi-active control systems are evolution of passive control technologies to improve the effectiveness and efficiency of vibration control devices. In such systems, controlling forces are applied to the damper through external source powers like actuator(s) based on the feedback from sensors that measure the excitation and/or the response of the structure. The major drawback of these systems is that the power source which is essential to activate the dampers might be disrupted during seismic events. In addition, instruments of active or semi-active systems such as actuators, sensors or computer are very costly and a relatively short service life is still a problem for these instruments [5].

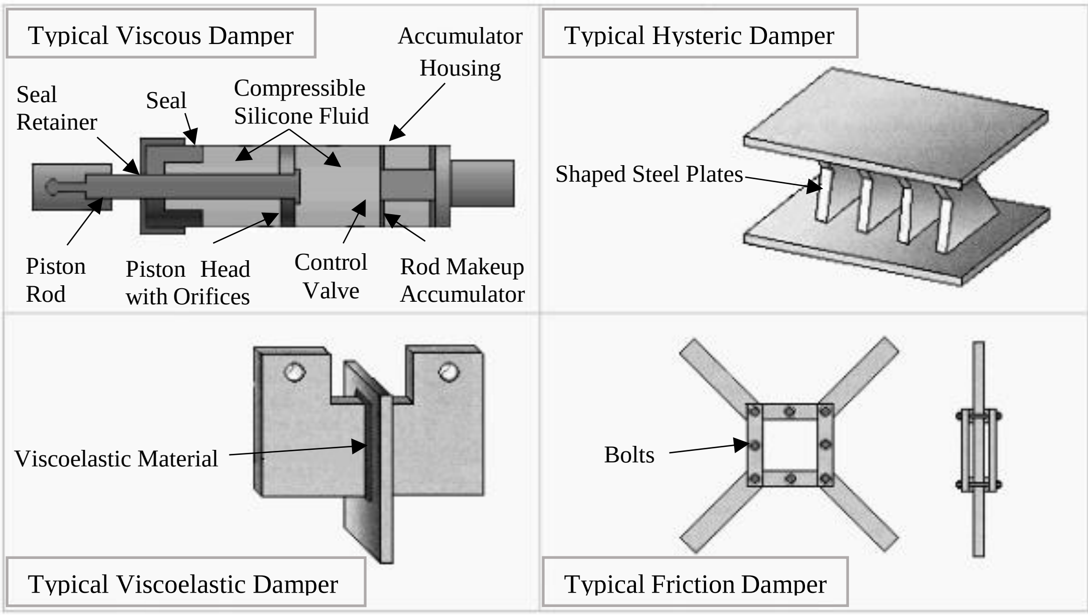

Figure 1.2 Example of typical passive energy dissipating devices based on Soong T.T. et al, 1997 [6]

Because passively controlled devices do not require an external power source for operation and utilize the motion of the structure to develop the control forces, the implementation of this type of devices has outdistanced significantly the implementation of others [7]. In this study, a novel viscoelastic damper is proposed to improve the seismic performance of structures and to overcome the drawbacks of the conventional viscoelastic damper. The proposed damper consists of a single layer viscoelastic material sandwiched between two steel plates. The damper is placed in the mid-span of a beam and connects to two braces that form an inverted V shape. The effectiveness of the proposed viscoelastic damper was evaluated experimentally and numerically. The proposed viscoelastic damper shares the advantages of a variety of existing dampers and can dissipate input energy under all levels of vibrations. The main advantage of this new damper is that it does not occupy the span of entire frames. Therefore, from architectural point of view such configuration is preferable especially when it comes to seismic retrofit via viscoelastic (VE) damper.

1.2 Problem statement

The use of passive energy dissipation devices has become very popular in recent years. The performance of these devices in reducing the seismic response of buildings was extensively investigated experimentally as well as numerically and their effectiveness were widely proven. Currently, viscoelastic dampers are widely used in many countries as energy dissipation devices to reduce earthquake-induced vibrations in new and existing buildings. Viscoelastic dampers do not only have the advantages of easier installation as well as manufacturing, good durability and low cost, but also they have high energy dissipation capacity. Conventionally, viscoelastic dampers are generally installed within a diagonal brace configuration for structures such as buildings. The application of the devices in the traditional configuration, however, could present some disadvantages, particularly when they are applied in building retrofits. In fact, even if in new structures the columns are designed to bear the additional axial forces induced by the dampers, in existent buildings these forces can create an untimely failure of the columns that are connected to the VE dampers [8]. In addition, the aforementioned configuration provides a stiff structural system which may lead to lower shear deformation in VE material, thus lowering their efficiency and energy dissipation. Excluding these matters, the application of this type of retrofitting often interferes with architectural requirements such as open space and unobstructed view as the configuration occupies entire bays in frames [8]. In recent years, several new configurations have been developed including the toggle-brace and the scissor-jack dissipation system [9, 10]. However, analysis and detailing of these configurations are so complex. In this research, a novel viscoelastic damper is proposed in order to improve the seismic performance of steel structures and to overcome the drawbacks of the conventional VEDs. The proposed VED can be used in design of new structures or retrofitting of existing structures. The configuration of the proposed VED results in magnifying the displacement of the damper and increases its efficiency. In addition, using the proposed VED results in less axial forces applied to the column and is preferred for retrofitting purpose. In this research, damper induced column axial forces are addressed quantitatively by degree of plastic hinge formation and are fully explained later. On the other hand, the configuration is preferred from architectural point of view as it does not occupy the span of entire frames in contrast to the conventional VED.

1.3 Objective of the research

The main aim of this project is to develop a novel viscoelastic damper for seismic retrofit of steel structures. Specific objectives are:

i) To study dynamic behavior of frame with and without the conventional viscoelastic damper.

ii) To propose a new type of viscoelastic damper considering drawbacks of the conventional viscoelastic dampers.

iii) To investigate experimentally and numerically the efficiency of the proposed viscoelastic damper installed inside a scaled down steel structure.

iv) To determine numerically the effect of different viscoelastic layer dimensions on the performance of the proposed viscoelastic damper.

v) To propose a simplified numerical model for the viscoelastic dampers in structural analysis of multi-storey structures.

vi) To evaluate numerically the seismic performance of the proposed viscoelastic damper in multi-storey structures by using the proposed simplified model.

1.4 Scope of the research

This research is intended to propose a novel viscoelastic device to improve seismic performance of structures and to overcome the deficiency of the conventional viscoelastic damper. Effectiveness of the proposed damper is evaluated through comparing responses of a 3-story scaled down bare frame to a frame with and without the conventional and proposed viscoelastic damper. Both experimental and numerical approaches are employed for this purpose. In addition, seismic performance of the damper is investigated by nonlinear time history analysis of full-scale 10-story frame. The main response parameters that are studied in this research are displacement and acceleration through the height of the building. The scope of this investigation is as follow:

- Conventional viscoelastic damper uses two layers of viscoelastic material with the size of 60 mm×20 mm×5 mm.
- In this research, the effect of changes in the dimensions of viscoelastic layer on performance of the proposed viscoelastic damper are only investigated.
- In this study, different sizes of viscoelastic layers are employed for the proposed viscoelastic damper. The size of viscoelastic layers includes 900 mm^2 (30 mm×30 mm), 2500 mm^2 (50 mm×50 mm) and 4900 mm^2 (70 mm×70 mm) in area with thickness of 3 mm, 5 mm and 7 mm.
- The mechanical properties of viscoelastic material are tested at various frequencies ranged from 0.1 Hz to 5 Hz and strains of 5 %, 20 % and 50 %.
- The effect of temperature on the properties of viscoelastic material are not considered in this research.
- Performance of the damper installed at the first level of a 3-story steel frame with scale of 1:3 is investigated experimentally under harmonic excitation only.

- Due to limitation of harmonic shaking table, responses of the fully damped frame is studied numerically using ABAQUS software.
- Excitation frequency included 20 % below and above the frame’s resonance frequency.
- Response of a 10-story building equipped with the proposed damper was studied numerically using SAP2000 software.

1.5 Outline of the research

This research is subdivided into six chapters. The chapters are organized as follow:

i. Chapter 1 presents an introduction and background of the study as well as objectives and scope of the research, and explains problem statement and motivation of this research.

ii. Chapter 2 presents a literature review on technical background of issues related to the viscoelastic dampers. In addition, nature of seismic loads and an overview of several supplemental damping devices are explained.

iii. Chapter 3 describes research methodology to attain the objectives of this study. In this chapter, both experimental and numerical approach are discussed in details.

iv. Chapter 4 presents the results obtained experimentally for performance evaluation of the proposed viscoelastic damper. The results of mechanical properties of materials used for experimental tests are also displayed in this chapter.

v. Chapter 5 presents the results obtained by numerical studies for performance evaluation of the proposed viscoelastic damper. In addition, effect of the viscoelastic layer sizes on the performance of the proposed viscoelastic damper is investigated in this chapter. Finally, a simplified model is proposed for analysis of high rise buildings.

vi. Chapter 6 summarizes the results and presents a final conclusion along with recommendations for future work.

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