

ULTIMATE BEHAVIOUR OF REINFORCED CONCRETE SHEAR WALLS
WITH OCTAGONAL OPENINGS

SOMAIEH HATAMI

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Specially dedicated to my:

Supportive Father

Devoted Mother

Sincere Husband

Lovely Son

and everyone who had involved in this study.

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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 kelakuan 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 konkrit bertetulang skala kecil yang mempunyai susunan bukaan yang berbeza. Bukaan bersesudut ini dipanggil bukaan segilapan dan diuji pada beban tumpu statik datar berkisar pada aras atas struktur. Kaedah teori berdasarkan pendekatan keserasian ketegangan dan Konsep Jumlah Momen dan Analisis Unsur Terhingga Tak Linear (NLFEA) dengan berbantuan 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 melewati 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.

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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
$I_{eff,2}$	-	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 neutral axis of wall 1, tension wall
x_2	-	Depth of neutral 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
$\tilde{\epsilon}_c^{pl}$	-	Equivalent plastic strain in compression
$\tilde{\epsilon}_t^{pl}$	-	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_ν	-	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.

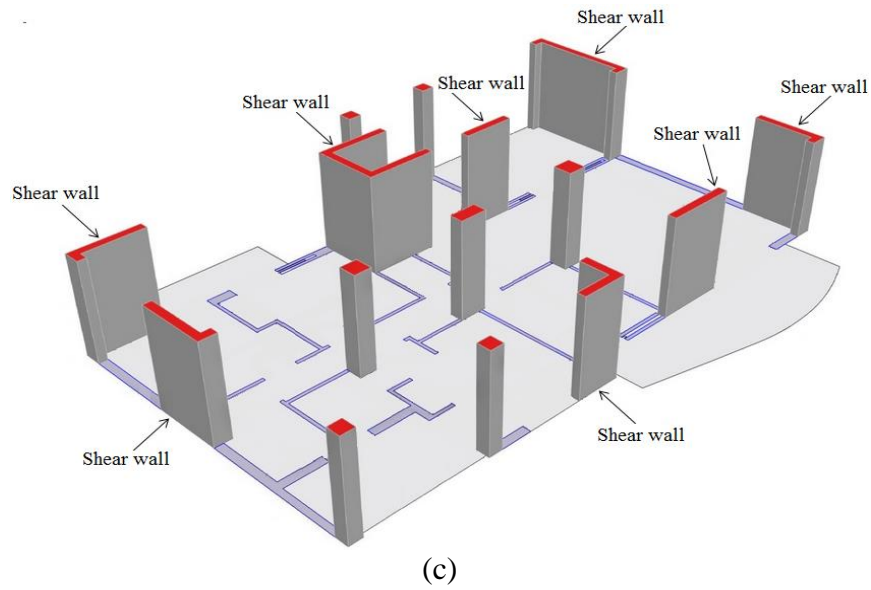
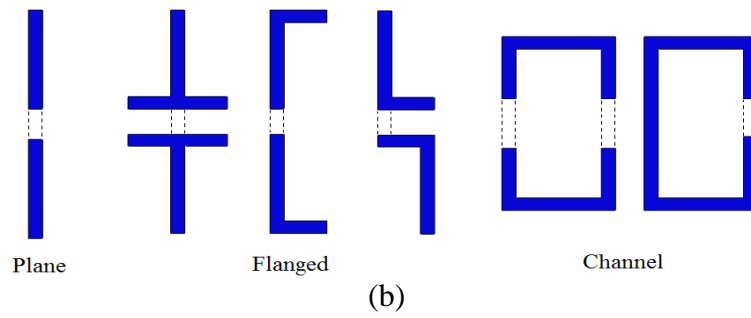
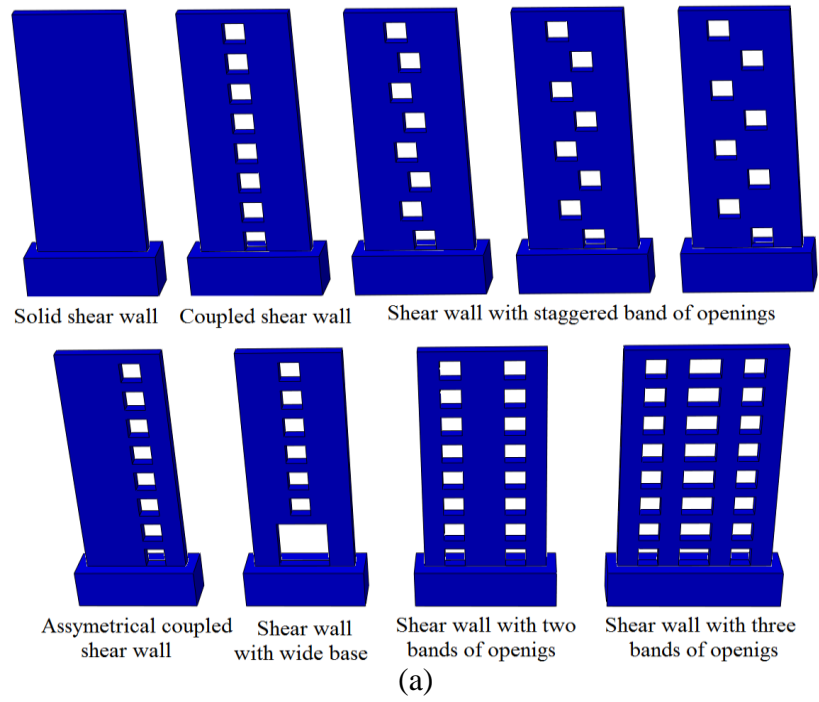


Figure 1.1 a) typical types of shear walls b) typical plan sections of shear walls c) a plan view of a building with different type of shear wall section

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.

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