SEISMIC BEHAVIOUR OF REINFORCED CONCRETE STRUCTURE WITH VERTICAL STEEL SHEAR LINK

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ABSTRACT

Steel cross bracing system is a simple, economical and effective method of resisting lateral loadings for multi-story buildings. Vertical Shear Link (VSL), known as steel shear panel, is an efficient passive control system suitable for construction resistance against earthquakes. VSL has been installed between the joints of invert V-brace and reinforced concrete beams. VSL absorbs earthquake energy through the yielding of steel, while other structure's members stay in an elastic condition. Limited numerical studies have been conducted on VSL applied to Reinforced Concrete (RC) building frames with eccentric steel bracing. Furthermore, studies seeking to identify performance level and the seismic response of RC structures using VSL and plastic hinge formations are also limited. A study of ductility and stiffness of RC frames with/without VSL is required. Therefore, a lateral load transfer mechanism, from RC frame to VSL, needs to be investigated. The aim of this research is to conduct a numerical study, verification and parametric investigation through time history and pushover analyses. The experimental intention is to study the stiffness, ductility and energy absorption of RC frame using VSL. This system has the ability to control the stiffness and ductility of a structure; while both are important structural seismic characteristics. The experimental study is conducted on a conventional RC frame in comparison with a VSL retrofitting system. The experimental findings are used to validate Finite Element Analysis (FEA) models using ABAQUS software. Further parametric studies are developed to evaluate the effect of VSL shear capacity. Two categories of RC frame i.e., low-level and mid-level, are analysed using SAP 2000 structural analysis software. Two types of analysis are considered i.e., nonlinear static (pushover) and nonlinear time history. The parameters considered are invert V-brace and RC structure with VSL. FEA results show that the frame with the VSL system increased shear force capacity to 170% compared to the conventional RC frame. Meanwhile, invert V-brace increased the shear force capacity of the frame to approximately 200%. The ductility of the RC frame reduced to 160% due to buckling of the invert V-brace, while the RC frame with VSL satisfied the ductility. Observations from the experimental test show that VSL worked correctly inside the RC frame. The VSL system could properly absorb the imported lateral force to the RC frame; where the shear yielding mechanism of the VSL could prevent buckling of the braces. The VSL system, as a proposed alternative method to construct ductile structures, is clarified with great lateral stiffness. Moreover, the axial forces developed in the braces can be controlled by the VSL system.

ABSTRAK

Sistem perembat bersilang keluli adalah keadah yang mudah, ekonomi dan berkesan untuk menahan beban sisi bagi bangunan berbilang bertingkat. Perangkai ricih tegak (VSL) yang dikenali sebagai panel ricih keluli adalah satu sistem binaan kawalan pasif yang berkesan dan sesuai untuk memberi rintangan terhadap gempa bumi. VSL dipasang di antara sambungan perembat-V terbalik dangan rasuk konkrit bertetulang. VSL boleh menyerap tenaga gempa melalui alahan bahan keluli manakala anggota struktur lain masih kekal dalam keadaan elastik. Kajian ke atas VSL yang digunakan untuk pembinaan bangunan konkrit bertetulang (RC) dengan kesipian bagi perembat keluli adalah didapati sangat terhad. Tambahan pula, kajian tentang gerak balas seismik bagi struktur RC yang menggunakan VSL, dan pembentukan engsel plastik bagi mencari tahap prestasi sistem juga didapati masih terhad. Satu kajian tentang kemuluran dan kekukuhan kerangka RC dengan kehadiran dan tanpa kehadiran VSL adalah perlu. Mekanisme pemindahan beban sisi daripada kerangka RC kepada peranti VSL juga didapati perlu dikaji. Tujuan penyelidikan ini adalah untuk menjalankan kajian numerik dan kajian parametrik serta pengesahan dengan menggunakan analisis sejarah masa dan analisis tolak lebih. Satu ujikaji makmal dijalankan untuk mengkaji kekukuhan, kemuluran dan penyerapan tenaga bagi kerangka RC yang dilengkapi dengan VSL. Kajian ujikaji dijalankan terhadap kerangka RC konvensional dan dibandingkan dengan sistem yang dipasang dengan VSL. Data ujikaji digunakan untuk mengesahkan model unsur terhingga (FE) menggunakan perisian ABAQUS. Dimana kajian parametrik yang lebih terperinci telah dibangunkan bagi menilai kesan keupayaan ricih VSL. Dua kategori kerangka RC pada aras rendah dan aras sederhana bagi kerangka telah dianalisis menggunakan perisian SAP 2000. Dua jenis analisis telah dijalankan, iaitu analisis statik tak lelurus (tolak lebih) dan analisis sejarah masa tak lelurus. Parameter yang dipertimbangkan ialah perembat-V terbalik dan struktur RC dengan VSL. Keputusan analisis FE menunjukkan kerangka dengan sistem VSL boleh meningkatkan keupayaan daya ricih sehingga 170% berbanding dengan kerangka RC konvensional. Sementara bagi perembat-V terbalik, ia boleh meningkatkan keupayaan daya ricih kerangka sehingga kira-kira 200%. Kemuluran kerangka RC didapati berkurang sehingga 160% disebabkan oleh lengkokan pada perembat-V terbalik manakala kerangka RC dengan VSL didapati memenuhi kemuluran. Pemerhatian daripada ujian ujikaji menunjukkan bahawa VSL berfungsi dengan baik di dalam kerangka RC. Sistem VSL dapat menyerap tenaga dengan baik bagi daya sisi yang dipindahkan kepada kerangka RC dengan pencapaian mekanisme alahan ricih VSL dan dapat menghalang lengkokan seterusnya bagi perembat. Sistem VSL yang dicadangkan ini boleh dijadikan sistem alternative untuk menghasilkan pembinaan struktur yang mulur dengan kekukuhan sisi yang tinggi. Selain itu, daya paksi dalam perembat juga boleh dikawal oleh sistem VSL.

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LIST OF ABBREVIATIONS

ACI	American Concrete Institute
AISC	American Institute of Steel Construction
ATC	Applied Technology Council
CP	Collapse Prevention
FEA	Finite Element Analysis
FEM	Finite Element Model
FEMA	Federal Emergency Management Agency
HHT	Hilber-Hughes-Taylor
IO	Immediately Occupancy
IVB	Invert Brace
LS	Life safety
MF	Moment Frame
MRF	Moment Resistant Frame
NSA	Nonlinear Static Analysis
NTA	Nonlinear Time History Analysis
RC	Reinforced Concrete
VSL	Vertical Shear Link
CRC	conventional reinforcement concrete
RCVSL	Reinforcment concrete with vertical shear link

LIST OF SYMBOLS

μ	ductility
C_v	velocity-dependent seismic coefficient
d	beam depth
e	Link segment
F_y	yield strength
I	Building importance factor
M_p	plastic moment capacity
R	response modification factor for lateral force resisting system
T	elastic fundamental period of vibration
t_f	flange thickness
V	total design lateral force or shear at the base
V_p	plastic shear capacity
z	Seismic Zone factor
Z	plastic module
γ	link rotation angle
ζ_{eq}	equivalent viscous damping factor
μ_Δ	Displacement ductility ratio
Δy	Yield displacement taken from bilinear representation of the response envelope
Δ_u	Ultimate displacement taken from bilinear representation of the response envelope
Ω	lateral strength of a structure against
R_μ	ductility factor

CHAPTER 1

INTRODUCTION

1.1 General

The structural properties of strength, ductility and stiffness are three principle concepts in designing structures. Accordingly, structural members should have adequate strength to resist internal stress such as shear stress, flexure stress and have sufficient stiffness to limit lateral displacement. Furthermore, the structure should have the ability to undergo inelastic deformation under lateral load during earthquake event. Notably, ductility is a measure of the structure's ability to transform. Recently, many building codes suggest designing ductile structures instead of building high-strength structures, especially in seismic activity zones.

For example, the American Code separates reinforced concrete (RC) structures into special moment frames, normal moment frames, and moment frames. where, special moment frames have a higher ductility than normal moment frames and moment frames. Whereas, moment frames are capable of energy dissipation especially during seismic earthquake events through the creation of plastic hinges located at the end of the beams. Furthermore, to control drift for structures with moment frames, lateral displacement control is vital in some cases, to increase column and beam size. However, this increases the construction costs and self-weight of the building. An alternate method to control drift is using a shear wall in the concrete moment frame in front of the lateral load. This system increases the lateral stiffness of the structure but is less ductile.

Moreover, the steel cross bracing system is a simple, economical and efficient method to resist against lateral loading in multi-storey buildings. Over the last few decades, several studies have highlighted the efficient use of steel bracing in RC frames. Steel bracing of RC buildings was initially used as a starting measure to strengthen earthquake-damaged buildings or to increase the load resisting capacity of existing buildings. Bracing systems are of two types: concentricity and eccentricity braces. Typically, structures with concentricity braces have higher strength and stiffness although; energy depreciation is minimal given buckling in the compressive brace member being small. Eccentrically braced frames (EB) are known for their distinctive elements of structural typology, deemed suitable for satisfying distinctive design objectives of modern performance-based seismic engineering in medium or high-rise steel buildings.

Notably, EB frames are frequently proposed as being less expensive and are a valid alternative to more common moment resisting frames (MR) and concentrically braced frames (CB). As such, they incorporate the good qualities of the above mentioned structures. Furthermore, EB systems are seismic lateral load resisting systems that comprise a ductile, energy dissipating portion of the beam's elements, known as the link beam (AISC 2005). The link beam can be installed horizontally or vertically in the frame (see Figure 1.1). Also, the characteristics of this system can provide both high lateral stiffness and high energy dissipation capacity which are the required parameters for the seismic design of structures.

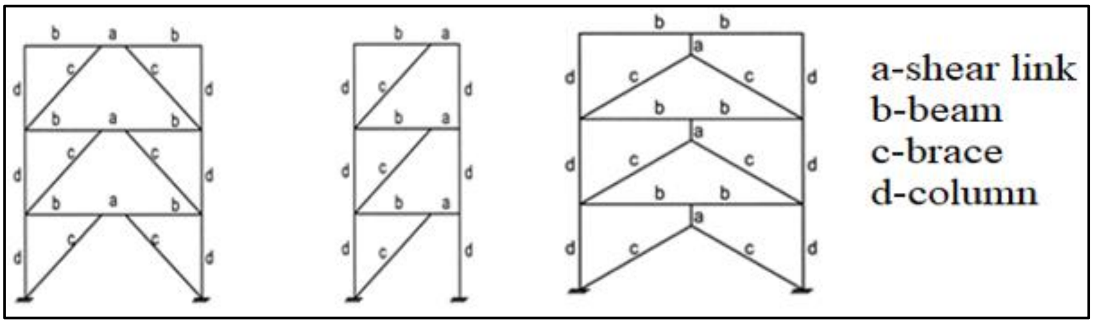

Figure 1.1 Eccentricity brace with a horizontal and vertical link

The concept surrounding the design of the link beam centres on the inelastic behaviour of the member during an earthquake event. Furthermore, when the link beam is installed horizontally, this member then becomes a segment of the main beam. Therefore, maintenance (i.e. repair) and replacement of the horizontal link is complicated and expensive. Furthermore, the inelastic behaviour of this member can cause a concrete roof to collapse. Conversely, the vertical steel link (VSL) is separate from the main beam and therefore, the repair and replacement of this device are easy and can be used for retrofitting an old building.

Figure 1.2 shows the free body diagram of a one-story and one-bay frame with the VSL, while the lateral load is applied on top of the frame and the beam to column connection is fixed.

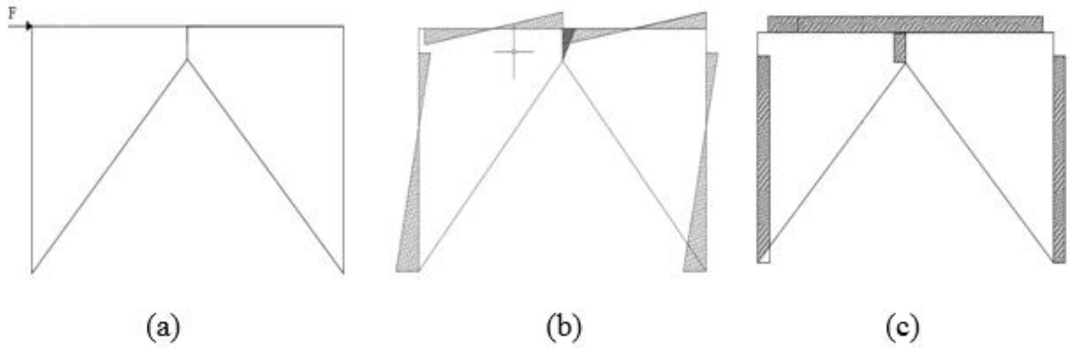

Figure 1.2 Free body diagram of frame with vertical link a) Load direction; b) Moment diagram; c) Shear diagram

1.2 Problem Statement

Steel cross bracing is one of the simplest, economical and efficient systems used for multi-story buildings to resist lateral loads. Additionally, this system has been successfully used to retrofit old concrete buildings that have only been designed to cater for gravity loading. Moreover, a review of the literature has confirmed that the installation of the steel cross bracing system in reinforced concrete frames needs further investigation given the dynamic behaviour that the combined system exhibits during ground motions (Wang Da-peng, Yu An-lin and Xue Li-ming, 2012). Notably, at this stage, limited numerical studies have been carried out on the application of the Vertical Steel Link (VSL) damper to RC frames equipped with eccentric steel bracing (Azad and Topkaya, 2017). Also, there are limited studies that adequately address the plastic hinge formation mechanism and the seismic performance level of RC structures equipped with a VSL damper. Therefore, further studies need to be undertaken to investigate the changes in the ductility and stiffness of the RC frame with, and without a VSL damper. Also, the lateral load transfer mechanism from the RC frame to the VSL device is another key area that requiring a study.

1.3 Objectives

The primary objectives of this study are:

(a) To investigate the seismic performance of RC frames such as ductility, energy dissipation and damping while equipped with vertical shear links through experimental works.

(b) To examine numerically the shear capacity effects of shear link and concrete compressive strength on the seismic behaviour of RC frames equipped with vertical shear links.

(c) To determine the seismic response modification factor of RC frames equipped with vertical shear links.

(d) To investigate numerically the efficiency of the vertical shear link for enhancing seismic performance of low and mid-rise RC frames.

1.4 Scope of the Study

The scope of this study is to investigate seismic behaviour of reinforced concrete (RC) structures with a vertical shear link (VSL) device under lateral load.However, the experimental programme is conducted at University Technology Malaysia (UTM) as presented in Chapter 3. The test results are used to verify the finite element (FE) model analysis using ABAQUS and SAP2000 softwares.

Five groups of RC structures are considered in this study. Group 1: two specimens one conventional RC frame (CRC) and the other one RC frame with a VSL device for the experimental tests. The concrete compressive strength is 30 MPa for both. Group 2: consists of a RC structure with invert V braces (RCIVB) to compare the behaviour of the RC structure with the IVB and VSL device. The dimensions and material properties are identical to those in group 1. Group 3: four

RC frames with a VSL and with different concrete compressive strength are considered. In group 4: five RC frames with various sections of VSL are examined where the concrete compressive strength for all RC frames is 30 MPa and dimensions matching to those in the group 1. Group 5: consists of two multi-story structures with four and eight stories with each braced with an IVB and a VSL. The height of each story, span and material properties are the same.

The specimens in the first group were tested experimentally for failure under lateral load to observe RC structural behaviour with the VSL and to verify the FE results. The FE analysis was performed for the second, third and fourth group specimens applying lateral load. Moreover, nonlinear time history analysis (NTH) was undertaken for the specimens in group 5. The test results and additional findings were achieved via FE and NTH analysis thereby aiding the research in developing the behaviour of the RC structure with the VSL device in front of the seismic loads.

1.5 Significance of the Research

As presented before, the EB system can provide both high lateral stiffness and high ductility; however the study about the behaviour of RC structures with EB system is very limited. And also, most of the studies were about the effects of the link beam lengths on the behaviour of structures. While the study about the concrete strength and the seismic parameters of RC structures with EB system was very limited. Therefore it is important to obtain an easy and cheaper method for seismic retrofitting of RC structures under gravity loads. Furthermore, there is a need to study the seismic behaviour of RC structure with VSL devices to obtain the response modification factors for design and construction of new buildings in the seismic areas.

1.6 Thesis Outline

The research in this study consists of seven chapters, as outlined below:

Chapter 1 presents the background to the study, the research performed specifically on the RC structure with braces and describing many of the challenges identified in the literature. The scope, objectives and significance of the study are lastly presented.

Chapter 2 presents a comprehensive literature review of the dampers, brace system and nonlinear analysis, including details regarding the experimental, numerical, and analytical findings.

Chapter 3 discusses the experimental program and testing procedures applied to the specimens. The chapter also describes the specimens in detail, along with presenting the experimental setup for the tests.

Chapter 4 details the findings of the experimental tests including the failure modes, lateral load versus displacement, and the load-strain responses of strain gauges.

Chapter 5 presents the nonlinear FE method applied for all elements and the FE models used to verify the behaviour in the CRC frame, and RCVSL achieved experimentally. Useful parameters such as the concrete strength and VSL section on the RC structure are also examined and discussed along with the results.

Chapter 6 describes the results of the NTH analysis for seven earthquakes ground motions. Also, the amount of drift and base shear for a multi-story RC structure with a VSL and IVB are presented and examined.

Chapter 7 presents the conclusions based on the results from performing the study along with proposed recommendations for future investigation and research

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