ULTIMATE BEHAVIOUR OF REINFORCED CONCRETE SHEAR WALLS WITH OCTAGONAL OPENINGS

SOMAIEH HATAMI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

NOVEMBER 2015

Specially dedicated to my:

Supportive Father

Devoted Mother

Sincere Husband

Lovely Son

and everyone who had involved in this study.

ACKNOWLEDGEMENT

I gratefully acknowledge the contribution of my supervisor, Assoc. Prof. Dr. Abdul Kadir bin Marsono, for his invaluable critics, excellent guidance and positive encouragement.

I would like to thank all technical staff of Structural and Materials Laboratory of Universiti Teknologi Malaysia (UTM) for their cooperation and support in conducting the experimental work.

I also wish to express my gratitude to Dr. Seyed Esmaeil Mohammadyan Yasouj for his assistance throughout the experimental program in the laboratory.

Finally, I wish to express my deepest appreciation to my husband, Dr. Saeed Jamei, and my son, Amir Mohammad, and my parents. Without their constant support and encouragements, this research would not have been as presented here.

ABSTRACT

Reinforced concrete shear wall is an in-plane vertical structural component with an ability to resist both the gravity and lateral forces. It has a good behaviour in resisting the building structures in earthquakes. In tall buildings layout, shear wall configuration generally makes access difficult to the public areas at the base or other floor levels such as the car park area and the entrance to the lifts or staircases. This can be solved by providing an opening in the shear wall structures. Shear walls that is perforated with openings are called coupled walls. The number, location and size of openings are directly affect the behaviour of the shear walls and cause to decrease the strength and stiffness of the structure. This study proposes adding haunches to the corners of rectangular opening as a method of strengthening the shear walls. In order to evaluate the behaviour of the shear wall structure in the presence of haunches, five small scale models of reinforced concrete shear walls with different arrangements of rectangular and octagonal openings were tested under a cyclic static horizontal point load at the top of the structure. Furthermore, theoretical method based on strain compatibility approach and the Total Moment Concept and Nonlinear Finite Element Analysis (NLFEA) with the aid of ABAQUS software have been performed to detailed study and verify the experimental outputs. A simple analytical equation has been proposed to calculate the maximum displacement of shear walls by considering the effective stiffness of cracked sections of shear wall components. The results demonstrated that the haunches caused a delay to the formation of cracks and increased the capacity of coupling beams and enhanced the ultimate strength and stiffness of shear wall structures. The accuracy of suggested maximum displacement equation was assessed and concluded that the results were in good agreement with experiment.

ABSTRAK

Dinding ricih konkrit bertetulang adalah komponen struktur dalam satah tegak bangunan yang berkeupayaan untuk menahan kedua-dua graviti dan beban sisi. Ia mempunyai kelakunan struktur yang teguh merintang gempa bumi pada struktur bangunan. Dalam susun atur bangunan tinggi, konfigurasi dinding ricih secara amnya membuatkan akses yang sukar dikawasan awam di tingkat bawah, pada aras lantai dan pintu masuk ke lif atau tangga serta ditempat letak kereta. Keadaan ini boleh diselesaikan dengan menyediakan bukaan pada struktur dinding ricih. Dinding ricih yang berlubang dengan bukaan dipanggil dinding ganding. Jumlah, lokasi dan saiz bukaan secara langsung memberi kesan kepada kekukuhan dinding ricih dan menyebabkan pengurangan kekuatan dan kekukuhan struktur. Kajian ini mencadangkan penambahbaikan dengan membina sesudut ke bukaan segi empat bukaan untuk memperkukuhkan dinding ricih. Kelakuan struktur dinding bersesudut ini dinilai dari kajian lima model konkit bertetulang skala kecil yang mempunyai susunan bukaan yang berbeza. Bukaan bersesudut ini dipanggil bukaan segilapan dan diuji pada beban tumpu statik datar berkitar pada aras atas struktur. Kaedah teori berdasarkan pendekatan keserasian ketegangan dan Konsep Jumlah Momen dan Analisis Unsur Terhingga Tak Linear (NLFEA) dengan berbantukan perisian ABAQUS juga telah dijalankan secara terperinci dan mengesahkan hasil ujikaji. Persamaan analisis mudah telah dicadangkan untuk mengira anjakan maksimum dinding ricih dengan mempertimbangkan kekukuhan berkesan dinding ricih yang retak. Keputusan kajian menunjukkan bahawa sesudut pada bukaan telah melewatkan pembentukan retak dan meningkatkan keupayaan rasuk ganding dan meningkatkan kekuatan muktamad dan kekukuhan struktur dinding ricih. Ketepatan persamaan anjakan maksimum yang dicadangkan telah dinilai dan memberi keputusan yang bersamaan dengan hasil ujikaji.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATION

ACI	-	American Concrete Institute
ASCE	-	American Society of Civil Engineers
CCM	-	Continuous Connection Method
CFRP	-	Carbon Fibre Reinforced Polymer
CSA	-	Canadian Standards Association
DoC	-	Degree of Coupling
FEA	-	Finite Element Analysis
FEMA	-	Federal Emergency Management Agency
FRC	-	Fibre Reinforced Concrete
HPFRC	-	High-Performance Fibre Reinforced Concrete
LVDT	-	Linear Variable Displacement Transducer
NFEM	-	Nonlinear Finite Element Method
NLFEA	-	Nonlinear Finite Element Analysis
NZS	-	New Zealand Standard
OPC	-	Ordinary Portland Cement

LIST OF SYMBOLS

$A_{eff,1}$	-	Effective area of wall 1, tension wall
$A_{eff,2}$	-	Effective area of wall 2, compression wall
A_g	-	Gross area of concrete section
A_s	-	Cross sectional area of bars
a	-	Length of coupling beam or connection
b	-	Width of coupling beam or connection
C_c	-	Concrete crushing force
c_1	-	Length of wall 1, tension wall
c_2	-	Length of wall 2, compression wall
d	-	Effective depth of the coupling beam
d'	-	Bottom cover of main longitudinal bars
d''	-	Top cover of main longitudinal bars
d_c	-	Compression degradation variable
d_e	-	Effective depth of coupling beam or connection
d_t	-	Tension degradation variable
E_0	-	Initial elastic modulus of material
E_c	-	Modulus of elasticity of concrete
E_s	-	Modulus of elasticity of steel
f_{ck}	-	Concrete compressive strength
f_{ct}	-	Concrete splitting strength
f_u	-	Ultimate strength of steel reinforcement
f_y	-	Yield strength of steel reinforcement
H	-	Total height of the wall
h	-	Storey height
h'	-	Depth between main bars in coupling beams or connections
I_1	-	Moment of inertia of wall 1, tension wall

I_2	-	Moment of inertia of wall 2, compression wall
$I_{eff,1}$	-	Effective moment of inertia of wall 1, tension wall
$I_{eff,1}$	-	Effective moment of inertia of wall 2, compression wall
$I_{eff,cb}$	-	Effective moment of inertia of the coupling beam
$I_{g,cb}$	-	Moment of inertia of the gross sectional area of coupling beam
k	-	Stiffness reduction factor
L_c	-	Effective length of the coupling connection
L_{cb}	-	Effective length of the coupling beam
l	-	Distance between axial forces in walls
l_1	-	Half the horizontal length of tension wall
l_2	-	Half of the horizontal length of compression wall
M_n	-	Nominal flexural strength of section
M_o	-	Restoring moment
M_r	-	Rotational moment
$M_{res,composite}$	-	Resistance moment of the wall in composite action
$M_{res,concrete}$	-	Sum of moment of resistance of concrete force
$M_{res,steel}$	-	Sum of moment of resistance of vertical bar forces
M_{res1}	-	Moment of resistance of wall 1, tension wall
M_{res2}	-	Moment of resistance of wall 2, compression wall
P_{add}	-	Required additional force to maintain the equilibrium of coupling beams or connection section
P	-	External lateral force
P_n	-	Nominal axial strength of section
P_o	-	Nominal axial strength at zero eccentricity
P_{st}	-	Ultimate forces in main horizontal bars
P_u	-	Ultimate strength of coupling beams or connections
P_{ult}	-	Ultimate load of shear wall structure
q	-	Shear force per unit height in connecting medium
S_A	-	Scale factor of area
S_E	-	Scale factor of modulus of elasticity
S_ε	-	Scale factor of strain
S_L	-	Scale factor of length

S_P	-	Scale factor of concentrated load
S_x	-	Scale factor of displacement
S_ν	-	Scale factor of Poisson's ratio
S_σ	-	Scale factor of stress
T	-	Force in main bar
T_1	-	Axial force imposed by coupling beams or connections in wall 1, tension wall
T_2	-	Axial force imposed by coupling beams or connections in wall 2, compression wall
V	-	Vertical forces at support section of coupling beams or connections
x_1	-	Depth of neural axis of wall 1, tension wall
x_2	-	Depth of neural axis of wall 2, compression wall
ε_c	-	Total strain in compression
ε_t	-	Total strain in tension
ε_y	-	Yield strain of steel bars
ε_c^{el}	-	Elastic strain in compression
ε_t^{el}	-	Elastic strain in tension
$\tilde{\varepsilon}_c^{pl}$	-	Equivalent plastic strain in compression
$\tilde{\varepsilon}_t^{pl}$	-	Equivalent plastic strain in tension
δ_{max}	-	Maximum horizontal displacement of shear wall structure
λ	-	Degree of relative flexibility of the coupling beams and walls
ν	-	Poisson's ratio
ρ_s	-	Longitudinal reinforcement ratio
ρ_v	-	Transverse reinforcement ratio

CHAPTER 1

INTRODUCTION

1.1 Introduction

Tall buildings have been increasing all around the world in the last decades to pool resources and centralize activities. Historically, the development of high-rise buildings was related to the need for more living and working space in overcrowded cities. High demand, lack of township land and human ambition to create taller structures has led to many developers turned to construct high-rise buildings. Tall buildings are expected to perform a multiple functions such as office, apartment and shopping centres within a single high-rise tower.

The earliest tall building systems were constructed of bricks, mortar and masonry. Nowadays features such as adaptability of function and form, economy, fire resistance and the effects of time is making the concrete as an ideal building material. The availability of raw materials for concrete and simplicity of cement manufacturing are the key factors to select the concrete in construction. Using of cast-in-situ reinforced concrete shear walls for lateral load resistant elements in tall buildings is widespread in many countries. This form of construction has been used since the 1960s in cities for medium to high-rise structures.

Several reports show a good behaviour of reinforced concrete shear walls in past earthquakes. Inspection reports indicate tremendously good seismic performance of these buildings, with negligible damage or zero damage at all. Nevertheless an earthquake performance of buildings with shear walls in some earthquakes is only associated to poor construction quality such as insufficient wall density in the horizontal direction, inadequate amount and/or detailing of wall reinforcement, the lack of lateral confinement in the walls, weak condition of soil and site effect [1-3].

1.2 Background of the Problem

The lateral and gravity load resisting system of the buildings involves of reinforced concrete walls and slabs. Shear wall structures are the main vertical structural features with a role of resisting both the gravity and lateral forces. Thickness of the wall depends on the number of storey and it varies from 140 mm to 500 mm. These walls are commonly reinforced continuously throughout the height of the building. However, some shear walls are discontinued at the basement level or street front to permit for parking spaces or commercial purposes.

Shear wall structures are typically regular in plan and elevation as shown in Figure 1.1. Efficiency of shear walls is described in terms of stiffness. Solid shear walls are most efficient so it is highly desirable but openings often are required in shear walls for functional necessity (e.g., doors and windows). Though, in some buildings, lower levels are used for commercial purposes and the structures are considered with bigger plan dimensions at those floors. Generally, shear wall buildings are used for residential purposes and may house from 100 to 500 inhabitants per building.

Shear walls with openings are called coupled walls. These walls perform as cantilevered walls connected by coupling beams (spandrel beams or lintels) for bending and shear effects. An important criteria used in the design of concrete shear walls are based on providing the required strength and stiffness to avoid or limit the damage under frequent earthquakes while ensuring adequate wall deformation capacity [4]. When designed in a ductile manner, these beams and connections can act as fuses and are used to dissipate seismic energy.

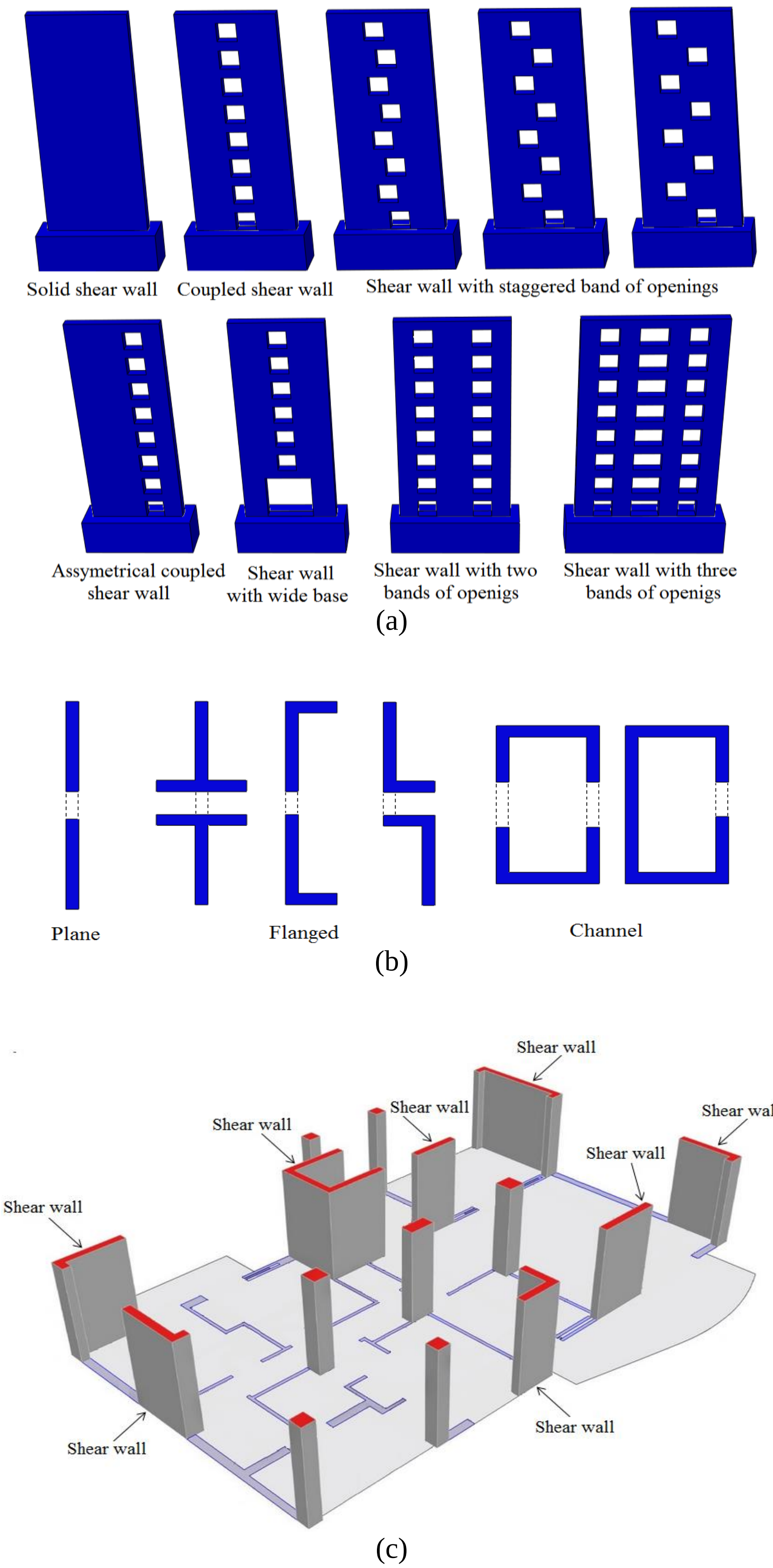

Figure 1.1 a) typical types of shear walls b) typical plan sections of shear walls c) a plan view of a building with different type of shear wall section

1.3 Problem Statement

Generally, configuration of shear wall in tall buildings makes access difficult to the public lobby areas at floor levels especially ground floor such as the car park area and the entrance to lifts or staircases. In view of this, a large opening at the base floor is required. This can be achieved by providing openings in the shear wall. On the other hand, the location, number, and size of openings affect the overall behaviour of the shear wall structure as well as stresses in the wall and cause to decrease its stiffness.

Furthermore, in a common office and residential buildings, typically the depth of the coupling beams and connections cannot be too much due to limitation of height between the floors and the clear height of floors. Therefore, the coupling beams and connections cannot be very stiff and as a result the effect of coupling on shear walls may not be adequately predominant. Adding haunches is proposed as a useful method to increase the stiffness of the coupling beams in order to increase the effect of couplings in the regular wall connections.

In the past decades large amount of research carried out for shear wall structures with different arrangements of rectangular openings. They used theoretical and experimental methods to analyse the shear wall structures. Recently some finite element software with the ability of defining the nonlinear geometry and material have been developed and utilized in analysing the shear wall structures.

Some methods are suggested to increase the strength of shear wall structures. The common methods are based on the strengthening of the coupling beams, using diagonal reinforcement and steel beams, confining the concrete at the base, and increase the material strength by using high-strength concrete.

To this date there is no investigation on the effect of adding haunches to the corners of rectangular opening in the behaviour of reinforced concrete shear wall structures with openings. This research suggests a method to increase the strength and stiffness of shear wall significantly. It also will become economical solution for shear walls due to the reduction in material use.

From architectural point of view, in high-rises, shear wall with octagonal openings may have small thickness compared to shear wall with rectangular openings. Furthermore, this kind of configuration of opening, allows the architecture and designer to install a larger opening with different shape than typical rectangular form of opening.

1.4 Aim of the Study

The aim of this research is to propose a new strategy to increase the strength and stiffness of shear wall with openings by adding haunches to the corners of rectangular openings of shear wall elements of tall buildings.

1.5 Objectives of the Study

In order to achieve the aim of this research, the following objectives are considered:

1. To determine the structural nonlinear behaviour of reinforced concrete shear walls with different arrangements of rectangular and octagonal openings.
2. To compare the load-displacement curve, crack distribution, critical areas, mode of failure and ultimate load of shear walls with rectangular and octagonal openings.
3. To propose a simple theoretical method to calculate the maximum displacement of shear wall models based on reduced stiffness and cracked section.

4. To develop a finite element model to determine the behaviour of reinforced concrete shear walls with rectangular and octagonal openings.

1.6 Scope of the Study

The scopes of this research are focusing on experimental analysis of five scaled models of reinforced concrete shear walls with different arrangements of openings. The following configurations are investigated:

- Shear wall with single band of rectangular openings (Model 1Rec.)
- Shear wall with single band of octagonal openings (Model 1Oct.)
- Shear wall with different arrangements of staggered octagonal openings (Model 2Oct, Model 3Oct. and Model 4Oct.)

The efficiency and accuracy of the proposed models will be verified by performing static lateral cyclic loading on the approximately 1:30 scale models in the laboratory. The research is involved with ordinary concrete with maximum aggregate size of 5 mm. The foundation of the models is restrained against displacement and a point load is applied horizontally near the top of the wall through stages of incremental loading and unloading, until the ultimate failure of shear wall. The effect of building vertical loads is not considered. The only vertical load is the self-weight of the shear wall specimens. The evaluation of the experimental behaviour of the reinforced concrete shear walls with octagonal openings is mainly based on the load versus displacement response and mechanism of failure.

Nonlinear Finite Element Analysis (NLFEA) with the aid of ABAQUS software version 6.12-1 is performed on the models. In order to achieve the research objective and to reduce the required time and capacity for the analysis, two-dimensional models of shear walls with octagonal openings are generated with similar scale of experimental models.

In addition, theoretical analysis proposed by the previous researchers [5-8] is employed to calculate the ultimate strength of shear walls with rectangular and octagonal openings and proposed a theoretical equation. This equation can be used to estimate the maximum displacement at top of the structure at ultimate load level and is also applicable for other level of loading as a stiffness matrix can be formed for structural analysis that it is beyond the scope of this research.

1.7 Significance of the Research

An obvious and important significance of this study is to increase the strength and performance of shear wall structures in earthquake regions in order to protect the human life all around the world. Other importance that would be gained from this research is as follow:

1. Present an economical solution for shear wall with openings and consequently for structure due to the reduction in material use and time. This can be achieved by designing and constructing a larger size of octagonal openings instead of rectangular openings with the same ultimate load level.
2. Offer a new configuration of openings in reinforced concrete shear wall compared to typical shape of openings architecturally.

1.8 Structure of the Thesis

This thesis is organized in eight chapters. The first chapter is a brief introduction to the shear wall structure, followed by a statement of the research objective and scope. A review on different forms of structural system and relevant research work of reinforced concrete shear wall structures is presented in Chapter 2. Chapter 3 is the methodology of experimental program and consists of reinforcing details of the specimens, the materials properties, load protocols, and discussion on other testing issues. The theoretical analysis method and simulating procedure in ABAQUS software are presented through Chapter 4. The result of experimental work are presented and discussed in Chapter 5. In Chapter 6 the results of analytical method in the format of ultimate capacity of coupling beams and connections, behaviour of shear walls, maximum load and displacement of the shear wall models are presented and compared with experiments in order to validate the accuracy of proposed method. Chapter 7 focuses on the NLFEA results using ABAQUS software. The outputs in terms of crack pattern, crushing areas, strain of steel bars, and load-displacement curves are discussed and compared with experimental results. The main conclusions regarding the effect of using octagonal opening in shear wall structures and recommendations drawn from this study are provided in Chapter 8.

REFERENCES

1. Gioncu, V. and Mazzolani, F. Problems of Seismic Behaviour of Buildings Situated in Urban Habitats. *Urban Habitat Constructions under Catastrophic Events: Proceedings of the COST C26 Action Final Conference*. September 16-18. Naples, Italy: CRC Press. 2010. 87-92.
2. Marius, M. Seismic Behaviour of Reinforced Concrete Shear Walls with Regular and Staggered Openings after the Strong Earthquakes between 2009 and 2011. *Engineering Failure Analysis*. 2013. 34: 537-565.
3. Wen, Z., Hu, Y. and Chau, K. Site Effect on Vulnerability of High-Rise Shear Wall Buildings under Near and Far Field Earthquakes. *Soil Dynamics and Earthquake Engineering*. 2002. 22(9-12): 1175-1182.
4. Massone, L. M. and Wallace, J. W. Load-Deformation Responses of Slender Reinforced Concrete Walls. *ACI Structural Journal*. 2004. 101(1): 103-113.
5. Subedi, N. K. RC Coupled Shear Wall Structures. II: Ultimate Strength Calculations. *Journal of Structural Engineering.* 1991. 117(3): 681-698.
6. Subedi, N. K., RC-Coupled Shear Wall Structures. I: Analysis of Coupling Beams. *Journal of Structural Engineering*. 1991. 117(3): 667-680.
7. Subedi, N. K., Marsono, A. K. and Aguda, G. Analysis of Reinforced Concrete Coupled Shear Wall Structures. *The Structural Design of Tall Buildings*. 1999. 8(2): 117-143.
8. Marsono, A. K. *Reinforced Concrete Shear Walls with Regular and Staggered Openings*. Ph.D. Thesis. University of Dundee; 2000.
9. Colaco, J. P. Coull, A. and Stafford Smith, B. Elastic Analysis. *Tall Building Monographs, ASCE.* Vol. CB. 1978: 147-168.
10. Barr, J. Skyscrapers and Skylines: New York and Chicago, 1885–2007. *Journal of Regional Science*. 2013. 53(3): 369-391.

11. Iyengar, H. S. Preliminary Design and Optimization of Tall Buildings. *Proceedings of International Conference on Tall Buildings*. August 21-26. New York: ASCE. 1972.

12. Khan, F. R. and Sbarounis, J. A. Interaction of Shear Walls and Frames. *Journal of the Structural Division*. 1964. 90(3): 285-338.

13. Smith, B. S. and Coull, A. *Tall Building Structures: Analysis and Design*. New York: John Wiley & Sons, Inc. 1991.

14. Coull, A. and Puri, R. Analysis of Coupled Shear Walls of Variable Cross-Section. *Building Science*. 1968. 2(4): 313-320.

15. Coull, A. and Subedi N. K. Coupled Shear Walls with Two and Three Bands of Openings. *Building Science*. 1972. 7(2): 81-86.

16. Rosmon, R. Approximate Analysis of Shear Walls Subject to Lateral Loads. *ACI Journal Proceedings*. 1964. 61(6): 717-734.

17. Elkholy, I. and Robinson, H. An Inelastic Analysis of Coupled Shear Walls. *Building Science*. 1974. 9(1): 1-8.

18. Paulay, T. An Elasto-PIastic Analysis of Coupled Shear Walls. *ACI Journal Proceedings*. 1970. 67(11): 915-922.

19. Pekau, O. and Gocevski, V. Elasto-Plastic Analysis of Coupled Shear Walls. *Engineering Structures*. 1981. 3(2): 87-95.

20. Glück, J. Elasto-Plastic Analysis of Coupled Shear Walls. *Journal of the structural Division*. 1973. 99(8): 1743-1760.

21. Arvidsson, K. Interaction between Coupled Shear Walls and Frames. *ICE Proceedings*. 1979. 67(3): 589-596

22. Aksogan, O., Turkozer, C. D., Emas, E. and Resatoglu, R. Dynamic Analysis of Non-Planar Coupled Shear Walls with Stiffening Beams Using Continuous Connection Method. *Thin-Walled Structures*. 2014. 82: 95-104.

23. Candy, C. Analysis of Shear-Wall Frames by Computer. *New Zealand Engineering*. 1965. 20(5): 199-200.

24. Clough, R. W., King, I. P. and Wilson, E. L. Structural Analysis of Multistory Buildings. *Journal of the Structural Division*. 1964. 90(3): 19-34.

25. Lew, I. P. and Narov, F. Three-Dimensional Equivalent Frame Analysis of Shear Walls. *Concrete International*. 1983. 5(10): 25-30.

26. MacLeod, I. Technical Note. General Frame Element for Shear Wall Analysis. *ICE Proceedings*. 1976. 61(4): 785-790.

27. MacLeod, I. A. and Hosny, H. M. Frame Analysis of Shear Wall Cores. *Journal of the Structural Division.* 1977. 103(10): 2037-2047.

28. Majid, K. and Onen, Y. The Elasto-Plastic Failure Load Analysis of Complete Building Structures. *ICE Proceedings*. 1973. 55(3): 619-634.

29. Schwaighofer, J. and Wing, N. H. An Elasto-Plastic Analysis of a Core Structure. *Building and Environment*. 1977. 12(3): 199-204.

30. Stafford Smith, B. and Girgis, A. Deficiencies in the Wide Column Analogy for Shear Wall Core Analysis. *Concrete International*. 1986. 8(4):58-61.

31. Kwan, A. Improved Wide-Column-Frame Analogy for Shear/Core Wall Analysis. *Journal of Structural Engineering*. 1993. 119(2): 420-437.

32. Smith, B. S. and Girgis, A. Simple Analogous Frames for Shear Wall Analysis. *Journal of Structural Engineering*. 1984. 110(11): 2655-2666.

33. Koumousis, V. and Peppas, G. A. Stiffness Matrices for Simple Analogous Frames for Shear Wall Analysis. *Computers and structures*. 1992. 43(4): 613-633.

34. Kwan, A. Equivalence of Finite Elements and Analogous Frame Modules for Shear/Core Wall Analysis. *Computers and structures*. 1995. 57(2): 193-203.

35. Al-Mahaidi, R. S. and Nilson, A. H. Coupled Shear Wall Analysis by Lagrange Multipliers. *Journal of the Structural Division*. 1975. 101(11): 2359-2366.

36. Cook, R. D., Avoidance of Parasitic Shear in Plane Element. *Journal of the Structural Division*. 1975. 101(6): 1239-1253.

37. Macleod, I. A., New Rectangular Finite Element for Shear Wall Analysis. *Journal of the Structural Division.* 1969. 95(3): 399-409.

38. Girijavallabhan, C. V. Analysis of Shear Walls with Openings. *Journal of the Structural Division*. 1969. 95(10): 2093-2104.

39. Cheung, Y. and Swaddiwhdhipong, S. Analysis of Frame Shear Wall Structures Using Finite Strip Elements. *ICE Proceedings*. 1978. 65(3):517-535.

40. Cheung, Y., Au, F. and Zheng, D. Analysis of Deep Beams and Shear Walls by Finite Strip Method with C^0 Continuous Displacement Functions. *Thin-walled structures*. 1998. 32(4): 289-303.

41. Chan, H. and Cheung, Y. Analysis of Shear Walls Using Higher Order Finite Elements. *Building and Environment*. 1979. 14(3): 217-224.

42. Choi, C. K. and Bang, M. S. Plate Element with Cutout for Perforated Shear Wall. *Journal of Structural Engineering*. 1987. 113(2): 295-306.

43. Eisenberger, M. and Perry, B. Analysis of Coupled Shear Walls Using High Order Finite Elements. *Finite elements in analysis and design.* 1989. 5(2): 181-194.

44. Kwan, A. Analysis of Buildings Using Strain-Based Element with Rotational DOFs. *Journal of Structural Engineering*. 1992. 118(5): 1191-1212.

45. Kim, H. S. and Lee, D. G. Analysis of Shear Wall with Openings Using Super Elements. *Engineering Structures*. 2003. 25(8): 981-991.

46. Paknahad, M., Noorzaei, J., Jaafar, M. S. and Thanoon, W. A. Analysis of Shear Wall Structure Using Optimal Membrane Triangle Element. *Finite Elements in Analysis and Design*. 2007. 43(11): 861-869.

47. Husain, M. A. Analysis of Shear Wall with Openings Using Brick Element. *European Journal of Scientific Research*. 2011. 51(3): 359-371.

48. Eberhard, M. O. and Sozen, M. Behavior-Based Method to Determine Design Shear in Earthquake-Resistant Walls. *Journal of Structural Engineering*. 1993. 119(2): 619-640.

49. Farrar, C. and Baker, W. Measuring the Stiffness of Concrete Shear Walls During Dynamic Tests. *Experimental Mechanics*. 1992. 32(2): 179-183.

50. Wood, S. L. Shear Strength of Low-Rise Reinforced Concrete Walls. *ACI Structural Journal*. 1990. 87(1): 99-107.

51. Lin, C. and Kuo, C. Behavior of Shear Wall with Opening. *Proceedings of 9th World Conference on Earthquake Engineering*. August 2-9. Tokyo: Science Council of Japan. 1988. 535-540.

52. Lopes, M. Experimental Shear-Dominated Response of RC Walls: Part I: Objectives, Methodology and Results. *Engineering Structure*s. 2001. 23(3): 229-239.

53. Mo, Y. and Kuo, J. Experimental Studies on Low-Rise Structural Walls. *Materials and Structures*. 1998. 31(7): 465-472.

54. Pilakoutas, K. and Elnashai, A. Cyclic Behavior of Reinforced Concrete Cantilever Walls. I: Experimental Results. *ACI Structural Journal*. 1995. 92(3): 271-281.

55. Tasnimi, A. Strength and Deformation of Mid-Rise Shear Walls under Load Reversal. *Engineering Structures*. 2000. 22(4): 311-322.

56. Yanez, F. V., Park, R. and Paulay, T. Seismic Behaviour of Walls with Irregular Openings. *Proceedings of the 10th World Conference on Earthquake Engineering*. July 19-24. Madrid, Spain: CRC Press. 1992. 3303-3308.

57. Qaqish, S. and Daqqaq, F. Effect of Horizontal Forces on Shear Walls with Small Openings. *Proceedings of the Fourteenth Conference on Engineering Mechanic*s. May 21-24. Austin, Texas: ASCE. 2000.

58. Chowdhury, S. R., Rahman, M. A., Islam, M. J. and Das, A. K. Effects of Openings in Shear Wall on Seismic Response of Structures. *International Journal of Computer Applications (0975-8887)*. 2012. 59(1): 10-13.

59. Kotsovos, M. D. and Pavlovic, M. *Structural Concrete: Finite-Element Analysis for Limit-State Design*. London: Thomas Telford. 1995.

60. Vecchio, F. J. Finite Element Modeling of Concrete Expansion and Confinement. *Journal of Structural Engineering*. 1992. 118(9): 2390-2406.

61. Kwan, A. and He, X. Finite Element Analysis of Effect of Concrete Confinement on Behavior of Shear Walls. *Computers and Structures*. 2001. 79(19): 1799-1810.

62. Paulay, T. and Binney, J. Diagonally Reinforced Coupling Beams of Shear Walls. *ACI Special Publication*. 1974. 42: 579-598.

63. Sittipunt, C., Wood, S. L., Lukkunaprasit, P. and Pattararattanakul, P. Cyclic Behavior of Reinforced Concrete Structural Walls with Diagonal Web Reinforcement. *ACI Structural Journal*. 2001. 98(4): 554-562.

64. Shiu, K. N., Barney G. B. Fiorato A. E. and Corley W. G. Reversed Load Tests of Reinforced Concrete Coupling Beams. *Proceedings of the Central American Conference on Earthquake Engineering.* January 9-14. El Salvador: UCA/Ediutores-El Salvador. 1978. 239-249.

65. Harries, K. A., Mitchell, D., Coll, W. D. and Redwood, R. G. Seismic Response of Steel Beams Coupling Concrete Walls. *Journal of Structural Engineering*. 1993. 119(12): 3611-3629.

66. Shahrooz, B. M., Remmetter, M. E. and Qin, F. Seismic Design and Performance of Composite Coupled Walls. *Journal of Structural Engineering*. 1993. 119(11): 3291-3309.

67. Qizhi, L. and Xiaolei, H. The Behavior of Stiffening Beams and Lintel Beams under Cyclic Loading. *Journal of South China University of Technology (Natural Science)*. 1995. 23(1): 27-33.

68. Gong, B., Shahrooz, B. M. and Gillum, A. J. Seismic Behavior and Design of Composite Coupling Beams. *Composite Construction in Steel and Concrete III ASCE*.1997. 258-271.

69. Meftah, S., Mohri, F. and Daya, E. Seismic Behavior of RC Coupled Shear Walls with Strengthened Coupling Beams by Bonded Thin Composite Plates. *KSCE Journal of Civil Engineering*. 2013. 17(2): 403-414.

70. Liao, W. I., Zhong, J., Lin, C. C., Mo, Y. L. and Loh, C. H. Experimental Studies of High Seismic Performance Shear Walls. *Proceedings of the 13th World Conference on Earthquake Engineering*. August 1-6. Vncouver: 13WCEE Secretariat. 2004. Paper No. 501.

71. Kim, K., Parra-Montesinos, G. J. and Naanman, A. E. Behavior of HPFRCC Low-Rise Walls Subjected to Displacement Reversals. *High Performance Fiber Reinforced Cement Composites (HPFRCC 4)*. 2003: 505-515.

72. Parra-Montesinos, G. J. High-Performance Fiber-Reinforced Cement Composites: An Alternative for Seismic Design of Structures. *ACI Structural Journal*. 2005. 102(5): 668.

73. Lequesne, R., Setkit, M., Kopczynski, C., Ferzli, J., Cheng, M. Y., Parra-Montesinos, G. and Wight, J. K. Implementation of High-Performance Fiber Reinforced Concrete Coupling Beams in High-Rise Core-Wall Structures. *Advances in FRC Durability and Field Applications*. 2011. SP280(7): 94-105.

74. Jianxin, L., Hongnan, W., Benliang, L., Meichun, Z. and Hongwei, W. Nonlinear Analysis and Design of Staggered Shear Wall Structure for High-Rise Buildings. *International Conference on Electric Technology and Civil Engineering (ICETCE)*. April 22-24. Piscataway N.J.: IEEE. 2011. 464-467.

75. Mosoarca, M. and Stoian, V. Seismic Energy Dissipation in Structural Reinforced Concrete Walls with Staggered Openings. 2012. 2(15): 71-78.

76. Mosoarca, M. and Stoian, V. Modelling by Theoretical and Experimental Analysis of RC Shear Walls With Staggered Openings Subjected to Seismic Actions. Reduction of Rigidity. *International Conference on Modeling and Simulation ICMS, World Academy of Science and Technology*. January 15-17. Zurich, Switzerland. 2012. 687-697.

77. Mosoarca, M. Failure Modeling Using Simplified Computational Methods of RC Shear Walls with Staggered Openings Subjected to Seismic Actions.

International Conference on Modeling and Simulation ICMS, World Academy of Science and Technology. January 15-17. Zurich, Switzerland. 2012. 970-978.

78. Marsono, A. K. and Subedi, N. K. Analysis of Reinforced Concrete Shear Wall Structures with Staggered Openings, Part II: Non-Linear Finite Element Analysis (NLFEA). *Proceeding of the 4th Asian-Pacific Structural Engineering and Construction Conference (APSEC2000)*. September 13-15. Kuala Lumpur. 2000. 341-355.

79. Federal Emergency Management Agency, and Applied Technology Council. *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*. United States, Vol. 1. 1997.

80. Applied Technology Council. *Seismic Evaluation and Retrofit of Concrete Buildings.,* Redwood City, ATC-A40. 1996.

81. Federal Emergency Management Agency. *Prestandard and Commentary for the Seismic Rehabilitation of Buildings.* Washington, DC, FEMA-356. 2000.

82. Englekirk, R. E. *Seismic Design of Reinforced and Precast Concrete Buildings*. New York: John Wiley and Sons. 2003.

83. American Institute of Steel Construction. *Seismic Provisions for Structural Steel Buildings*. Chicago, AISC(2002). 2002.

84. Park, R. and Paulay, T. *Reinforced Concrete Structures*. New York: John Wiley and Sons. 1975.

85. Paulay, T. The Design of Ductile Reinforced Concrete Structural Walls for Earthquake Resistance. *Earthquake Spectra*. 1986. 2(4): 783-823.

86. Paulay, T. A Displacement-Focused Seismic Design of Mixed Building Systems. *Earthquake Spectra*. 2002. 18(4): 689-718.

87. Harries, K. A. Ductility and Deformability of Coupling Beams in Reinforced Concrete Coupled Walls. *Earthquake Spectra*. 2001. 17(3): 457-478.

88. Kappos, A. and Penelis, G. *Earthquake Resistant Concrete Structures*. London and New York: Taylor and Francis Group. 2010.

89. Harries, K. A., Fortney, P. J., Shahrooz, B. M., Brienen, P. J. Practical Design of Diagonally Reinforced Concrete Coupling Beams-Critical Review of ACI 318 Requirements. *ACI structural journal*. 2005. 102(6): 876-882.

90. Galano, L. and Vignoli, A. Seismic Behavior of Short Coupling Beams with Different Reinforcement Layouts. *ACI structural Journal*. 2000. 97(6): 876-882.

91. Harries, K. A., Mitchell, D., Redwood, R. G. and Cook, W. D. Seismic Design of Coupled Walls-A Case for Mixed Construction. *Canadian Journal of Civil Engineering*. 1997. 24(3): 448-459.

92. Harries, K. A., Mitchell, D., Cook, W. D. and Redwood, R. G. Seismic Response of Steel Beams Coupling Reinforced Concrete Walls. *ASCE Journal of the Structural Division*. 1992. 119(12): 3611-3629.

93. Motter, C. J. *Large-Scale Testing of Steel-Reinforced Concrete (SRC) Coupling Beams Embedded into Reinforced Concrete Structural Walls*. Ph.D Thesis. University of California; 2014.

94. El-Tawil, S., Fortney, P. J., Harries, K., Shahrooz, B. M. and Kurama, Y. *Recommendations for Seismic Design of Hybrid Coupled Wall Systems (SEI/America Society of Civil Engineers).* Reston, Virginia: ASCE. 2010.

95. Santhakumar, A. R. *Ductility of Coupled Shear Walls*. Ph.D. Thesis. University of Canterbury; 1974.

96. Lequesne, R., Wight, J. and Parra-Montesinos, G. Seismic Detailing and Behavior of Coupled-Wall Systems with High-Performance Fiber-Reinforced Concrete. *9th National and 10th Canadian Conference on Earthquake Engineering Proceedings.* July 25-29. Torento, Canada. 2010. 25-29.

97. Shiu, K. N., Aristizabal-Ochoa, J. D., Barney, G. B., Corley, W. G. *Earthquake Resistant Structural Walls: Coupled Wall Tests*. a report Submitted to Construction Technology Laboratories, Portland Cement Association. 1981.

98. Tassios, T. P., Moretti, M. and Bezas, A. On the Behavior and Ductility of Reinforced Concrete Coupling Beams of Shear Walls. *ACI Structural Journal*. 1996. 93(6): 711-720.

99. Kwan, A. and Zhao, Z. Z. Cyclic Behaviour of Deep Reinforced Concrete Coupling Beams. *Proceedings of the ICE-Structures and Buildings*. 2002. 152(3): 283-293.

100. American Concrete Institute. *Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary*. Farmington Hills, ACI 318-11. 2011.

101. Elwood, K. J. and Eberhard, M. O. Effective Stiffness of Reinforced Concrete Columns. *ACI Structural Journal*. 2009. 106(4): 476-484.

102. Berry, M., Parrish, M. and Eberhard, M. *PEER Structural Performance Database User's Manual*. University of California: Pacific Earthquake Engineering Research Center. 2004.

103. American Society of Civil Engineers. *Seismic Rehabilitation of Existing Buildings*. Reston, Virginia, ASCE/SEI 41-06. 2007.

104. Concrete Design Committee P 3101. *Concrete Structures Standard - The Design of Concrete Structures.* New Zealand, NZS 3101. 1995.

105. Thomas, P. and Priestley, M. *Seismic Design of Reinforced Concrete and Masonry Buildings*. New York: Wiley-Interscience. 1992.

106. Canadian Standards Association. *Design of Concrete Structures*. Canada, A23. 3-94. 1994.

107. Taranath, B. *Steel, Concrete, and Composite Design of Tall Buildings*. 2nd ed. New York: McGraw-Hill. 1998.

108. Vu, N. S., Li, B. and Beyer, K. Effective Stiffness of Reinforced Concrete Coupling Beams. *Engineering Structures*. 2014. 76: 371-382.

109. Fenwick, R. and Bull, D. What Is the Stiffness of Reinforced Concrete Walls. *SESOC Journal.* 2000. 13(2): 23-32.

110. MacGregor, J. G. and Hage, S. E. Stability Analysis and Design of Concrete Frames. *Journal of the Structural Division*. 1977. 103(10): 1953-1970.

111. Li, B. and Xiang, W. Effective Stiffness of Squat Structural Walls. *Journal of Structural Engineering*. 2011. 137(12): 1470-1479.

112. Jalali, A. and Dashti, F. Nonlinear Behavior of Reinforced Concrete Shear Walls Using Macroscopic and Microscopic Models. *Engineering Structures*. 2010. 32(9): 2959-2968.

113. Orakcal, K. and Wallace, J. W. Flexural Modeling of Reinforced Concrete Walls-Experimental Verification. *ACI Structural Journal*. 2006. 103(2): 196-206.

114. Pekau, O. and Cistera, V. Behaviour of Nonlinear Coupled Shear Walls with Flexible Bases. *Canadian Journal of Civil Engineering*. 1989. 16(1): 45-54.

115. Khatri, D. and Anderson, J. Analysis of Reinforced Concrete Shear Wall Components Using the ADINA Nonlinear Concrete Model. *Computers and Structures*. 1995. 56(2): 485-504.

116. Yasuyuki, M., Hiroshi, N., Naomitsu, Y., Masaki, N. and Yutaka, S. Application of ADINA to Nonlinear Analysis of Reinforced Concrete Shear Walls with Openings. *Computers and Structures*. 1981. 13(5): 727-736.

117. Oyen, P. E. *Evaluation of Analytical Tools for Determining the Seismic Response of Reinforced Concrete Shear Walls*. Ph.D. Thesis. University of Washington; 2006.

118. Chang, G. and Mander, J. B. *Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part 1-Evaluation of Seismic Capacity (Technical Report)*. New York: National Center for Earthquake Engineering Research. 1994.

119. Yang, J., Wallace, J. W. and Lu, X. Nonlinear Analysis of Reinforced Concrete Walls Using New Concrete Model in Opensees. 5th International onference on *Measuring Technology and Mechatronics Automation (ICMTMA)*. January 16-17. Hong Kong:IEEE. 2013. 724-728.

120. Musmar, M. A. Analysis of Shear Wall with Openings Using Solid65 Element. *Jordan Journal of Civil Engineering*. 2013. 7(2): 164-173.

121. Zhao, Z., Kwan, A. and He, X. Nonlinear Finite Element Analysis of Deep Reinforced Concrete Coupling Beams. *Engineering Structures*. 2004. 26(1): 13-25.

122. Nazem, M., Rahmani, I. and Rezaee-Pajand, M. Nonlinear FE Analysis of Reinforced Concrete Structures Using a Tresca-Type Yield Surface. *Scientia Iranica A*. 2009. 16(6): 512-519.

123. SIMULIA 6.12-1. *ABAQUS Analysis User's Manual.*

124. Lubliner, J., Oliver, J., Oller, S. and Onate, E. A Plastic-Damage Model for Concrete. *International Journal Of Solids And Structures*. 1989. 25(3): 299-326.

125. Lee, J. and Fenves, G. L. Plastic-Damage Model for Cyclic Loading of Concrete Structures. *Journal of Engineering Mechanics*. 1998. 124(8): 892-900.

126. Buckingham, E. On Physically Similar Systems; Illustrations of the Use of Dimensional Equations. *Physical Review*. 1914. 4(4): 345-376.

127. Harris, H. G. and Sabnis, G. *Structural Modeling and Experimental Techniques*. 2nd ed. New York: CRC press. 1999.

128. El-Tawil, S. and Kuenzli, C. M. Pushover of Hybrid Coupled Walls. II: Analysis and Behavior. *Journal of Structural Engineering*. 2002. 128(10): 1282-1289.

129. British Standards Institution. *Eurocode 2: Design of Concrete Structures: Part 1-1: General Rules and Rules for Buildings*. Milton Keynes, EN 1992-1-1. 2004.

130. Paulay, T. *The Coupling of Shear Walls*. Ph.D. Thesis. University of Canterbury; 1969.