SEISMIC PERFORMANCE OF INNOVATIVE DOUBLE LAYER SPACE SHEAR WALL

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DEDICATION

I would like to dedicate this thesis to my beloved wife, Reihaneh, for her support and unconditional love.

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ABSTRACT

Various kinds of seismic structural systems could not completely satisfy engineers due to excessive rigidity and low ductility. Then engineers innovate advanced ductile structural systems like viscous elastic dampers to dissipate earthquake forces and insulate important structural elements in safe zone; however these systems have not been pervasive in construction industry due to high production cost. Indeed, optimization of stiffness, ductility, and construction cost are the major challenges facing the engineering profession in designing a perfect lateral system. This research introduces Space Shear Wall (SpaSW), as an innovative earthquake resistant system for structures and evaluates its feasibility and seismic performance through three-dimensional linear and nonlinear-static, linear-dynamic, and finite element analysis carried out by ETABS and ANSYS program. Space shear wall is defined as a double-layer diagonal space frame structure with ball joints vertically used as infill wall. The comparative study between SpaSW and steel bracing used in typical low to high-rise structures expressed that structural drift of SpaSW is slightly higher than steel bracing. However the ductility, energy dissipation, members' stress and distribution of earthquake force in SpaSW are significantly better than typical steel bracing. In addition, failure mechanism of SpaSW were favourable due to its gradual process through many ball joints. Moreover, lightness, industrialization, maintainability and reparability, compatibility with architectural considerations, low cost, simple and fast fabrication are other realized advantages. Developing this concept would be considered in the future studies through optimization of material, grid patterns, connection, and additional dampers.

ABSTRAK

Pelbagai jenis sistem struktur seismik tidak dapat memenuhi keperluan para jurutera dengan sepenuhnya disebabkan oleh ketegaran struktur yang berlebihan dan kemuluran yang rendah. Dengan itu jurutera telah mencipta system struktur mulur yang lebih maju seperti penyerap likat anjal yang dapat mengurangkan daya gempa bumi dan seterusnya melindungi elemen struktur utama dalam zon selamat. Namun demikian sistem ini belum lagi meluas penggunaanya dalam industri pembinaan disebabkan oleh kos pengeluaran yang tinggi. Sebenarnya, pengoptimuman ketegangan, kemuluran, dan kos pembinaan adalah cabaran utama yang dihadapi oleh bidang kejuruteraan dalam mereka bentuk sistem sisian yang sempurna. Kajian ini memperkenalkan “Space Shear Wall” (SpaSW), sebuah sistem struktur inovatif yang mempunyai daya ketahanan seismik yang dapat menilai kebolehlaksanaan dan prestasi seismik melalui analisis linear, statik bukan linear, dinamik linear dan unsur terhingga tiga-dimensi yang dilaksanakan oleh ETABS dan program ANSYS. Dinding ricih ruang ditakrifkan sebagai struktur kerangka ruang pepenjuru dua lapisan dengan sendi bola, digunakan secora menegak sebagai dinding isian. Kajian perbandingan diantara SpaSW dan keluli perembatan yang dijalankan ke atas struktur yang bertingkat rendah ke struktur yang bertingkat tinggi, membuktikan bahawa kecondongan struktur adalah sedikit tinggi berbanding dengan keluli perembatan. Walau bagaimanapun, kemuluran, pelepasan tenaga, tekanan dan taburan tenaga gempa bumi bagi SpaSW adalah jauh lebih baik daripada keluli perambatan biasa. Di samping itu, kegagalan mekanisme SpaSW lebih memihak kepada proses berperingkat melalui sendi sambungan bebola yang banyak. Selain daripada itu, keringanan, perindustrian, penyelenggaraan, pembaik pulihan, keserasian dengan pertimbangan seni bina arkitek, kos rendah, fabrikasi mudah dan pantas adalah kelebihan lain yang realistik. Konsep yang selanjutnya akan dipertimbangkan dalam kajian pada masa hadapan melalui pengoptimuman bahan, corak grid, sambungan terperinci, dan penyerap tambahan.

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LIST OF ABBREVIATIONS

AISC	-	American Institute of Steel Construction
ASCE	-	American Society of Civil Engineers
ATC	-	Applied Technology Council
BR	-	Bracing
CB	-	Cross Bracing
CM	-	Center of Mass
CBF	-	Concentrically Braced Frames
DCR	-	Demand-Capacity Ratio
Dspl	-	Displacement
EBF	-	Eccentrically Braced Frames
EDA	-	Elastic Dynamic Analysis
ESA	-	Equivalent Static Analysis
FEA	-	Finite Element Analysis
FEM	-	Finite Element Model
IBC	-	International Building Code
IBS	-	Industrialized Building System
ISA	-	Inelastic Static Analysis
I-V	-	Inverted-V
IDA	-	Inelastic Dynamic Analysis
JBDPA	-	Japan Building Disaster Prevention Association
MDOF	-	Multi Degree of Freedom
OECD	-	Organisation for Economic Co-operation and Development
QCA	-	Quasi-Static Cyclic Analysis
RC	-	Reinforced Concrete
SBR	-	SpaSW-Bracing Ratio
SCBF	-	Special Concentrically Braced Frames
SDOF	-	Single Degree of Freedom
SEAOC	-	Structural Engineers Association of California

SpaSW	-	Space Shear Wall
SPSW	-	Steel Plate Shear Wall
THA	-	Time History Analysis
UBC	-	Uniform Building Code
UFD	-	Unbraced frame
BF	-	Braced frame
H	-	Wide flange sections
S	-	Square tube sections

LIST OF SYMBOLS

I_S	Ratio of the horizontal load
${}_RI_S$	I_S after reinforcement
α	Safety factor
I_{SO}	Required I_S
ΔI_S	Increased "I_S" by using SNE-Truss
S_D	Reduction factor
T	Period
C	Strength index
F	Ductility index
M	Mass
m	Metre
mm	Millimetre
c	Damping factor
k	Stiffness of structures
$u(t)$	Function of displacement
$\dot{u}(t)$	Velocity
$\ddot{u}(t)$	Acceleration
$F(t)$	Time dependent Force
ω_0	Modal natural frequency
z	Damping ratio
P	Constant participating factor
F_a	Site coefficient
F_v	Site coefficient
S_1	Mapped maximum considered
S_{DS}	Design spectral response
S_{D1}	Design spectral response
T	Fundamental period of the structure
ω	Angular frequency
T_a	Approximate fundamental period
C_t	Seismic factor
h_n	Structural height
N	Number of stories above the base
V	Seismic base shear
Cs	Seismic response coefficient
W	Effective seismic weight
R	Response modification factor
I_e	Importance factor
T_L	Long-period transition period
V_x	Seismic design story shear in any
F_i	Portion of the seismic base shear

S_a	A
T_0	Intial Period
R_j	Maximum modal response
R_k	Maximum modal response
C_{jk}	Modal coupling factor
g	Acceleration due to gravity
$I\,g\,/\,R$	Response spectrum scale factor
δ_x	Deflection δ_x at level x
C_d	Deflection amplification factor
δ_{xe}	Deflection at the location required
E	Seismic load effect
E_h	Effects of horizontal seismic forces
Ev	Effects of vertical seismic forces
D	Dead load
E	Earthquake load
H	Load due to lateral earth pressure
L	Live load
Lr	Roof live load
R	Rain load
S	Snow load
W	Wind load
SDS	Design spectral response
QE	Effect of horizontal seismic forces
ρ	Redundancy factor
μ_ε	Material ductility
μ_θ	Structural element or joint ductility
μ_δ	Structural ductility
ε_υ	Maximum deformation
ε_ψ	Yield deformation
V_g	Gravitational potential energy
W	Constant weight
h	Constant gravitational field of
v	Velocity
V_k	Kinetic energy
E_h	Hysteresis ductility
$E_{h,tot}$	Total dissipated energy
E_h^+	Area of hysteresis curve above the
E_h^-	Hysteresis curve below the strain
SBR	SpaSW over bracing ratio
F_a	Force
K_a	Stiffness
d	Displacement
t	Time
$u(t)$	Time dependent Displacement
c	Damping
k	Stiffness
E	Young’s modulus
A	Cross section area
L	Length of bracing
K	Stiffness of bracing

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Over the past decades, earthquake and wind hazards have seriously influenced structural engineering principles. In this respect, major advances in earthquake engineering have occurred in both understanding and practice of seismic force-resisting systems. Therefore, various kinds of seismic systems were created to protect buildings from natural disasters but most of these systems could not completely satisfy engineers. Critics of current seismic systems believe that common rigid systems absorb the earthquake energy and transfer it to the structural elements. Hence engineers introduced ductile seismic systems to dissipate dynamic forces and insulate important structural elements in safe zone.

A ductile seismic system under earthquake loading dissipate earthquake forces and insulate important structural elements in safe zone like a fuse box in an electrical board, which is an essential safety device that cut off the flow of electricity if a fault occurs and protect the individual circuits that convey electricity to the various applications. However, the use of ductile systems has resulted in invention of many advanced systems like viscous elastic dampers, but these high-tech systems have not commonly been used due to their high costs and complicated fabrication. Indeed, optimisation of stiffness, ductility, and construction cost are the major challenges facing the engineering profession in designing a perfect lateral system, which is a ductile structural system with adequate stiffness that efficiently functions to resist lateral loads from wind or earthquake.

Space structure is a three dimensional truss with high stiffness and ductility due to its numerous members and flexible joints. Space structure is used where there is a need to carry vertical loads across long spans due to its high stiffness. A huge number of large scale and complex civil structures such as high-rise buildings and large-span structures have been constructed in the form of space structures. .

This study investigates the seismic performance of an innovative lateral system called Space Shear Wall (SpaSW). This name is inspired by spatial form of space structure and its application as infill wall surrounded by columns and beams to resist the shear force generated by earthquake activities. The preliminary literature researches by author show that SpaSW is an innovative application of space structure to enhance the lateral stability of structures.

Integration of a typical two dimensional lateral system like steel cross bracing with structural frame makes a stable structure, as shown in Figure 1.1. Since most of the common seismic systems such as steel bracing and concrete shear wall mainly perform under in-plane loads, a new concept could be discovered through integration of spatial seismic systems with structural frames, as demonstrated in Figure 1.2. This concept has originally been inspired by a special tree with diagonally long extended roots towards the ground's surface to protect the tree against wind loads as per Figure 1.3. This natural example points out that lateral stability of any structure might be enhanced by struts distributed spatially. Figure 1.4 illustrates the preliminary proposal for Space shear wall that is a double-layer two-way space structure surrounded in a R.C. frame.

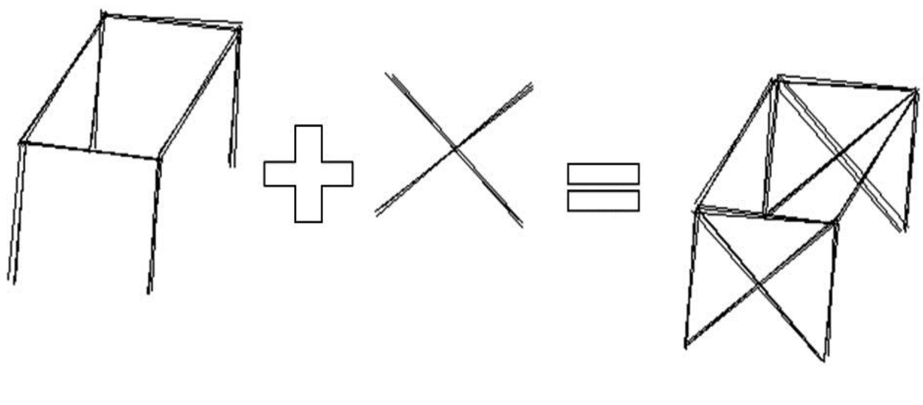

Figure 1.1 : Concept of cross bracing systems

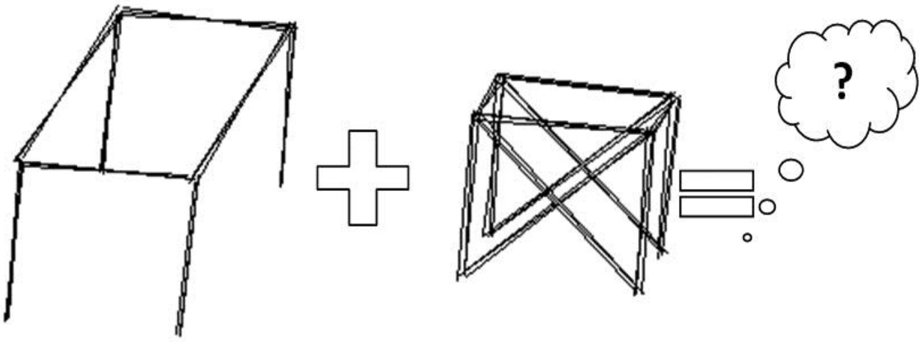

Figure 1.2 : Early concept for Space Shear Wall (SpaSW)

Figure 1.3 : Initial natural inspiration of SpaSW

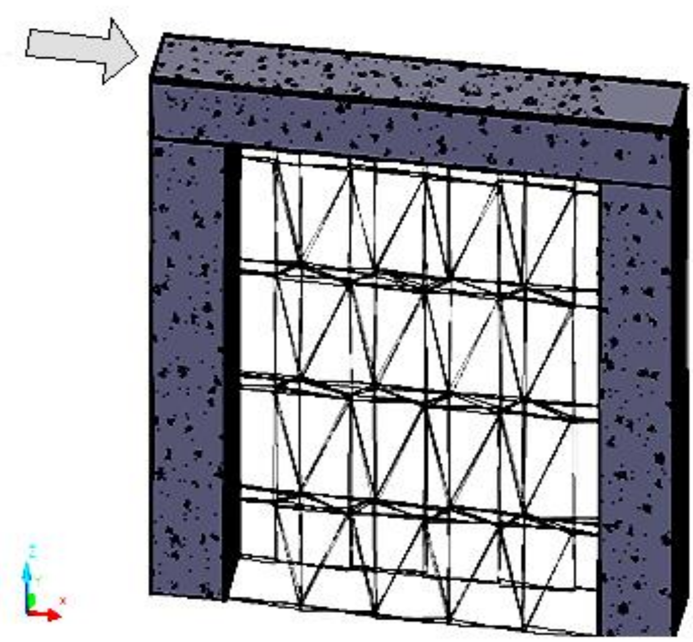

Figure 1.4 : Early conceptual model for SpaSW

1.2 Statement of the Problem

The world has been inflicted with heavy damages due to the common occurrence of natural hazards. A recent study (Leoni et al., 2011) revealed that close to 2.4 billion people were affected and a million people lost their lives by disasters during the past decades. In this regard, different kinds of seismic protection systems were designed to optimize buildings performance and increase the reliability in the wake of natural disasters. However, most of these structural systems have not effectively mitigated damages due to the inefficient integration of ductility, stiffness, and structural performance. For example, steel cross bracing that is commonly used in building structures has poor ductility due to its brittle connections. Recent earthquakes e.g. 1994 Northridge, 1995 Kobe, and 1999 Chi-Chi have shown that brittle fractures in connections of brace-to-column and beam-to-column affect the whole ductile response and energy dissipation capacity of structures under seismic loads (Di Sarno and Elnashai, 2009).

In addition, concrete shear wall as another widely used system in most parts of the world, is inconvenient in terms of its industrialization's difficulties. Moreover, the new ductile systems, like viscous elastic dampers, are very expensive due to limited availability of knowledge and technology for design and fabrication (Kelly, 2007)

Therefore, this study proposes space shear wall as an innovative individual seismic resistant structural system to enhance the lateral stability of structures and resist the forces of earthquake. This system uses a double layer spatial truss with interconnected members and flexible joints absorbing hazardous energy from earthquake. This system effectively transmits the imposed lateral and vertical loads into tensile and compressive force to be carried by SpaSW designed structural elements and reduce lateral movements.

It is high time that engineering society take serious effort in creating effective seismic systems to improve the structural performance and minimize damages from earthquake. This research comparatively investigates seismic performance of SpaSW that is introduced as an innovative seismic resistant structural system.

1.3 Objectives of the Study

The main objective of this research is to explore an innovative seismic structural system using available technologies to improve the seismic performance of buildings. The specific research objectives are:

i. To propose an innovative seismic structural system (double layer SpaSW) to enhance the lateral stability of structure under lateral force
ii. To assess the seismic performance of SpaSW in terms of ductility level, and failure mechanism via elastic-static, inelastic-static, and elastic dynamic analysis
iii. To verify the proposed system on multi-story frame with comparative study with a typical steel cross bracing

1.4 Research Questions

This research shall respond to the following questions:

i. How SpaSW is determined as an effective seismic system to increase the lateral stiffness of structures?
ii. How the current concerns of integration of stiffness, ductility, and industrialization are addressed in SpaSW system?

iii. How is the seismic performance of SpaSW under various types of seismic analysis?
iv. What is the difference between the SpaSW and the steel bracing which is a common lateral system?

1.5 Significance of the Study

Although currently there are various kinds of seismic structural systems, most of them could not efficiently reduce earthquake damages, as shown in Chapter 2. The findings of this study are important to help the engineering society to find out effective seismic systems to improve the performance of complex structural systems and minimise hazardous effects of earthquake.

1.6 Scope of the Study

Considering the successful performance of space structures in sustaining the lateral loads, it is anticipated that the SpaSW would efficiently enhance the stability of structures under wind and earthquake forces. This study is mainly dedicated to implement, and evaluate the seismic performance of innovative SpaSW system. This assessment is delimited to static analysis to determine the seismic performance of SpaSW through lateral drift, reaction force, and member stress factors.

1.7 Methodology and Research Framework

This section briefly discusses the methodology of the research. The evaluation performance of the innovative seismic system includes four basic steps: modeling, analysis, design, and validation of the results. Firstly, the new concepts of the seismic system were simulated using three-dimensional software, 3D MAX and AutoCAD, to visualise and assess the viability of proposed concept. Then, the conceptual model was analysed under static and dynamic loads via ETABS program to monitor the seismic performance of SpaSW. In this research, lateral drift, reaction force, and member stress ratio were the major criteria to realize seismic behaviour. In the third step, the constituent members of SpaSW were designed to verify the feasibility of SpaSW model. Finally, the analytical results were validated with an experimental study and verified through a comparative study between SpaSW and steel bracing.

1.8 Definition of Terms

Seismic Performance:

Seismic performance is the structural response of a building to earthquake forces which is evaluated by strength, deformation demands, ductility level, and failure mechanism of structural systems.

The seismic performance factors could be used in the context of linear analysis and response to equivalent static forces (SEAOC, 1995; ASCE, 2010 and IBC, 2011). This research focuses on deformation and strength of structures using SpaSW under equivalent static, response spectrum, pushover, time history, and finite element analysis to assess the seismic performance of SpaSW system.

Innovative System:

According to the Oslo Manual, the foremost international guideline on innovation activities, “a technological product innovation is the implementation or commercialization of a product with improved performance characteristics such as to deliver objectively new or improved services to the consumer.”(OECD, 2005). There is an important distinction between the innovation and invention. “Invention is the first occurrence of an idea for a new product or process while innovation is the first attempt to carry it out into practice.” Innovation vs. invention: Knowing the difference makes a difference (Gurel, 2007). This study investigates on an innovative seismic system integrating the others’ invention of space structures and Mero joints.

Space Shear Wall (SpaSW):

Space shear wall is an innovative application of space structures performing as seismic system to resist the lateral earthquake force. This system involves the tubular members with ball joint system connected to the surrounding frames.

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