UNIVERSITI PUTRA MALAYSIA

ASSESSMENT OF PROPOSED LATERAL RESISTANCE SYSTEM USED WITH FRAMED STRUCTURES

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By

AMIR FATEH

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

Every challenging work needs self efforts as well as guidance of those who are very close to our hearts.

My humble effort I dedicate to my sweet and lovely father and mother, whose affection, love, encouragement and pray of day and night make me able to get such success and honor, Along with My dearest wife, who leads me through the valley of darkness with light of hope and support.

Moreover this thesis is dedicated to my loveliest daughter with a hope that she would one day realise that education is a “weapon” to fight ignorance and poverty and a key to open doors for success.

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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January 2016

Chair : Farzad Hejazi, PhD
Faculty : Engineering

Vibration due to dynamic loadings can cause excessive oscillations in the building, which may lead to structural failure. Since Safety assurance, the functionality of structure and economic design are the most important concerns of structural engineers, many studies have been conducted to improve aforementioned issues. The variable stiffness concept, which is one of the vibration energy dissipation techniques, has been implemented in the different structures and mechanical devices to provide system stability and mitigate the undesirable damages induced by vibration effects. Numerous studies have been conducted, specifically in structural engineering, to develop and evaluate the dynamic performance of energy dissipation systems based on the variable stiffness concept, such as active, semi-active, and passive variable stiffness methods. Whereas the, most of the variable stiffness systems are operated using high-tech signal processors, controllers, and external electrical supply. Additionally, the aforesaid systems are highly dependent on controller, energy resources and required repetitive maintenance. Therefore, developing a real-time system without any dependency on abovementioned conditions are highly required.

This study develops two types of adaptive variable stiffness devices: variable stiffness bracing (VSB) and nonlinear spring conical bracing (NCSB). These devices are applicable as lateral resistant and vibration absorbers in a framed building subjected to dynamic loadings. The research methodology in the current study can be categorized into two general sections include of numerical simulation and experimental test. Configurations of devices and mathematical models are established. The specific finite element algorithms are developed and implemented in the finite element program code for the nonlinear analysis of RC framed buildings. Various analyses, including pushover and time history, are conducted on different framed building models equipped with both the proposed devices. The developed finite element program and efficiencies of the offered devices in terms of structural response are evaluated. The possibilities of plastic hinge formations in structural components are also identified through nonlinear dynamic analysis. Results obtained from numerical

analyses confirm the effectiveness of the developed devices in maintaining the structural stability of the framed buildings. Experimental section is divided into two main sections consisted of the cyclic test and direct compression test. Cyclic test conducted based on displacement control approach in steel and RC frames. Four steel and three RC frame specimens subjected to cyclic displacement history on their top nodes. These models included of the frame without and with attached VSB and NCSB devices and conventional X-braced frames. The efficiency of VSB and NCSB applications in frames compared with bare and brace frames in terms of ductility characteristics, maximum capacity, stiffness and etc.

Based on parametric time history analysis on the single degree of freedom models, the application of VSB and NCSB caused to decrease the maximum displacement up to 60% and 33% respectively compare to bare model. These devices reduced the maximum velocity and acceleration values. Additionally, results from parametric 3D pushover analysis show the noticeable increase in terms of failure capacity up to 43% and 15% for model furnished by VSB and NCSB devices. Generally, the results from the parametric study reveal that the geometry specification of devices plays an important role in the structural response and plastic hinge formation in structural elements. Moreover, results from 3D time history analysis on model equipped with VSB and NCSB devices illustrate the maximum value of shear and moment forces as well as the number of plastic hinge formations in structural components reduced dramatically.

Aside from the numerical analysis, an experimental test is conducted to assess the functionality and performance of the developed adaptive systems in different structural types that consist of steel and RC frames subjected to cyclic dynamic test equipped with NCSB and VSB devices. The ductility behavior, overall stiffness and failure mechanism enhanced in both RC and steel frames compared with the bare frame. In brief, the experimental results show a noticeable improvement in the performance of RC and steel frames equipped with the abovementioned devices.

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

PENILAIAN CADANGAN SISTEM RINTANGAN SISIAN KEKAKUAN YANG DIGUNAKAN DENGAN STRUKTUR KERANGKA

Oleh

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Getaran disebabkan oleh bebanan dinamik boleh menyebabkan osilasi yang berlebihan di dalam bangunan, yang boleh membawa kepada kegagalan struktur. Oleh kerana jaminan keselamatan, kefungsian struktur dan reka bentuk ekonomi adalah aspek yang paling penting , keprihatinan Jurutera struktur dalam aspek ini jadi keutamaan dan banyak kajian telah dijalankan untuk meningkatkan pengenaan aspek tersebut di atas. Konsep pembolehubah kekakuan, yang merupakan salah satu teknik disipasi tenaga getaran, telah dilaksanakan di dalam struktur yang berbeza dan pada peranti mekanikal untuk menyediakan kestabilan sistem dan mengurangkan kerosakan tidak diingini akibat oleh kesan-kesan getaran. Banyak kajian telah dijalankan, khususnya dalam kejuruteraan struktur, untuk membangunkan dan menilai prestasi dinamik sistem disipasi tenaga berdasarkan kepada konsep Kekakuan yang berubah-ubah, seperti kaedah pembolehubah kekakuan aktif, separuh aktif dan pasif. Bilamana, sebahagian sistem pembolehubah kekakuan dikendalikan menggunakan isyarat pemproses berteknologi tinggi, pengawal dan bekalan elektrik luar dan tambahan pula, sistem tersebut adalah sangat bergantung kepada pengawal, punca tenaga dan penyelenggaraan berulang-ulang yang berterusan, Oleh itu, membangunkan satu sistem masa-nyata tanpa sebarang pergantungan syarat-syarat yang tersebut di atas yang sangat diperlukan.

Kajian ini membangunkan dua jenis peranti kekakuan berubah-ubah yang mudah suai: perembatan kekakuan berubah-ubah(VSB) dan perembatan pegas konika tak selanjar (NCSB). Alat-alat ini boleh digunakan sebagai rintangan sisian dan penyerap getaran di kerangka bangunan dibawah kenaan bebanan dinamik. Kaedah penyelidikan dalam kajian ini boleh dikategorikan kepada dua bahagian-bahagian umum termasuk simulasi berangka dan ujian eksperimen. Tatarajah peranti dan model matematik akan ditubuhkan. Algoritma unsur terhingga tertentu akan dibangunkan dan dilaksanakan dalam Kod program unsur terhingga untuk analisa kerangka tetulang konkrit bangunan tak selanjar. Analisis yang pelbagai, termasuk analisis pushover dan analisis sejarah masa, dilaksanakan secara berbeza dirangka binaan model-model yang dilengkapi dengan kedua-dua peranti yang dicadangkan.

Program unsur terhingga yang dimajukan dan kecekapan alat-alat yang ditawarkan akan dinilai dari segi nilai tindakbalas struktur. Kemungkinan formasi ensel plastik dalam komponen struktur juga dikenalpasti melalui analisis dinamik tak selanjar. Keputusan yang diperolehi daripada analisis berangka mengesahkan keberkesanan peranti dimaju dalam mengekalkan kestabilan struktur bangunan-bangunan bekerangka. Seksyen eksperimen dibahagikan kepada dua Seksyen utama terdiri daripada ujian cara kitaran dan ujian cara mampatan langsung. Ujian kitaran dijalankan berdasarkan pendekatan kawalan anjakan dalam bingkai keluli dan tetulang konkrit. Empat spesimen rangka keluli dan tiga rangka tetulang konkrit di berikan sejarah anjakan berkitar pada nod teratas kerangka. Model ini termasuk bingkai rembatan tanpa dan dengan peranti VSB dan NCSB dan bingkai konvensional tersiap sedia X. Keberkesanan aplikasi VSB dan NCSB sebegini dibandingkan dengan bingkai tampa rembatan dan bingkai berembat dari segi ciri-ciri kemuluran, kapasiti maksima, Kekakuan dan lain-lain.

Berdasarkan analisis sejarah masa berparameter ke atas, bagi model darjah kebebasan tunggal, penggunaan VSB dan NCSB untuk mengurangkan anjakan maksimum sehingga 60% dan 33% tiap tiap satu berbanding dengan bingkai tampa rembatan. Alat-alat ini kurangkan nilai halaju dan pecutan maksima. Di samping itu, hasil daripada analisis pushover 3D berparameter menunjukkan peningkatan ketara dari segi kapasiti kegagalan sehingga 43% dan 15% untuk model dibekalkan oleh peranti VSB dan NCSB. Secara umumnya, hasil daripada kajian berparameter mendedahkan bahawa geometri spesifikasi peranti memainkan peranan penting dalam sambutan struktur dan pembentukan ensel plastik dalam unsur-unsur struktur. Selain itu, hasil daripada analisis masa sejarah 3D , model yang dilengkapi dengan alat VSB dan NCSB menggambarkan nilai maksimum kekuatan ricih dan momen serta bilangan formasi ensel plastik dalam komponen struktur dikurangkan secara dramatik.

Selain daripada analisis berangka, ujian experimen dijalankan untuk menilai kefungsian dan prestasi sistem mudah suai yang dimaju ini keatas jenis struktur yang berbeza yang terdiri daripada bingkai keluli dan tetulang konkrit tertakluk kepada ujian kitaran dinamik yang dilengkapi peranti NCSB dan VSB. Tingkah laku kemuluran, kekakuan keseluruhan dan mekanisme kegagalan dipertingkatkan di bingkai tetulang konkrit dan bingkai keluli berbanding dengan bingkai tampa rembatan. Secara ringkas, keputusan eksperimen menunjukkan peningkatan yang ketara dalam prestasi tetulang konkrit dan kerangka keluli yang dilengkapi dengan peranti tersebut.

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I certify that a Thesis Examination Committee has met on 29 January 2016 to conduct the final examination of Amir Fateh on his thesis entitled "Assessment of Proposed Lateral Resistance System Used with Framed Structures" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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CHAPTER 1

INTRODUCTION

1.1 Background

Earthquake risk reduction is a complex task that involves many people in many disciplines, considerable information, opinions, decisions, and actions. Managing the required changes to reduce earthquake risk is a challenging task. All people in any given region are explicitly or implicitly involved. The largest component of earthquake risk reduction is traditionally known as the earthquake resistant design. A standout amongst the most vital concerns, especially in the seismic design of buildings, is the improvement of the seismic performance of a building, particularly in terms of structural safety. Therefore, proper building design and vibration control technologies are applied to avoid the destructive failure of buildings. The principal approach in seismic design codes is based on the structural ductility tendencies to absorb and dissipate the conveyed earthquake energy in the building, which is the most economically feasible design method.

In the last two decades, considerable research has been conducted to enhance the seismic resistance of a structural system and the control technique to achieve an economical and safe design (Spencer and Nagarajaiah, 2003). Traditional seismic design philosophy contains the dissipation of input seismic energy with the aid of the inherent ductility capacity of structural elements through large strains in the aforementioned components. Conversely, this approach may lead to structural damages or unrealistic designs. For this reason, energy dissipation devices that do not belong to the main load resisting system have been suggested and designed specifically as external devices to absorb seismic energy. These devices can be simply substituted after severe excitation (Soong and Dargush, 1997). A variety of control schemes have been employed in design practices and are generally categorized into three types: active (Yao, 1972), passive (Ruge, 1938), and semi-active control (Karnopp et al., 1974). Among these methods, passive control systems were developed at the earliest phase and have been utilized more often in seismic design procedures because of the minimum maintenance and elimination of the external power supply to function.

In recent years, active variable stiffness (AVS), a system for structural control, has gained considerable attention and interest. Previous studies have proven that AVS systems result in desired effects and improve the structural performance during earthquake excitation (Kobori at al., 1993; Yang et al., 1996b). Such a system has been investigated experimentally with implementation in full-scale buildings in Japan (Kamagata and Kobori, 1994; T Kobori and Kamagata, 1992). With meticulous observation, most of the available variable stiffness systems are operated using an external electrical controller, which may cause a delay in system performance. These systems are highly dependent on energy resources and require repetitive maintenance. Developing a real-time system without any dependency on energy recourse, complicated processors, and maintenance procedure is necessary.

1.2 Problem statement

The brief literature review above highlights the following problems:

i. Most of available variable stiffness systems are dependent on external electrical sensors and controller and work as active or semi-active techniques. The new mechanical system, which operates independently of the aforementioned electrical component, is not addressed properly, and future studies are required.

ii. Current earthquakes have been revealed the seismic vulnerabilities of the structures, and proved the necessity of retrofitting techniques. So, seismic retrofit of existing buildings absorbed a lot of attentions among structural engineers and researchers. In high seismicity regions, moment resisting frames are regularly selected due to adequate energy dissipation capacity, which is granted by large plastic deformation of elements in the moment frames. This ability permits the structural engineers to design the moment resisting frames under the lowest lateral design force compared with other structural systems. Nevertheless, unanticipated severe events might bring unacceptable great storey displacement. Prior vigorous earthquake events have emphasized the need of seismic retrofitting of present moment frames. Previous studies tried to evaluate and observe the seismic response of MRF structures which is equipped with numerous energy dissipation methods. Further studies are still in progress to improve and enhance MRF retrofitting system behavior in seismic response reduction.in brief there is little information about retrofitting techniques of moment resisting frame without reducing the effect of inherent ductility.

iii. Little information is observed on the application of the mechanical spring as an adaptive stiffness system in the framed structures.

iv. Finite element modeling and mathematical and finite element models are not presented for adaptive systems using mechanical springs

v. A comprehensive study on structural dynamic performance is to be conducted on structures equipped with adaptive stiffness system using mechanical spring as energy dissipation components.

vi. The geometry specifications, element layout of springs, and the fabrication process of above-mentioned adaptive stiffness systems are yet to be developed.

vii. Calculations of the strength reduction (R) factor are not available for framed structure with furnished by adaptive stiffness devices with mechanical springs as lateral resistant schemes.

This study develops, designs and fabricates two types of adaptive variable stiffness devices without any dependency on a controller, energy resources and maintenance. These devices operated mechanically whenever the displacement occurred. These devices are applicable as lateral resistant and vibration absorbers in a framed building subjected to dynamic loadings. Furthermore, the mathematical model of abovementioned devices derived. Specific finite element algorithms developed and implemented in the finite element program code for the nonlinear analysis of RC framed buildings.

1.3 Objective of the study

The general objective of the current study is to develop a new adaptive variable stiffness system as a supplementary structural element that provides stability against lateral loads and dissipates vibration energy induced by dynamic excitation. The specific objectives are as follows:

1. To formulate the mathematical and finite element models of the proposed adaptive stiffness devices based on flexible bar and telescopic conical spring concepts.

2. To develop finite element algorithm to evaluate the nonlinear dynamic performance of 3D RC structures equipped with developed bracing techniques.

3. To assess and verify the dynamic performance of structures equipped with proposed adaptive variable stiffness devices through numerical study and experimental test.

1.4 Research questions

The primary aim of this study is to propose adaptive stiffness devices using mechanical spring elements. In order to achieve the study objectives, the following research questions were responded:

1. How can the mechanical springs be implemented as variable stiffness component as dynamic controller of structure?

2. What are the mathematical and finite element models of proposed adaptive systems?

3. How to adopt and implement the finite element model and algorithm in the computational program to evaluate the dynamic behavior of framed building fitted with adaptive stiffness devices?

4. What are the effects of implementing the proposed devices in the overall structural performance of framed building subjected to dynamic loading?
5. What are the design and fabrication processes of adaptive stiffness bracing devices?

6. Do these adaptive stiffness devices work efficiently once fitted in real structural frames?

1.5 Scope and limitation of the work

The following sequences are conducted to achieve the above objectives:

1) The mathematical and finite element models of variable stiffness bracing and nonlinear conical bracing devices will be derived based on flexible bar and telescopic conical spring concepts respectively.

2) The dynamic analysis algorithm of the RC frame equipped with the proposed adaptive stiffness bracing devices will be developed using Newmark's method.

3) Finite element models and algorithm will be employed in an existing dynamic finite element package (ARCS3D, UPM, 2014)

4) Nonlinear static (pushover) and dynamic (time history) analyses will be performed to evaluate the performance of the developed bracing techniques in a few structural models using the computer program mentioned in step 3.

5) The damage detection of RC structures equipped with VSB and NCSB will be observed through plastic hinge formation in 3D structures.

6) The adaptive VSB systems designed, and physical prototypes are fabricated. Moreover, the fabrication processes of the proposed devices established based on availability of material and simplicity of manufacturing.

7) Evaluation of the fabricated prototype with different geometry specifications and materials will be done by using commercial finite element software.

8) Direct compression test will be performed to validate the accuracy of the adaptive VSB devices in reality with a mathematical model.

9) The efficiency of the VSB systems will be assessed not only through numerical analyses but also through dynamic experimental tests on different frames.

10) Three RC and four steel frames with height and width of 2 m will be tested experimentally subjected to monotonic cyclic displacement test. Furthermore, the concrete grade of RC frame will be considered as equal to 30 Mpa.

11) A parametric study is conducted on the geometry specification of the proposed devices using time history and 3D pushover analyses.

12) The seismic performance of the abovementioned devices evaluated using 3D nonlinear time history with developed finite element program.

The following issues are omitted from the scope of the present study due to lack of experimental facilitations.

1) The influences of soil structure interactions are not studied.

2) Seismic evaluations of proposed devices subjected to earthquake record are not studied.

3) The strength modification factor (R) is not calculated for the proposed systems.

1.6 Organization of the thesis

A brief narrative of the remaining chapters is presented as follows:

Chapter 2 provides a general overview of the seismic controller system and subsequently focuses on prior related research that implements the variable stiffness concept in devices to mitigate the vibration effects.

Chapter 3 presents the research methodology of the current study, including the mathematical model, finite element procedures, and numerical analyses of the proposed devices. Moreover, the process of the prototype fabrications and experimental test setups for direct compression and dynamic test are also discussed. Finally, the verification of the developed program code against available commercial software is demonstrated through a variety of analyses.

Chapter 4 extensively reports the seismic performance assessment of structures equipped with the developed VSB and NCSB devices through different numerical simulations, such as 3D pushover and dynamic analyses. In addition, the results obtained from the direct compression test on the leaf spring's models are compared with those of the finite element simulation. The experimental evaluation of VSB and NCSB applications in steel and RC frame specimens under cyclic displacement is also presented.

Chapter 5 summarizes the present study and provides its major and specific conclusions. The scope of future works and recommendations are also discussed.

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