ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL & ENVIRONMENTAL ENGINEERING

A STUDY ON THE EFFECTS OF OPENINGS ON SEISMIC BEHAVIOR OF REINFORCED CONCRETE SHEAR WALLS

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Master of Science (Structural Engineering)

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Addis Ababa, Ethiopia

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A STUDY ON THE EFFECTS OF OPENINGS ON SEISMIC BEHAVIOR OF REINFORCED CONCRETE SHEAR WALLS

By

Yohannes Kiross

This is to certify that the thesis prepared by Yohannes Kiross, entitled "*A Study on the Effects of Openings on Seismic Behavior of Reinforced Concrete Shear Walls*" and submitted in partial fulfillment of the requirements for the Degree of Master of Science (Structural Engineering) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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DEDICATION

This thesis is dedicated to

MY FAMILY

Without whose patience and devotion, this thesis would not be.

DECLARATION

I, the undersigned, declare that this thesis entitled *"A Study on the Effects of Openings on Seismic Behavior of Reinforced Concrete Shear Walls"* is my original work. This thesis has not been presented for any other university and is not concurrently submitted in candidature of any other degree, and that all sources of material used for the thesis have been duly acknowledged.

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Last but not least my gratitude to the almighty God is beyond words.

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40/60	A name for a group of Condominium Buildings in Ethiopia
A, A_g	Gross cross sectional area of wall elements
a_g	Peak ground acceleration
ASYM	Asymmetric location of openings
A_w	Shear area of coupling beams
B	Total thickness of shear walls
b	Thickness of coupling beams
CCBs	Conventionally reinforced coupling beams
CL	Vertical center line of shear wall
CLO	Vertical center line of shear wall opening
CQC	Complete-quadratic-combination rule
h	Overall depth of coupling beams
d	Effective depth of coupling beam
DCBs	Diagonally reinforced coupling beams
DFSZ	A shear wall model with different size of symmetric openings which gradually increases from the bottom storey to the topmost storey
E_C	Modulus of elasticity of concrete
ETABS	Extended 3D analysis of building structures
G	Shear modulus
H	Overall height of shear wall
I_e	Effective moment of inertia of coupling beams
I_g	Gross moment of inertia of coupling beams
k	Number of modes to be taken into account
K	Stiffness of coupling beams
k_{sh}	Shear stiffness of coupling beams
k_{fl}	Flexural stiffness of coupling beams
L	Overall length of shear wall
l, l_n	Length of coupling beams
LLRS	Lateral load resisting systems
LRG	Large size of openings
MDM	Medium size of openings

P	Axial force
q	Behavior factor
q_o	Basic behavior factor
RSA	Response spectrum analysis
S	Soil factor
$S_d(T)$	Design spectrum for horizontal seismic action
SLD	Solid shear wall without openings
SML	Small size of openings
SRSS	Square-root-of-sum-of-squares combination rule
STGRD	Staggered location of openings
SW1	Existing wall on 40/60 with *single band* of *window* openings
SW2	Existing wall on 40/60 with *single band* of *door* openings
SW3	Existing wall on 40/60 with *two bands* of *door* openings
SYM	Symmetric location of openings
T	Period of vibration
T_k	Period of vibration of mode k
V	Shear force
VLRG	Very Large size of openings
y	Lateral deflection of shear walls
α_s	Shear coefficient
β	Lower bound factor
γ_I	Importance factor
γ_{sh}	Shear factor
Δ	Total deformation of coupling beams
r_o	Peak value of any response quantity
r_{io}	Peak value of response quantity due to mode i
r_{no}	Peak value of response quantity due to mode n
λ	Damping correction factor
ν	Poisson’s ratio for concrete
ξ	Damping coefficient value

ABSTRACT

The objective of this study was to better understand the effects of size and location of openings on seismic behavior of reinforced concrete shear walls using response spectrum analysis and with the help of ETABS15.2.2, finite element software package. The shear walls on 22-storied 40/60 saving house projects were used as a case study. There are three types of shear walls in those buildings. The first shear wall, SW1, has single band of asymmetric window openings. The second shear wall, SW2, has single band of asymmetric door openings. The third shear wall, SW3, has two bands of symmetric door openings. The study was repeated in 10-storied and 40-storied models of the above mentioned shear walls in order to get more comprehensive conclusions. The lateral loads were applied according to ES EN 1998-1:2015's provisions by assuming as if all shear walls were located in the highest seismic zone of Ethiopia. Comparison of the different models was made relative to seismic responses (lateral displacement, storey drift, base shear and shell's internal force distributions) and the results were discussed, tabulated and/or plotted graphically. For each shear wall, the study was carried out by varying the sizes of openings from small to large openings. It was concluded that, though introducing smaller openings reduces the lateral displacement at the top, story drift and shell's internal forces of a wall, using very large size of openings throughout the height of the wall significantly increases the seismic responses. The effect of location of openings was also investigated by considering asymmetric, symmetric and staggered location of openings and it was concluded that, for almost all shear walls, the shear wall with symmetric location of both window and door openings gives less lateral displacement, storey drift and shell forces than the shear walls with asymmetric and staggered locations. Moreover, for almost all shear walls, using shear wall model with different size of symmetric openings, which gradually increases from the bottom storey to the top most storey, is more effective in reducing the seismic responses than even the corresponding solid shear wall without any opening or with symmetric and/or smaller openings. It was also concluded that asymmetric location of openings should be avoided as much as possible. Therefore, caution should be taken during providing openings in reinforced concrete shear walls and the architect and the structural engineer should initially work together in order to avoid unfavorable size and/or location of shear wall openings, which may perhaps leave the wall defenseless to transversal components of earth quake load.

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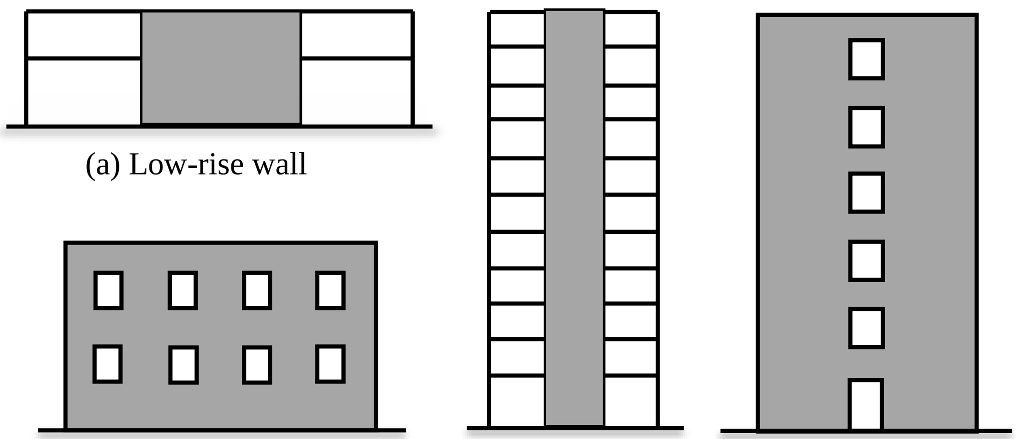
CHAPTER 1: INTRODUCTION

1.1 Background of the Study

The reinforced concrete shear wall is an important structural elements placed in multi-storey buildings which is situated in seismic zones because they have a high resistance to lateral loads such as wind or earthquake loads (Smith and Coull, 1991). Thus shear walls are introduced into modern tall buildings to make the structural system more efficient in resisting the horizontal and gravity loads, ground motions as well thereby causing less damage to the structure during earthquake. Shear walls in apartment buildings may be perforated with rows of openings that are required for windows in external walls or doorways or corridors in internal walls. Shear wall with vertical rows of either window or door openings are called coupled walls as shown in Figure 1.1. The size and location of openings may vary depending on the purposes of the openings and may have great impact on the seismic behavior of reinforced concrete walls. However, in most buildings, size and location of openings in shear wall are made without considering its effect on structural behavior of the shear wall.

Stairway and elevator cores are natural locations for structural walls, which serve a dual purpose of enclosing vertical shafts while providing efficient axial and lateral resistance. There are different forms of a structural wall: it may be solid without openings such as the squat or low-rise walls in Figure 1.1(a) and the high rise wall in Figure 1.1(c). A shear wall may also contain openings such as the perforated wall in Figure1.1(b) or the coupled walls in Figure 1.1(d) (Moehle et al, 2011).



(a) Low-rise wall

(b) Perforated wall

(c) Slender wall

(d) Coupled wall

Figure 1.1: Some illustrative structural wall elevations.

Isolated walls can be connected using coupling beams extending between window and door openings, creating a coupled wall system that is stiffer and stronger than the isolated pair of walls as shown in Figure 1.1 (d). This is because the coupling beam or spandrel helps the pair of walls to act and respond together to different earthquake actions (Moehle et al, 2011). Relative stiffness of shear walls is important since lateral forces are distributed to the individual shear wall according to their relative stiffness. The size and location of openings may also affect the stiffness of individual walls (i.e. piers and coupling beams in the case of coupled shear walls) and hence their deformation behaviour. Simplified methods for estimating the effective stiffness of coupling beams are recommended in several design guidelines as discussed in Section 2.8.2 of this thesis.

It is necessary to know the effects of size and location of openings on stiffness and seismic response of reinforced concrete shear walls so that a suitable configuration of openings in shear walls can be made. Hence, at the planning stage itself, architects and structural engineers must work together to ensure that the unfavorable features are avoided and good shear wall configuration is chosen. On this thesis, a study was done on the effect of size and location of openings on seismic behavior of reinforced concrete shear walls using response spectrum analysis, with the help of ETABS15.2.2, finite element software so that a suitable configuration of openings in shear walls can be obtained.

1.2 Objectives of the Study

1.2.1 General Objective

Generally, this study was carried out to understand the effects of openings on seismic behavior of reinforced concrete shear walls using modal response spectrum analysis and with help of ETABS15.2.2, finite element software package. The study was first carried out on 22-storied shear wall models. The study was conducted on 10-storied and 40-storied shear wall models too in order to get more comprehensive conclusion(s).

1.2.2 Specific Objectives

1. To determine the effect of size and location of openings on lateral displacement, inter storey drift, base shear and shell's internal force distributions of reinforced concrete shear walls.
2. To understand the effect of increasing the sizes of shear wall openings from bottom storey to the uppermost storey on seismic behavior of the wall.
3. To determine the factors affecting the effective stiffness of shear walls with openings.

1.3 Statement of the Problem

Shear walls in apartment buildings may have rows of openings that are required for windows in external walls or for doors ways or corridors in internal walls. It is also common to use door openings in reinforced concrete shear walls that houses elevator core. In most cases, sizes and locations of openings are made without considering its effect on the structural behavior of the shear wall and may vary from architectural and functional point of view. During modeling reinforced concrete shear walls, relative stiffness of shear walls is important since lateral forces are distributed to individual shear wall according to their relative stiffness. The size and location of openings in coupled shear walls may have adverse effect on stiffness of individual walls (i.e. piers and spandrels or coupling beams). In order to have good wall-frame interaction, a shear wall should be curtailed above a point on which the shear wall is not effective in reducing the seismic responses of shear walls. However, this sudden curtailment of shear wall at specific storey may cause stiffness and mass irregularities in a building. In this thesis, a new gradual stiffness and mass reduction technique of shear wall along its height was introduced and the effect of this new technique on seismic responses of the wall is studied.

1.4 Significance of the Study

Beginning from the planning stage, architects and structural engineers must work together to ensure that the unfavorable sizes and locations of openings in reinforced concrete shear walls are avoided and good shear wall configuration is chosen. Knowing the effect of size and location of openings on seismic behaviors of reinforced concrete shear walls will help the structural engineer to quickly judge whether the opening proposed by the architect is appropriate or not and to model the appropriate effective stiffness of individual walls (i.e. piers and spandrels or coupling beams). It can also be a nice input for the architects to avoid unfavorable configuration of openings in shear walls.

1.5 Scope and Limitation of the Research

The scope of this study was to study the effect of size and horizontal location of opening on seismic behavior of reinforced concrete shear walls using response spectrum analysis, and the modeling and analysis was carried out with the help of, ETABS15.2.2, finite element software package. Due to the unavailability of testing machines (cyclic loading testing machine) and economic constraints, experimental investigation required for this particular study is not covered in this thesis and no design work was also involved for all shear walls.

This study was conducted on the three different types of 22-storied reinforced concrete shear walls used in 40/60 saving house projects. The shear walls are; shear wall with single band of window opening (SW1), shear wall with single band of door opening (SW2) and shear wall with two bands of door openings (SW3) by assuming as if all buildings were located in the highest seismic zone of the country, which have approximate hazard level of 0.2g. The scope of this research work was not limited to only 22-storied shear walls but carried out in 10-storied and 40-storied shear walls to get more strong comments. Generally, this study attempted to model different shear walls with different sizes and locations of openings and their counterpart solid shear walls without openings subjected to earthquake loading and then employed a detail study on their seismic responses. The comparisons of results of all shear wall models were made with respect to the overall efficiency in reducing the seismic responses (lateral displacement, inter story drift, base shear and shell's internal force distributions) of the shear walls.

1.6 Thesis Organization

This thesis is organized into six main chapters. The *introductory* chapter presents the background of the study, statement of the problem, objectives of the study, significance of the thesis and scope and limitation of the thesis.

Chapter 2 deals with the review of literatures written by previous researchers and theoretical discussions related to the area of interest.

Chapter 3 presents the methodology and materials used to conduct the research, such as the input data in ETBAS15.2.2 for response spectrum analysis of all shear wall models.

Chapter 4 deals with the modeling and analysis of the sample shear walls with different sizes and locations of openings.

Chapter 5 presents the results and discussions of the study using tables and graphs. The results of all shear wall models are compared with respect to the seismic response parameters (displacement, drift, base shear and shell's internal force distributions).

Chapter 6 presents the conclusions drawn based on the results obtained and recommendations and suggestions for future studies. *Finally*, reference materials used during the study are listed and appendices have been given for assessment of certain information.

CHAPTER 2: LITERATURE REVIEW

2.1 General

Moment resisting frames, shear walls or combination of the two (Dual system) are some of the LLRSs frequently designed to bear horizontal (seismic) loads (Elnashai and Sarno, 2008). Reinforced concrete shear walls may contain different type of openings to accommodate door, window or any other functional requirements. Shear walls with vertical rows of door and/or window openings are called coupled shear walls. The seismic behavior of coupled reinforced concrete shear wall may highly depend on the types of openings used. The following is a review on earthquake actions, lateral load resisting systems, shear wall structural systems, shear walls with different types of openings, coupled shear walls, coupling beams, modes of failure of coupling beams, effective stiffness of coupling beams and modeling and analysis of shear walls with openings.

2.2 Earthquake Loads

The seismic motions of the ground do not damage a building by impact, as does a wrecker's ball, or by externally applied pressure such as wind, but by internally generated inertial forces caused by the vibration of the building mass. The earthquake shaking causes the foundation of a building to oscillate back and forth. The building mass has inertia and wants to remain where it is and therefore, lateral forces are exerted on the mass in order to bring it along with the foundation (Taranath, 2010).

2.3 Lateral Load Resisting Systems

The basic structural elements of an earthquake-resistant building are diaphragms, vertical elements, and the foundation. In reinforced concrete buildings, the vertical elements are usually either moment-resisting frames or structural walls, sometimes referred to as shear walls, acting singly or in combination with each other, dual system (Taranath, 2010). Structural walls will thus contribute to the total lateral force resistance, in proportion to their own stiffness. During a large earthquake, the story-to-story deflection (story drift) may be accommodated within the structural system by plastic hinging of the beam without causing column failure. However, the drift may be large and cause damage to elements rigidly tied to the structural system. Examples of elements prone to distress are brittle partitions, stairways, coupling beams and exterior walls.

2.4 Reinforced Concrete Shear Walls

A shear-wall is an efficient method of ensuring the lateral stability of tall buildings and also efficient against torsional effects when combined together with frame structures. Deflections due to lateral forces are relatively small unless the height-to-width ratio of the wall becomes large enough to cause overturning problems. This would generally occur when there are excessive openings in the shear walls or when the height-to-width ratio of wall is in excess of five or so (Taranath, 1998). Shear walls are generally characterized by high in-plane stiffness and strength which makes them ideally suited for bracing tall buildings. Taranath (1998) states that structural forms of shear wall are commonly used in buildings up to 40 storyes. Buildings engineered with structural walls are almost always stiffer than framed structures, reducing the possibility of excessive deformations and hence damage.

The strength and behavior of short, one or two-story shear walls (as shown in Figure 2.1(a)) generally are dominated by shear. According to MacGregor and Wight (2012), these walls having a height-to-length aspect ratio of less than or equal to 2, are called short or squat walls. If the monolithic wall is more than three or four stories in height and aspect ratio H/L>3, lateral loads are resisted mainly by flexural action of the vertical cantilever wall as shown in Figure 2.1(c) rather than by shear action. Shear walls with H/L ratios between 2 and 3 exhibit a combination of shear and flexural behavior as shown in Figure 2.1(b).

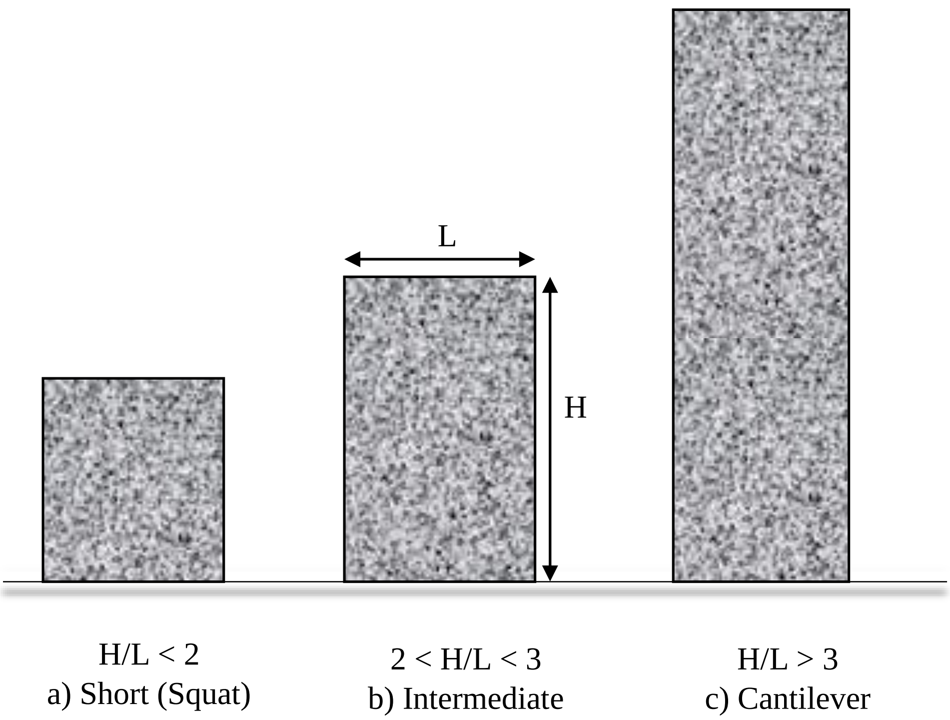


Figure 2.1: Elevation shapes of shear walls

2.5 Shear Wall-Frame Interaction

2.5.1 General

A wall-frame high-rise structure typically consists of the walls and frames that involve from the architectural plan of the building (Smith and Coull, 1991). The benefit of accounting for the wall-frame interaction in the lateral load analysis, as opposed to assuming that the walls carry all the lateral loading, is that it recognizes the increased lateral stiffness due to the interaction, and also the wall and frame members to be designed more correctly and economically.

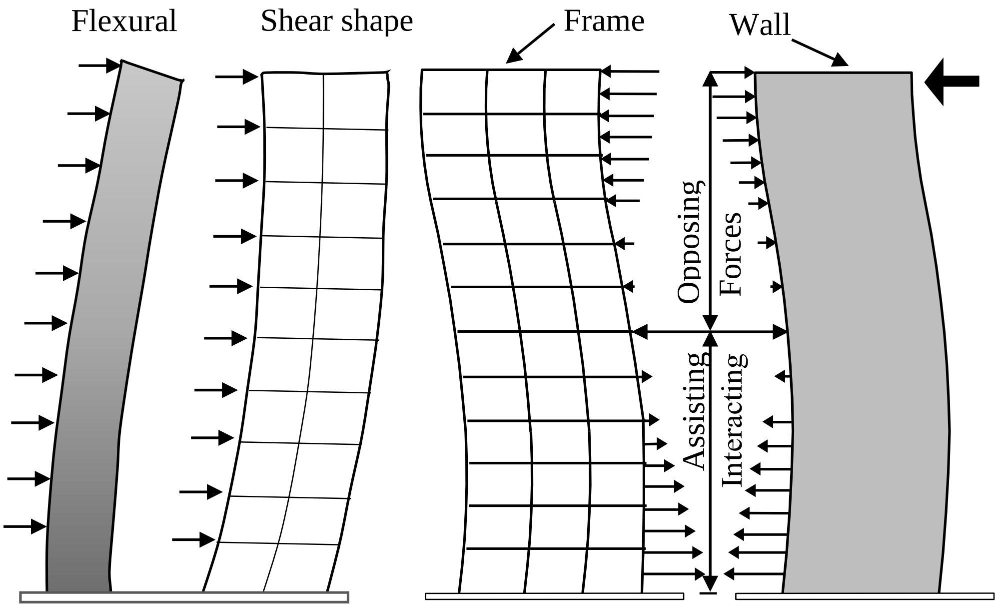


Figure 2.2: Frame-Shear wall interaction

In these systems, reinforced concrete frames interacting with shear walls together provide the necessary resistance to lateral forces, while each system carries its appropriate share of the gravity load (Taranath, 2010). Because the deflected shape of a laterally loaded wall is quite different from that of a frame, the wall responds as a propped cantilever as shown in Figure 2.2.

2.5.2 Curtailed or Interrupted Shear Walls

It is common in the design of practical wall-frame structures to reduce the size, or omit completely, the shear walls and cores in the upper parts of the building, where fewer elevator shafts are required (Smith and Coull, 1991).

The question of how this curtailment will affect the stiffness of the building can be answered by considering the behavior of the wall-frame structure with full-height shear walls or cores.

The “full-height” wall-frame structures shows that in the lower region of the structure the wall and frame both contribute to resisting the external moment and shear. In the upper region above the point of inflection, where moment is zero, however, the moment in the wall is reversed to be of the same sense as the external moment. Further, in the uppermost region above the level where shear is zero, the shear in the wall is also reversed, and so the shear in the frame exceeds the external shear. Consequently, if the wall is reduced or eliminated above the point of contra flexure, the moment on the upper part of the frame is reduced, and if the wall is reduced or eliminated above the level where the shear is zero, both the moment and the shear in the frame are reduced. In both cases the reduction or curtailment may reduce the lateral displacement at the top.

2.6 Shear Walls with Different Types of Openings

Shear wall may come in many forms and there are various types of opening shape due to architectural and planning requirement as shown in Figure 2.3 and 2.4. However, due to ease of analysis, design and construction, regular shapes with openings throughout the height are usually preferred by engineers (Marsono, 2000).

Since the issue “the effect of openings on the seismic behavior of reinforced concrete shear walls” is quite new in Ethiopia, there are no local published literatures related to this study. However, many researchers from different sides of the world have investigated the effect of opening on the seismic behaviour of reinforced concrete shear walls.

Khatami et al. (2012) tried to compare the effects of openings in concrete shear walls under Near-fault ground motions. They used SAP2000 to model the 10-Storied shear walls. They considered the location of square window openings and concluded that, the maximum lateral displacement of model with window opening at center of the wall was up to 8% less than maximum lateral displacement of the model with opening at the right end. They also revealed that the lateral displacement at the top of the model with solid shear wall (i.e. without opening) is 17% less than the lateral displacement of shear wall model with openings at the right end side. Generally, they concluded that the lateral displacement is large in shear walls with openings compared to those of complete shear walls without any openings.

Yanez, Park and Paulay (1992) studied on seismic behavior of R.C. walls with square openings of different size and arrangement under reversed cyclic loading. They concluded that the stiffness of walls is dependent on the size of the openings and not on their horizontal locations.

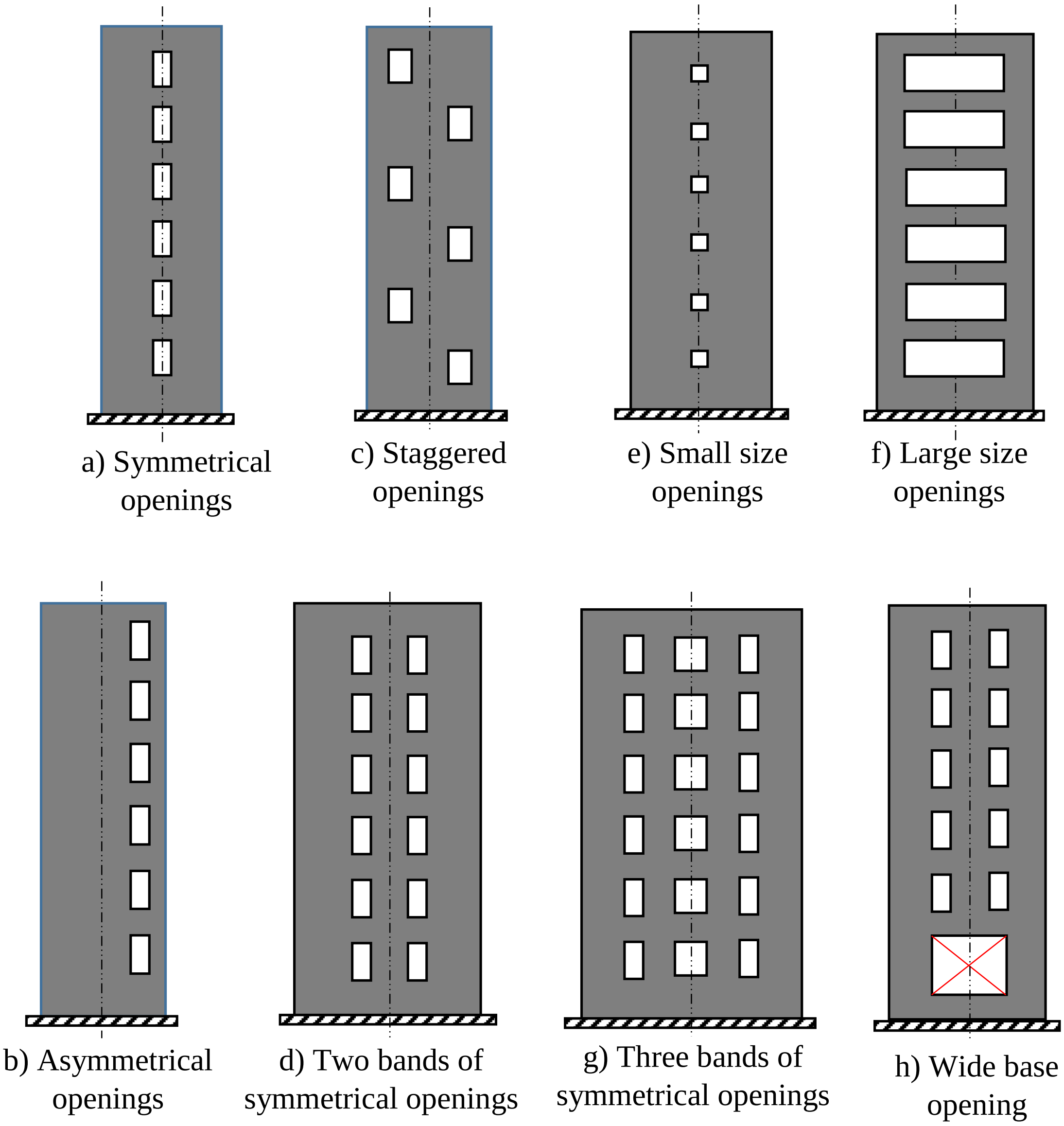


Figure 2.3: Typical elevation shapes of shear walls with openings

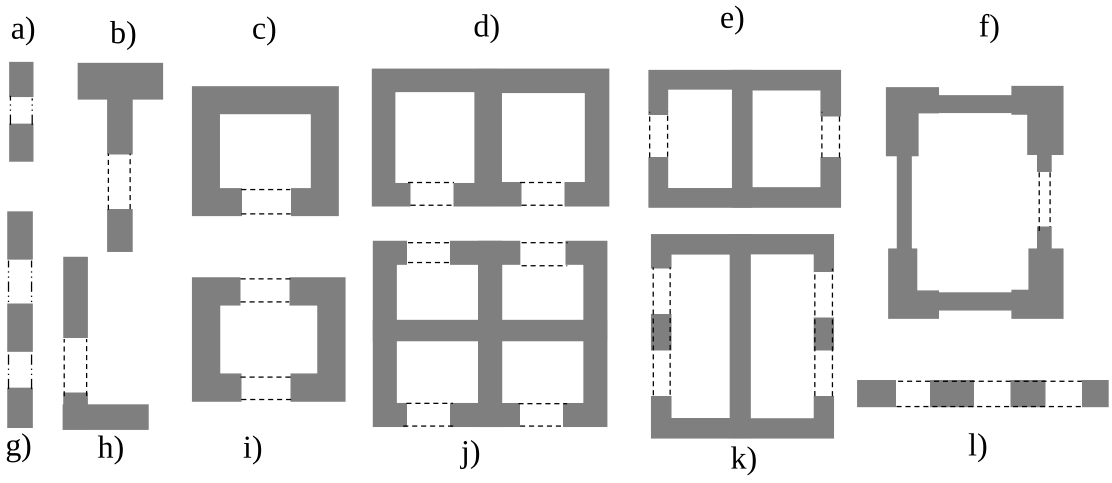


Figure 2.4: Typical plan shapes of shear walls with openings

In another research, effect of perforation of shear wall on various design parameters of a high rise buildings have been assessed by Baseer and Farrukh (2015). This study was carried out on a twenty storey frame-wall building using equivalent linear static analysis with the help of finite element software, ETABS. They tried to investigate the effect of sizes of shear wall openings by increasing the sizes of openings to 16 %, 30% and 36% and concluded that drift increases as the percentage of the openings increases. They also tried to investigate the effect of vertical location of openings by considering top, centered and bottom openings and finally concluded that the effect of location of openings on drift is not significant.

Pooja and Dr.SV Itti (2014) studied the effects of base openings in reinforced concrete shear walls. They analyzed a 5-storeyed shear wall using ANSYS software with wide opening at the lower storey only, and concluded that shear walls with symmetric wide openings at the base story performs better than eccentric openings when they are subjected to lateral loads. Hence eccentricity in the base opening must be avoided as far as possible.

Chowdhury et al. (2012) studied the effects of openings in shear wall on seismic response of structures using equivalent linear static analysis with help of ETBAS V9.6.0 software package. Their study revealed that stiffness as well as seismic responses of structures is affected by the size of the openings as well as their locations in shear wall. It is also concluded that more the area of opening more the displacements conceded by the building and this trend increases with increasing story level.

Elnashai and Sarno, (2008) states that If openings are very small, their effect on the overall state of stress in a shear wall is minor and SWs behave like monolithic cantilever columns. Large openings have more pronounced effect and if large enough results in a system in which typical frame action predominates. SWs with large openings behave as coupled walls under horizontal forces. The lateral deformability of coupled walls depends on the stiffness of connecting members. For example, each wall bends independently about its own axis for very flexible spandrels. Conversely, if rigid connecting members are present, coupled walls behave as a cantilever bending about a common centroid axis.

Architectural interests or clients' desires may lead, on the other hand, to location of openings in walls that are undesirable from a structural point of view. In collaborating with architects, however, structural engineers will often be in the position to advice as to the most desirable locations for structural walls, in order to optimize seismic resistance. Openings in walls are sometimes arranged in such a way that an extremely weak shear fiber results where inner edges of the openings lineup, as shown in Figure 2.5 (a). It is difficult to make such connections sufficiently ductile and to avoid early damage in earthquakes, and hence it is preferable to avoid such arrangement (Paulay and Priestley, 1992). A large space between the staggered openings would, however, allow an effective diagonal compression and tension field to develop after the formation of diagonal cracks as shown in Figure 2.5 (b).

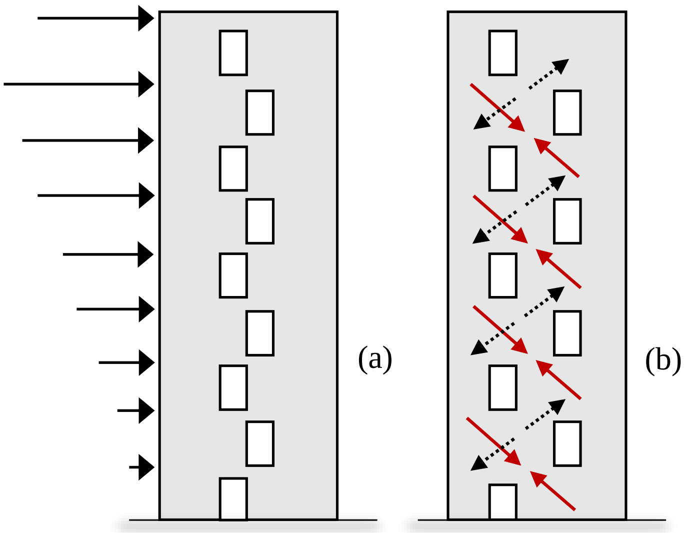


Figure 2.5: Shear strength of walls as affected by openings

2.7 Coupled Shear Wall Structures

Coupled shear wall is a continuous wall with vertical rows of openings created by windows and doors coupled by connecting beams. When two or more shear walls are interconnected by a system of beams or slabs, the total stiffness of the system exceeds the summation of the individual wall stiffness because the connecting slab or beam restraints the individual cantilever action by forcing the system to work as composite unit.

The load-resisting mechanisms in a coupled shear wall are shown qualitatively in Figure 2.6(b) and 2.6(c). It is seen that the total overturning moment, M, in the wall without openings shown in Figure 2.6 (a), is resisted at the base entirely by flexural stresses. On the other hand, in the coupled walls shown in Figure 2.6(b) and 2.6(c), axial forces as well as moments occur at the base to resist the overturning moment, M, resulting in the following equilibrium statement:

$$M = M_1 + M_2 + Td \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

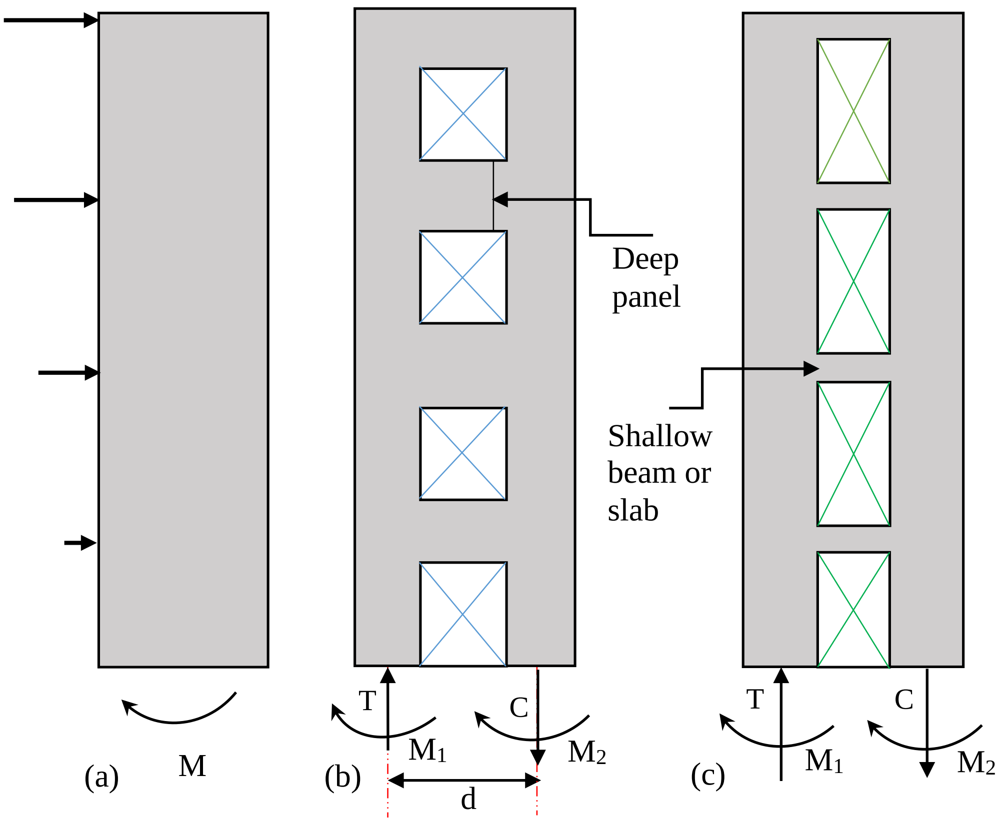


Figure 2.6: Lateral load-resistance of single and coupled shear walls

Designers sometimes face dilemma, particularly when considering shear strengths, as to whether they should treat coupled walls, such as shown in Figure 2.6(b) and 2.6(c), as two walls interconnected or as one wall with a series of openings. The issue may be resolved if one considers the behaviour and mechanism of resistance of a cantilever wall and compares these with those of coupled walls. These aspects are shown qualitatively in Figure 2.6, which compares the mode of flexural resistance of coupled walls with different strength coupling beams with that of a simple cantilever wall (Paulay and Priestley, 1992).

The magnitude of the axial force, T = C, is given by the sum of the shear forces occurring in the coupling beams above the level under consideration. When the coupling is relatively weak, as is often the case in apartment buildings because of limited beam depth, the major portion of moment resistance is due to moment components. On the other hand, if coupling beams are stiff, major moment resistance is by the couple generated by the equal and opposite axial forces in the wall piers.

2.8 Coupling Beams

Coupling beams can be defined as a connector between two or more vertical shear walls separated by regular openings created by windows or doors at each storey level along the shear wall height (Marsono, 2000). At lateral loaded state, shear walls undergo different movement between supporting ends. The coupling beams in between actually constraint the walls to deflect similarly and will be subjected to flexural, shear or combination of both types of deformation, as the beams are required to connect the walls and transfer forces between them. Local failure of coupling beams may lead to a more serious global failure of the whole lateral load resisting system of the building.

Oftentimes, coupling beams are deep in relation to their clear span resulting in their design being controlled by shear. They may be susceptible to strength and stiffness deterioration under severe earthquake loading. The ACI Code 318-89 (2000) defines a deep beam as a beam in which the ratio of the clear span l to the overall depth h is less than the limits 1.25 for simple spans and 2.5 continuous spans, while ES EN 1998-1-1:2015 clause 5.3.1 (3) states deep beam as a beams having an effective span/depth ratio (l/d) of less than 3.

Because diagonally oriented reinforcement is effective only if the bars are placed with large inclination, diagonally reinforced coupling beams are restricted to beams having an aspect ratio of $l/h < 4$ (Taranath, 1998). The design requirements for coupling beams with aspect ratio $l_n/d \geq 4$ shall satisfy the requirements of normal conventional beams. Coupling beams with aspect ratio $l_n/d < 4$ shall be permitted to be reinforced with two intersecting groups of diagonally placed bars symmetrical about the mid span.

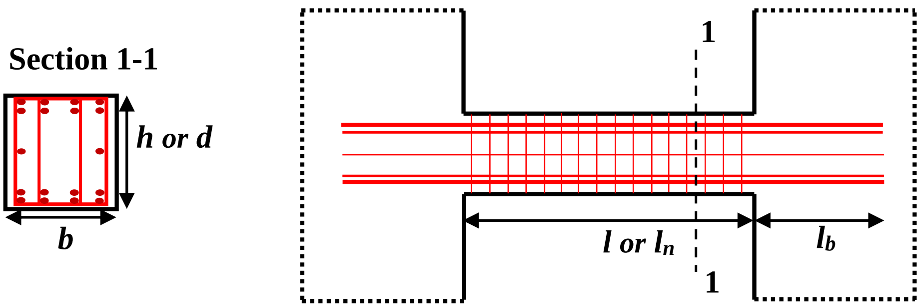


Figure 2.7: Typical conventionally reinforced coupling beam

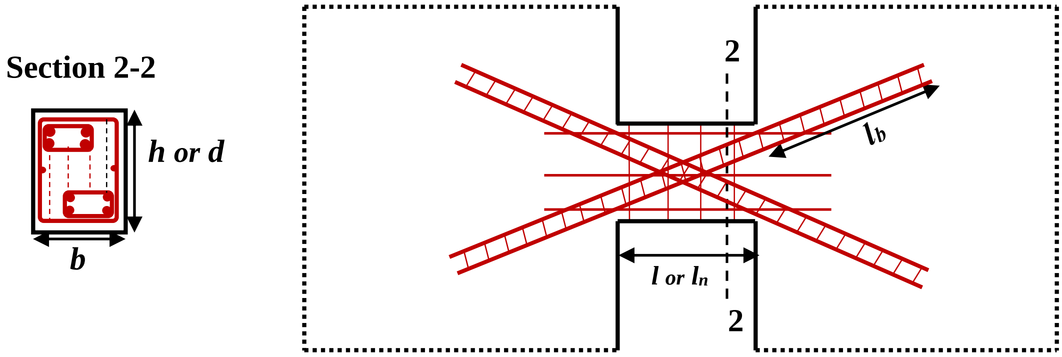


Figure 2.8: Typical diagonally reinforced coupling beam

For in-plane loading of coupled shear walls, coupling beams are subjected to extremely large rotational demands and shear deformations as a consequence of their short length. To prevent excessive strength degradation in such elements, special detailing measures are adopted using diagonal reinforcement as shown in Figure 2.8. In fact, it may be said that the coupling beams in high-rise buildings are designed for the most severe loading condition of any element within a concrete structure (Taranath, 2010).

2.8.1 A Review on Effective Stiffness of Coupling Beams

When analyzing a structural wall, it is important to model appropriately the cracked section stiffness of the wall and any coupling elements, as this stiffness determines the building periods, base shear, story drifts, and internal force distributions (Moehle et al., 2011). Earthquake actions depend strongly on deformation behavior and effective stiffness of structural members (Christian Greifenhagen, 2006). The following is a review on formulas used to determine the effective stiffness of coupling beams provided by different international codes and books.

2.8.1.1 EN 1998-1, (2004) and ES EN 1998-1-1, (2015)

Both Eurocode (EN 1998-1:2004) and the new Ethiopian Building Code Standard (ES EN 1998-1-1:2015) recommends the effective flexural and shear rigidity of reinforced concrete elements as 0.5Ig at ultimate limit state level. The factor 0.5 is a factor which takes in to account the effect of cracking and is applicable for all types of flexural reinforced concrete members. However, coupling beams needs further reduction in stiffness due to their squat behaviour.

2.8.1.2 American Concrete Institute Code, ACI-318-11 (2000)

ACI 318 (2000) provides the same effective stiffness values for frame and wall elements. But, this may be not appropriate for typical coupling beams as those are expected to sustain damage and concentrated end rotations associated with reinforcement slip from anchorage zones within the wall boundary before significant yielding occurs in walls, leading to further stiffness reduction. According to this building code, the effective flexural rigidity at ultimate state of concrete walls can be taken as 0.7Ig for uncracked sections and 0.35Ig for cracked sections. Another alternative way for estimating the effective stiffness of flexural members recommended by ACI 318-11 (2000) is;

$$\mathrm{Ie} = \begin{cases} (0.1 + 25\rho_s)\,(1.2 - 0.2\ \mathrm{b/d}\ )\ \mathrm{I_g} & \leq 0.5\mathrm{I_g} \\ 0.35\mathrm{I_g} & \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2.2)$$

Where ρ_s is the longitudinal reinforcement ratio, and b and d are the width and depth of the members respectively, I_e = is the effective moment of inertia of the members and I_g = is the gross moment of inertia of the members . The Iranian standards guidelines, also uses the same formula as those of ACI for estimating the effective flexural rigidity of reinforced concrete elements.

2.8.1.3 Standard of New Zealand, NZS 3101: Part-2(1995)

The Standard of New Zealand, NZS 3101 (1995) specifies an equation to estimate the effective stiffness of conventionally reinforced coupling beams (CCBs) solely as a function of the aspect ratio.

$$\text{For CCBs} \qquad I_e = \frac{0.4 I_g}{1 + 8\left(\frac{h}{l}\right)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2.3)$$

Where; h = depth of coupling beam (Figure 2.7)

l = length of coupling beam (Figure 2.7)

The standard also provides an equation estimating the effective stiffness of Diagonally reinforced coupling beams (DCBs) that depends on the aspect ratio and the expected ductility demand, μ as shown on equation (2.4) to equation (2.6) below.

$$For\ \mu_\Delta = 1.25 \qquad \mathrm{I_e} = \frac{\mathrm{I_g}}{1.7 + 1.3\left(\frac{h}{l_n}\right)^2} \ldots\ldots\ldots\ldots\ldots\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2.4)$$

For $\mu_{\Delta} = 3$ $$I_e = \frac{0.7I_g}{1.7 + 2.7\left(\frac{h}{l_n}\right)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.5)$$

For $\mu_{\Delta} = 6$ $$I_e = \frac{0.4I_g}{1.7 + 2.7\left(\frac{h}{l_n}\right)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.6)$$

Where l_n = length of coupling beam (Figure 2.8)

h = *depth of coupling beams (Figure* 2.8)

2.8.1.4 Canadian Concrete Design Handbook, CSA: A23.3-94 (2005)

The Canadian Concrete Standard, CSA (2005) recommends to use two different formulas in estimating the effective cracked stiffness of CCBs and DCBs such that DCBs are generally presumed to be somewhat stiffer than CCBs.

For CCBs, $$I_e = \frac{0.4I_g}{1 + 3\left(\frac{d}{l}\right)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.7)$$

Where d = depth of coupling beam

l = length of coupling beam

With respect to the uncracked stiffness, Equation 2.7 above can be modified by eliminating the factor 0.4 which takes into account the effect of cracking.

The code suggests that diagonally reinforced coupling beams (DCB) are twice as stiff as conventionally reinforced coupling beams:

For DCBs $$I_e = \frac{0.4I_g}{1 + 8\left(\frac{d}{l}\right)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.8)$$

Where d = depth of coupling beam

l = length of coupling beam

2.8.1.5 Taranath (1998)

Taranath (1998) provided an equation to calculate the effective stiffness of RC coupling beams of shear walls that take into account the effect of shear deformation in RC coupling beams as follows:

$$I_e = \frac{I_g}{1 + 2.4\left(\frac{d}{l}\right)^3 (1 + \nu)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.9)$$

Where d = depth of coupling beam

l = length of coupling beam

ν = Poissons ratio of concrete

2.8.1.6 FEMA-356 *(Nov. 2000)*, ATC-40 *(1996)* and ASCE-41(2007)

According to FEMA-356 (2000), component stiffness's shall be calculated considering shear, flexure, axial behavior and reinforcement slip deformations. Consideration shall be given to the state of stress on the component due to volumetric changes from temperature and shrinkage, and to deformation levels to which the component will be subjected under gravity and earthquake loading. Alternatively, FEMA-356 (2000) and ATC-40 (1996) recommend to use the effective stiffness values in Table 2.1.

Table 2.1:Effective stiffness values of reinforced concrete walls

Component	Flexural Rigidity	Shear Rigidity	Axial Rigidity
Wall-uncracked (on inspection)	$0.8E_cI_g$	$0.4E_cA_w$	E_cA_g
Walls-cracked	$0.5E_cI_g$	$0.4E_cA_w$	E_cA_g
Coupling Beams	$0.5E_cI_g$	$0.4E_cA_w$	-

Where E_c = elastic modulus of elasticity of concrete

I_g = Gross moment of inertia of the section

A_w = Effective shear area of the section

A_g = Gross cross sectional area of the section

For shear stiffness, the quantity $0.4E_c$ has been used to represent the shear modulus, G. To obtain a proper distribution of lateral forces in bearing wall buildings, all of the walls shall be assumed to be either cracked or uncracked. In buildings where lateral load resistance is provided by either structural walls only, or a combination of walls and frame members, all shear walls and wall segments discussed in this section shall be considered to be cracked. For coupling beams, the effective stiffness values given in Table 2.1 above shall be used unless alternative stiffness's are determined by more detailed analysis.

According to ATC-40 (1996), the effective initial stiffness may be based on the approximate values of Table 2.1 above. ASCE-41 (2007) suggests to use a lower value of effective stiffness of coupling beams than the value recommended by FEMA-356 (2000) and ATC-40 (1996). The recommended value is $0.3E_CI_g$.

However, the revised ATC-72 (2010) suggests that the effective stiffness of coupling beams should further be reduced because of concentrated end rotations associated with reinforcement slip from anchorage zones within the wall boundary. This code recommends to take $E_cI_e = 0.15E_cI_g$, with shear deformations calculated based on, shear rigidity, $G_c = 0.4E_c$ for $l_n/h \geq 2$ and $Gc = 0.1Ec$ for $l_n/h \leq 1.4$, with linear interpolation for intermediate aspect ratios.

2.8.1.7 Paulay and Priestley (1992) and Park and Paulay (1935)

Park and Paulay (1935) have tested both CCBs and DCBs against lateral loads. The results obtained from the experiments almost agree with the results obtained from the theoretical formulas they have recommended for estimating the effective stiffness of both conventionally and diagonally reinforced coupling beams. The theoretical formulas they used to predict the effective stiffness of CCBs and DCBs are almost similar to those of CSAs recommendations.

For CCBs, $$I_e = \frac{0.2I_g}{1 + 3\left(\frac{d}{l}\right)^2} \qquad (2.10)$$

For DCBs, $$I_e = \frac{0.4I_g}{1 + 8\left(\frac{d}{l}\right)^2} \qquad (2.11)$$

Where; d=depth of the coupling beam and l=clear span of the coupling beam

Paulay and Priestley (1992) use the same formulas as that of Park and Paulay (1935) and hence the Canadian Concrete Standard, CSA (2005) in estimating the effective stiffness of both conventionally and diagonally reinforced concrete coupling beams.

2.8.1.8 Robert E. Englekirk (2003)

According to Englekirk R.E. (2003), the effective moment of inertia (I_e) for a shear wall is 50% of the gross moment of inertia (I_g), and this is consistent with the experimental evidence provided by different tests. But, for coupling beams, Robert E. Englekirk recommends to use the effective stiffness formulas suggested by CSA and Paulay and Priestley for both conventionally reinforced coupling beams (CCBs) and diagonally reinforced coupling beams (DCBs).

2.9 Modelling and Analysis of Shear Walls with Openings

2.9.1 Modelling of Shear Walls with Openings

One method of modelling coupled shear walls for analysis is equivalent frame method (Smith and Coull, 1991). This requires the modeling of the interaction between the vertical shear walls and the horizontal connecting beams (coupling beams).

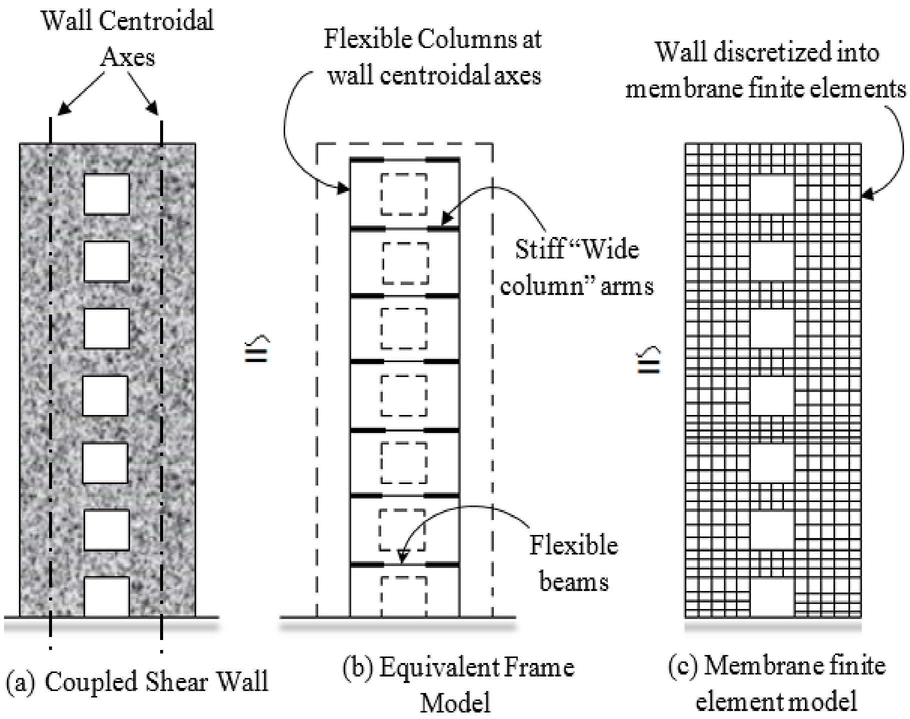


Figure 2.9: Modelling techniques of the coupled shear walls

In this method, the wall can then be represented by an equivalent column located at the centroidal axis, to which is assigned the axial rigidity EA and flexural rigidity EI of the wall. The rigid arms insure that the correct rotations and vertical displacements are produced at the edges of the walls.

The connecting beams (coupling beams) may be represented as line elements in the conventional manner, and assigned the correct axial, flexural and if necessary, shearing rigidities. Generally, shearing deformations should be included if the beam length/depth ratio is less than about 5. The coupled shear wall in Figure 2.9(a) may then be represented by the analogous wide column plane frame model shown in Figure 2.9 (b).

For most practical coupled shear walls structures, the equivalent frame technique will be the most versatile and accurate analytical method (Smith and Coull, 1991). In certain cases, however, notably with very irregular openings, such as those shown in Figure 2.10, or with complex support conditions, it may prove difficult to model the structure with any degree of confidence using a frame of beams and columns. In that case, the use of membrane finite elements is the only feasible alternative as shown in Figure 2.9(c).

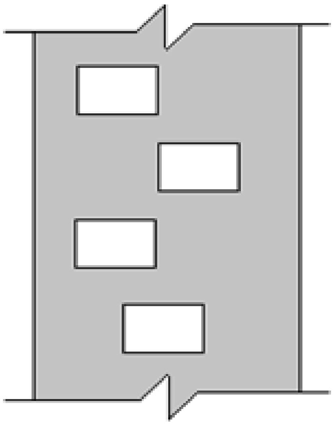


Figure 2.10: Shear wall with irregular Openings

2.9.2 Methods of Analysis

The equivalent static load type of analysis is suitable for the majority of the high-rise structures. If, however, either the lateral load resisting elements or the vertical distribution of mass are significantly irregular over the height of the building, an analysis that takes greater consideration of the dynamic characteristics of the building must be made (Smith and Coull, 1991). Usually, in such cases, a modal analysis will be appropriate. According to ES EN 1998-1:2015, there are two types of elastic analysis for determining the seismic effects depending on the structural characteristics of the building. These are:

- ✓ *Equivalent Static analysis*: For building that satisfies the criteria for regularity in plan & elevation. Additionally, the buildings should have fundamental periods of vibration in the two main directions less than 2 seconds.
- ✓ *Dynamic analysis*: It is applicable to all types of buildings.

2.9.2.1 Modal Response Spectrum Analysis

The purpose of modal analysis is to obtain the maximum response of the structure in each of its important modes, which are then summed in an appropriate manner. This maximum modal response can be expressed in several ways. In practice, the SRSS or the CQC is used for this purpose. In SRSS rule, the peak response in each mode is squared, the squared modal peaks are summed, and the square root of the sum provides an estimate of the peak total response as expressed on Equation 2.12.

$$r_o \cong \left(\sum_{n=1}^{N} r_{no}^2 \right)^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (2.12)$$

The SRSS of the modal quantities is typically used for its simplicity and its wide familiarity. This modal combination rule provides excellent response estimates for structures with well-separated natural frequencies (Chopra, 1995). In general, it gives satisfactory results, but, the most common instance where combination by the use of the SRSS is unconservative occurs when two modes have very nearly the same natural period. The CQC technique provides somewhat better results than the SRSS method for the case of closely spaced modes.

This limitation has not always been recognized in applying this rule to practical problems, and at times it has been misapplied to systems with closely spaced natural frequencies, such as piping systems in nuclear power plants and multistory buildings with unsymmetrical plan. The *complete quadratic combination* (CQC) rule for modal combination is also applicable to a wider class of structures as it overcomes the limitations of the SRSS rule. According to the CQC rule;

$$r_o \cong \left(\sum_{i=1}^{N}\sum_{n=1}^{N} \rho_{in} r_{io} r_{no}\right)^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.13)$$

Each of the N^2 terms on the right side of this equation is the product of the peak responses in the i^{th} and n^{th} modes and the correlation coefficient ρ_{in} for these two variables; ρ_{in} varies between 0 and 1 and $\rho_{in} = 1$ for $i = n$. Thus, the above equation can be rewritten as (Chopra A.K., 1995):

$$r_o \cong \left(\sum_{n=1}^{N} r_{no}^2 + \underbrace{\sum_{i=1}^{N}\sum_{n=1}^{N}}_{i \neq n} \rho_{in} r_{io} r_{no}\right)^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.14)$$

CHAPTER 3: METHODOLOGY

3.1 General

This section mainly focuses on the methods and materials used to conduct this research. This study mainly includes theoretical discussions and computer modeling and analysis works in order to study the effects of openings on seismic behaviour of reinforced concrete shear walls. Due to the unavailability of testing machines and economic constraints, experimental investigation required for this particular study was not covered in this thesis. Shear walls on 40/60 saving house projects (having single and two bands of door and window openings) were selected as a case study. A three dimensional finite element model is developed with the help of ETABS15.2.2, finite element software package. The results obtained from modal response spectrum analysis of all shear wall models were discussed with respect to the seismic response parameters such as lateral displacement, story drift, base shear and shell's internal force distributions.

3.2 Preliminary Study

The research methodology was started with problem identification on reinforced concrete shear walls and setting up the objectives and scope of the study. After the problem was identified, a preliminary study (desk study) was done by visiting different design offices and observing different reinforced concrete high-rise buildings to identify the types, sizes and locations of openings in reinforced concrete shear walls commonly practiced in Ethiopia. Coupled reinforced concrete walls contains openings to accommodate doors and/or windows and structural walls that houses lift shafts usually contains door openings. During the preliminary study, the types of coupled structural walls commonly practiced in Ethiopia were confirmed to be shear walls with single band of door and/or window openings and shear walls with two and sometimes three or more bands of window and/or door openings. Some of the buildings visited were 40/60 saving house projects and the shear walls on 22-storied 40/60 saving house projects (which contains both window and door openings with single and two bands of stacked openings), were selected as a case study for modeling and analysis purposes.

In this stage, several references were also used to obtain some information that are related to the area of interest, such as literatures from the previous researchers and plan and detail drawings of the shear walls on 40/60 saving house projects. The literature review involved interpreting and synthesizing what has been researched and published in the area of interest.

This was done by reading on what other people have previously written about the area of interest. In this study, the main sources of literature review are from journals, articles, conference papers and books. Since the issue (i.e. the effect of openings on seismic behavior of reinforced concrete shear walls) is quite new in Ethiopia, there are limited published documents from the local authorities. Therefore, all the articles are referred mainly from the Journals of Structural Engineering published by different society of civil engineers. This gives the valuable information to support or refute the arguments stated and the findings of the study. Besides, the literature review for the basic theory of structural modelling and analysis of reinforced concrete shear walls is mainly from books.

3.3 Materials Used

As mentioned above, due to the unavailability of testing machines in Ethiopia and economic constraints, experimental investigations required for this particular study was not covered in this thesis. As mentioned above, the shear walls on 22-Storied 40/60 saving house projects were used as a case study for modeling and analysis purposes. There are three types of shear walls in those projects as shown in Figure 4.1: shear wall with single band of window opening (SW1), shear wall with single band of door openings (SW2) and shear wall with two bands of stacked door openings (SW3). All shear wall models were modeled with the help of ETABS15.2.2, finite element software package, and using C20/25 concrete material.

The basic parameters used for this study were the size and location of shear wall openings. These parameters were first considered on the 22-storied shear walls mentioned above and then on 10-storied and 40-storied models in order to get more strong conclusions. All other parameters were kept constant to investigate the real effect of the required parameters. Table 3.1 shows the existing shear walls on 22-storied 40/60 saving house projects.

Table 3.1: Existing shear wall on 40/60 saving house projects

Parameters	SW1	SW2	SW3
Material	C20/25		
Length of the wall (mm)	6100	4650	6100
Thickness of wall (mm)	300	300	300
Floor to floor height (mm)	3200	3200	3200
Types of openings	Window	Door	Door
No of bands of openings	One	One	Two
Size of openings (mm)	1250X1500	800X2100	1200X2100
% of openings per storey wall area	9.61%	11.29%	25.82%
Initial location of openings	Asymmetric	Asymmetric	Symmetric
Asymmetry of openings (mm)	1825	1425	0

The 22-Storied shear wall models on Table 3.1 were used to study the effect of location of openings on the seismic behavior of reinforced concrete shear walls by changing the initial location of openings to asymmetric, symmetric and staggered locations. These shear walls were again used to study the effect of size of openings by using smaller or larger sizes of openings as discussed in Chapter 4. The study was then conducted in 10-storied and 40-storied reinforced concrete shear wall models in order to get more comprehensive conclusions.

The Shear walls selected in this study are assumed as if they were located in the highly seismic zone of Ethiopia (i.e. zone 5). The selection of the case study fits the area of interest, as the types of shear walls in those buildings almost represent the types of coupled reinforced concrete shear walls commonly practiced in many reinforced concrete buildings (i.e. walls with single and/or double bands of window and/or door openings). Drawings and shear wall design documents from 40/60 saving house projects provide many information: such as, size and location of existing openings, thickness of the shear walls and the material used to model the walls. The information obtained is used as an input data in ETABS15.2.2, structural finite element analysis software.

3.4 Procedures Used

After the scope, aim and objectives of the project were identified and methodology to conduct the research was planned, preliminary study was conducted, modeling and analysis of all sample wall models was carried out using ETABS15.2.2. The lateral loads were assigned according to ES EN1998-1:2015's provisions. The general ETABS procedures used during modeling and analysis of all shear wall models are briefly listed below.

1. *Defining material and section properties*: All shear wall models were defined using the geometric and material properties shown in Table 3.1. Shell element was used to define all shear walls.
2. *Drawing wall elements including openings*: The walls were drawn using shell element and the material and section properties defined before. Corresponding openings were also provided for each of the models.
3. *Defining modal response spectrum functions*: modal response spectrum parameters discussed in Chapter 4 of this thesis were used as an input in ETABS15.2.2. Ground type B and soil factor, S=1.2 were used for spectrum type 1 as discussed in Chapter 4. The values of T_B, T_C and T_D describing the shape of elastic response spectrum depends upon the ground type and are 0.15, 0.5 and 2.0 respectively for response spectrum type 1 and

ground type and soil factor mentioned above. 5% constant damping was used during defining the response spectrum functions in both horizontal directions. Ground acceleration ratio, a_g=0.2g and lower bound factor, Beta=0.2 with category of importance factor, $\gamma_i = 1.0$ were also used during defining the response spectrum function.

4. *Defining minimum number of modes*: The minimum number of modes taken into account for the 10-storied, 22-storied and 40-storied shear wall models are 10, 15 and 19 respectively as determined in Chapter 4.
5. *Defining load patterns and load cases*: The seismic load patterns (RSX and RSY) were defined in both orthogonal direction according to ES EN-1-1:2015's provisions discussed above and damping correction factor λ =1. The "*Complete Quadratic Combination"* (CQC) was used for combination of the response of different modes and *square-root-of-sum-of-squares* (SRSS) was used for directional combination of the modes as discussed in Chapter 4.
6. *Meshing of the wall element*: All shear wall models were discretized in to finite elements. The property assignments to meshed area objects are the same as the original area object. Load and mass assignments on the original area object are appropriately broken up onto the meshed area objects.
7. *Defining and assigning piers and spandrels*: Piers and spandrels were defined and assigned for each shear walls and auto line constraint was assigned to each wall elements of all models.
8. *Structural modeling and Analysis*: Different international codes have been discussed and compared in determining the stiffness of shear walls with openings. After effective stiffness of the shear wall components (Piers and Coupling Beams) and lateral loads were assigned to the models, modal response spectrum analysis was carried out with the help of ETABS15.2.2 software package to identify the effects of openings on seismic responses of reinforced concrete shear walls.

After the analysis was completed, comparison of the models of each shear wall was made based on the results obtained with respect to lateral displacement, storey drift, base shear, and shell's internal force distributions using tables and/or graphs for more clarity. Finally, conclusion was drawn and recommendation was suggested for future studies. Figure 3.4 shows the summary of the methodology used during the study.

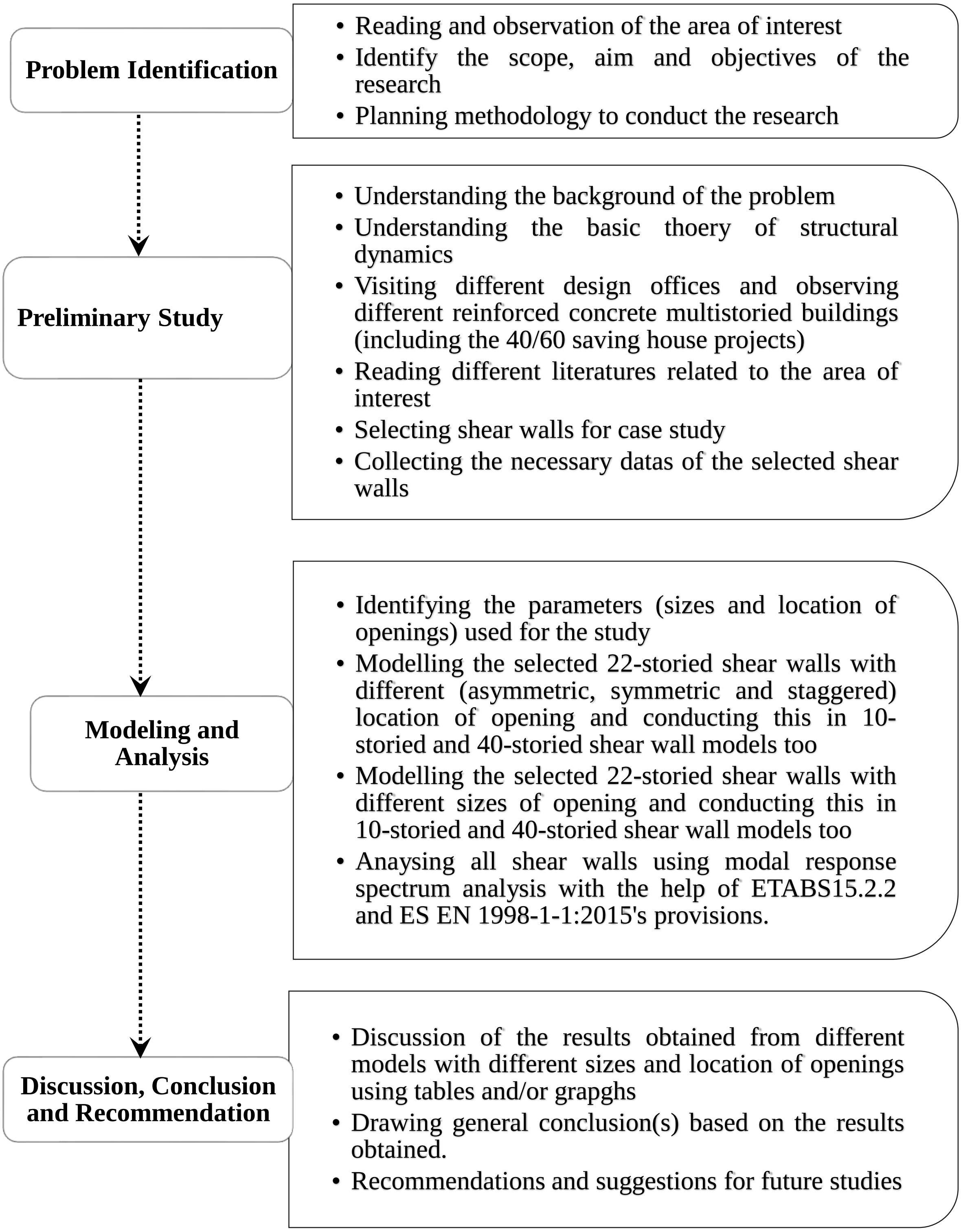


Figure 3.1: Summary of methodology for the study

CHAPTER 4: MODELLING AND ANALYSIS

4.1 General

There are lots of engineering soft wares that can be used for modelling, analyzing and designing of structures in civil engineering field. Among those, ETABS15.2.2 is one of the powerful software packages that is used for modeling, analyzing and designing of particularly building structures. Using ETABS15.2.2, structural engineers can analyze and design almost any type of Complex building structure with less time and error. As previously mentioned in Chapter 3, ETABS15.2.2 was used for modeling and modal response spectrum analysis of the selected case studies. The architectural design usually requires introducing openings in to the solid cantilever shear walls to accommodate door, window or other functional requirements. The basic parameters used in this particular study were the sizes (percentage per storey wall area) and location of openings in reinforced concrete shear walls.

4.2 Description of the Case Study

The types of coupled shear wall systems may differ from building to building due to different functional requirements of the openings provided in coupled wall system. Most of the time, openings are provided to accommodate doors and/or windows. As mentioned in Chapter 3, the types of reinforced concrete shear wall commonly practiced in Ethiopia were found to be either solid walls without any openings or coupled reinforced concrete walls with single or more bands of door and/or window openings. However, in some reinforced concrete buildings, it is sometimes common to see reinforced concrete walls with staggered types of openings.

The sample models selected for this particular study were the shear walls in 22-storied 40/60 saving house projects. There are three different types of reinforced concrete shear walls used in these reinforced concrete apartment building as shown in Figure 4.1. The first reinforced concrete shear wall, Shear Wall 1 (SW1), is a structural wall with asymmetrical (offset) single band of window openings as shown in Figure 4.1 (a). The depth and width of those window openings are 1500mm and 1250mm respectively which are located 1825mm to the left of the vertical axis of the wall as shown in Figure 4.1(d).

The second type of shear wall, Shear Wall 2 (SW2), is a coupled shear wall with non-symmetrical (offset) single band of door openings. The height and width of those door openings are 2100mm and 800mm respectively which are located 1425mm to the right of the vertical axis of the wall as shown in Figure 4.1 (e).

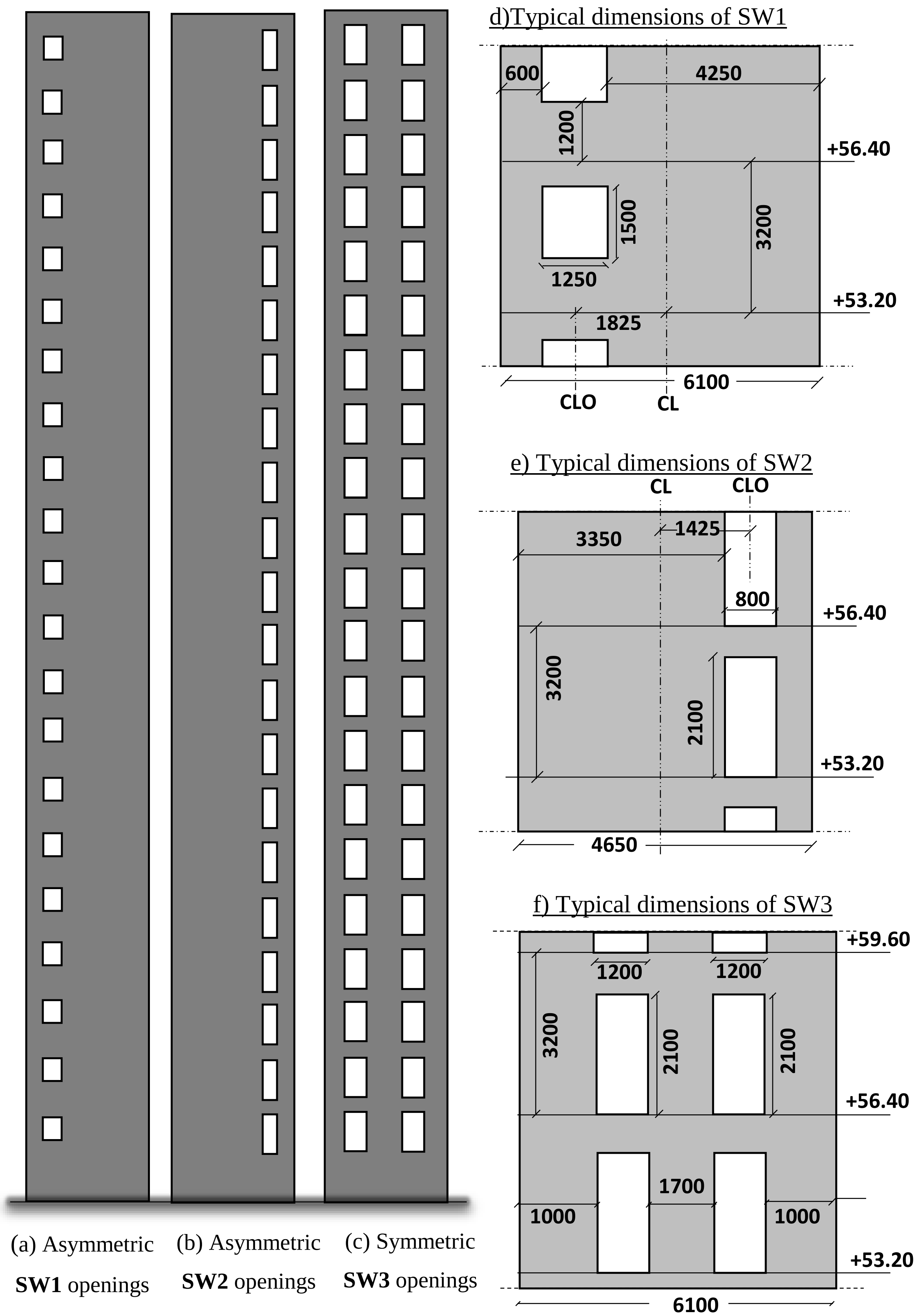


Figure 4.1: Existing shear walls on 22-storied 40/60 saving house projects

The third types of shear wall, Shear Wall 3 (SW3), used in this building is coupled reinforced concrete shear walls with two bands of stacked door openings which houses lift shafts as shown in Figure 4.1(c). These door openings have height of 2.1m and width of 1.2 m each as shown in Figure 4.1 (f). The thickness of all shear walls is 300mm.

4.3 Description of the Sample Shear Wall Models

In this study, the three reinforced concrete shear walls with different types of openings: SW1, SW2 and SW3 were categorized in to two main group of models, depending on the location or arrangements and sizes of its openings.

The first group of models was used to study effects of horizontal location of openings on seismic behaviour of reinforced concrete shear walls as shown in Table 4.1. The locations considered were asymmetric (ASYM), symmetric (SYM) and staggered (STGRD) arrangements with respect to the vertical axis of the wall. In this thesis, the words ‘centered’ and ‘symmetric’ may sometimes be used interchangeably. Similarly, the words ‘asymmetric’, ‘offset’ and ‘right or left aligned’ may also be used interchangeably. For each shear wall models, the corresponding solid shear wall without any opening was considered for comparison purposes.

Table 4.1: Models for investigating the effects of location of shear wall openings

Sizes of Openings	SW1	SW2	SW3
Solid shear walls *without* any openings	SW1-SLD	SW2-SLD	SW3-SLD
Shear walls with *Asymmetric* location of openings	SW1-ASYM	SW2-ASYM	SW3-ASYM
Shear walls with *Symmetric* location of openings	SW1-SYM	SW2-SYM	SW3-SYM
Shear walls with *Staggered* location pf openings	SW1-STGRG	SW2-STGRD	SW3-STGRD

For SW1, the asymmetry of the openings for **SW1-ASYM** was considered to be 1825mm (to the left of the vertical axis of the wall) as shown in Figure 4.3(a). Similarly, for **SW1-STGRD**, the asymmetry of the openings is 1825mm to right of the vertical axis of the wall in the bottom story and 1825mm to the left of the vertical axis of the wall in the story above the bottom story. This arrangement was used throughout the height of the wall giving the staggered arrangement of openings shown in Figure 4.3(a).

For SW2, the asymmetry of the openings for **SW2-ASYM** was considered to be 1425mm (to the right of the vertical axis of the wall) as shown in Figure 4.1(e) or Figure 4.4 (a). Similarly, for **SW2-STGRD**, the asymmetry of the openings is 1425mm to left of the vertical axis of the wall in the bottom story and 1425mm to the right of the vertical axis of the wall in the story above the bottom story. This arrangement was used throughout the height of the wall giving the staggered arrangement of openings shown in Figure 4.4(a).

For SW3, the model with symmetric openings (**SW3-SYM**) has the same opening configuration as the existing SW3 as shown in Figure 4.1(f). The asymmetry of the openings for **SW3-ASYM** and **SW3-STGRD** is shown in Figure 4.2(a) and Figure 4.2(b) respectively. The asymmetry of those openings is 950mm (i.e. the distance between the center of those openings (CLO) and vertical axis of the wall (CL)).

a) SW3-ASYM **b) SW3-ASYM**

Figure 4.2: Opening configuration for SW3-ASYM and SW3-STGRD

The second group of models were used to study the effects of size of openings on the seismic behaviour of reinforced concrete shear walls. Walls with small, medium, large and very large openings relative to the story wall area were considered for this study as shown in Figure 4.3(b), 4.4(b) and 4.5 (b). Table 4.2 shows the models considered to study the effect of sizes of openings on seismic behavior of reinforced concrete walls. For each shear walls, a shear wall with different sizes of symmetric openings which gradually increase from the lower story to uppermost story of the wall were also considered as shown in Figure 2.6.

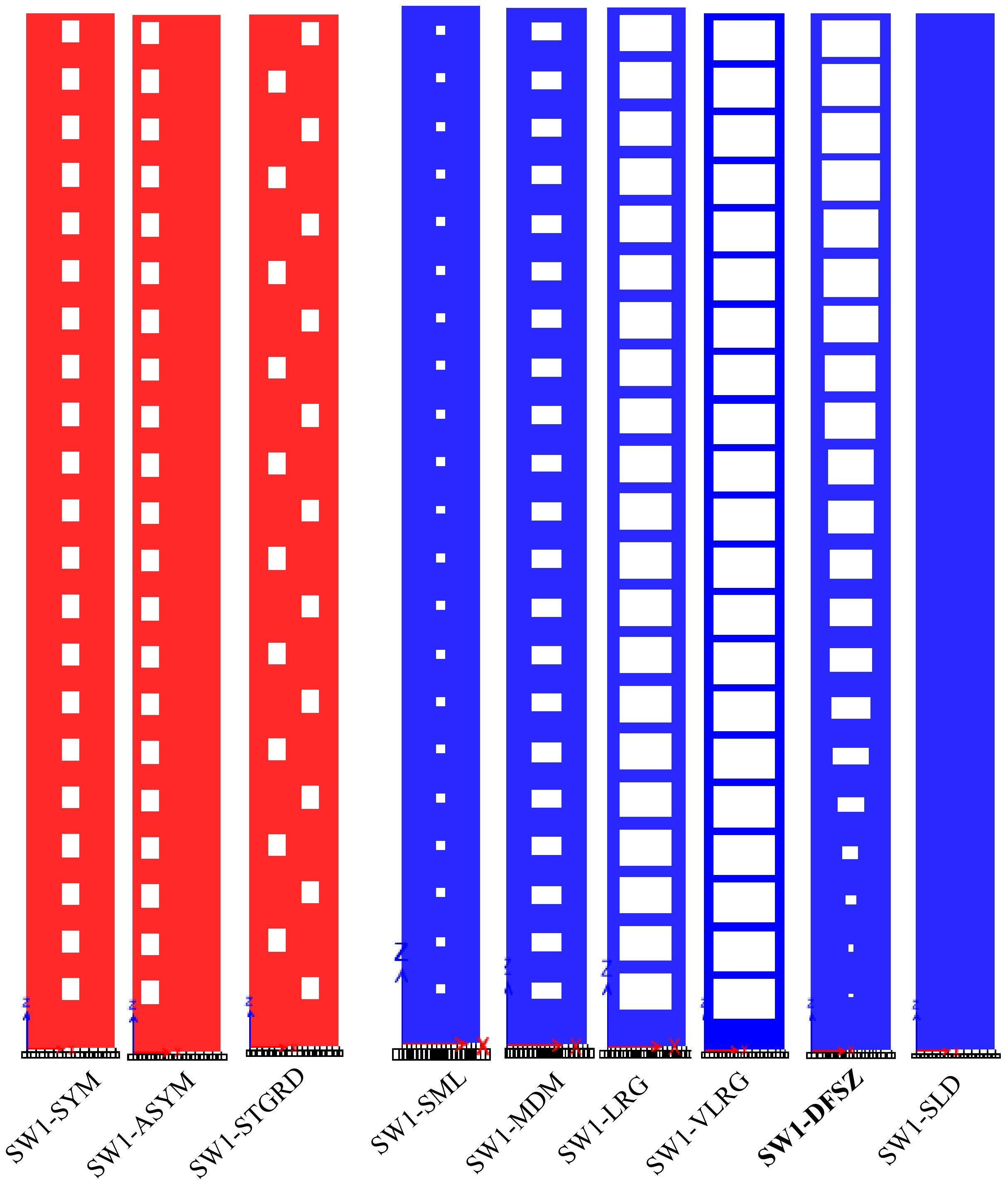
The reason to consider the shear wall with different sizes of symmetric openings, which gradually increases from bottom storey to topmost storey ***(DFSZ)***, is the need for good shear wall-frame interaction due to reduced or totally curtailed shear walls above a point on which the shear wall is not effective in reducing the seismic responses. Shear walls shall be curtailed or reduced above a point on which the shear wall is not effective in reducing the seismic responses of a building. However, curtailing shear wall at a specific storey may cause stiffness and mass irregularities. The question is therefore how can this reduction or curtailment can be carried out. In this thesis, a new shear walls reduction technique which eliminates or minimizes stiffness and mass irregularity is introduced by using very small or no opening at the bottom storey of the shear walls and then gradually increasing the sizes of the openings along the height of the shear walls as the DFSZ models in Figure 4.3 (b), 4.4 (b), 4.5(b) and Figure 4.6 and Table 4.3. Table 4.2 shows models with different sizes of different shear wall openings and their corresponding percentage per storey wall area.

Table 4.2: Models for investigating the effects of sizes of shear wall openings

Sizes of Openings	Models					
	SW1 (6100 X 3200)		SW2 (4650 X 3200)		SW3 (3200 X 6100)	
Shear walls with *small* sizes of openings	**SW1-SML**					
	Size	600x800				
	%	2.5				
Shear walls with relatively *medium* sizes of openings	**SW1-MDM**		**SW2-MDM**		**SW3-MDM**	
	Size	1200x2400	Size	800*2100	Size	1600*2100
	%	14.8	%	11.2903	%	17.2131
Shear walls with *large* size of openings	**SW1-LRG**		**SW2-LRG**		**SW3-LRG**	
	Size	2400x4000	Size	2800*2650	Size	3600*2800
	%	49.2	%	49.8656	%	51.6393
Shear walls with *very large* size of openings	**SW1-VLRG**					
	Size	2800*4900				
	%	70.3				

For each of the three 22-storied shear wall models, additional solid shear walls (without opening) were considered for comparative purposes. The names of the models were SW1-SLD, SW2-SLD and SW3-SLD for SW1, SW2 and SW3 respectively.

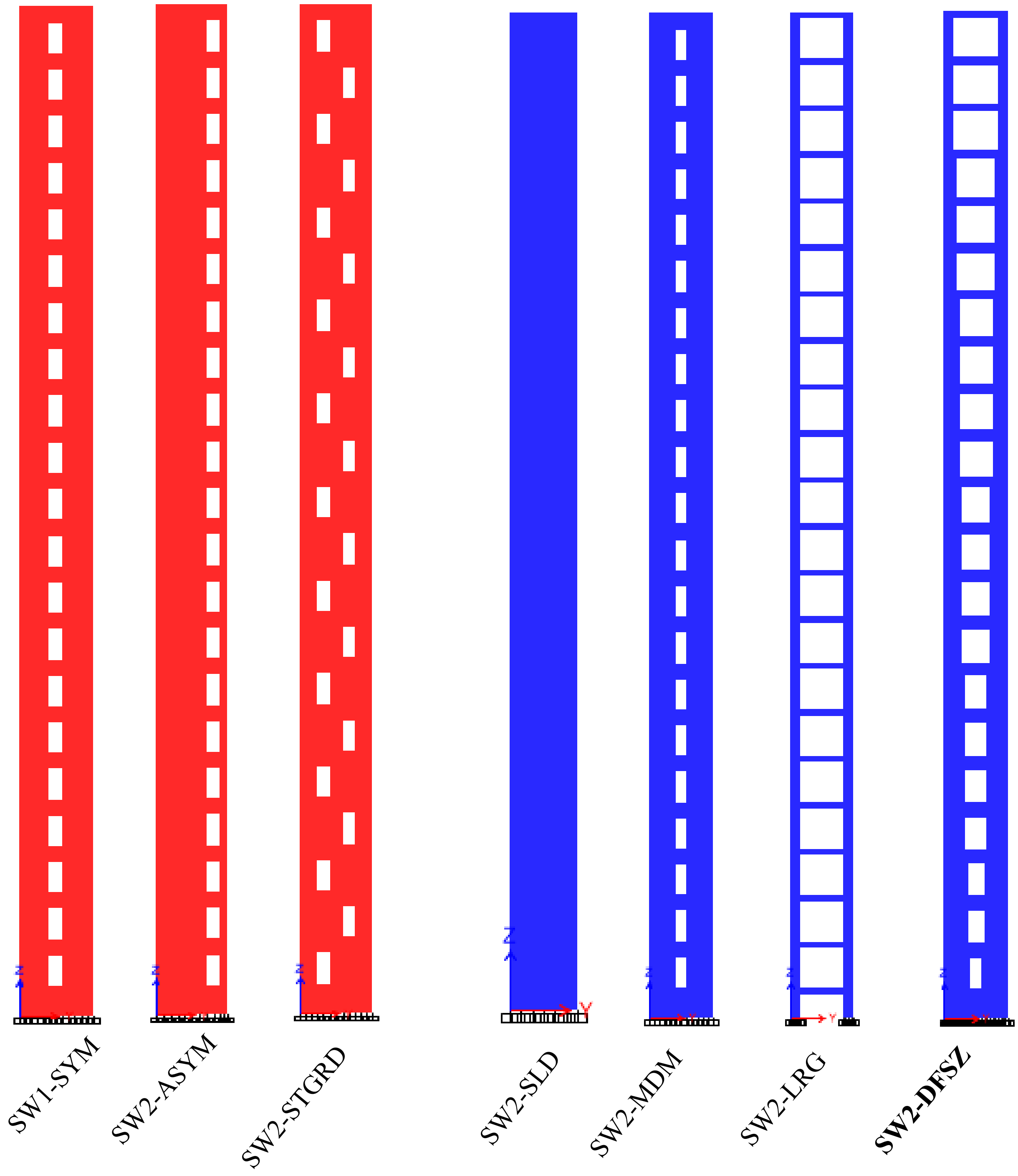
Table 4.3 shows the percentage of size of openings per storey wall area for each storey of all shear wall models on which their openings gradually increases from the bottom storey level to the top most storey level of the wall.



a) Sample models of 22-storied SW1 with different location of openings

b) Sample shear wall models of 22-storied SW1 with different sizes of openings

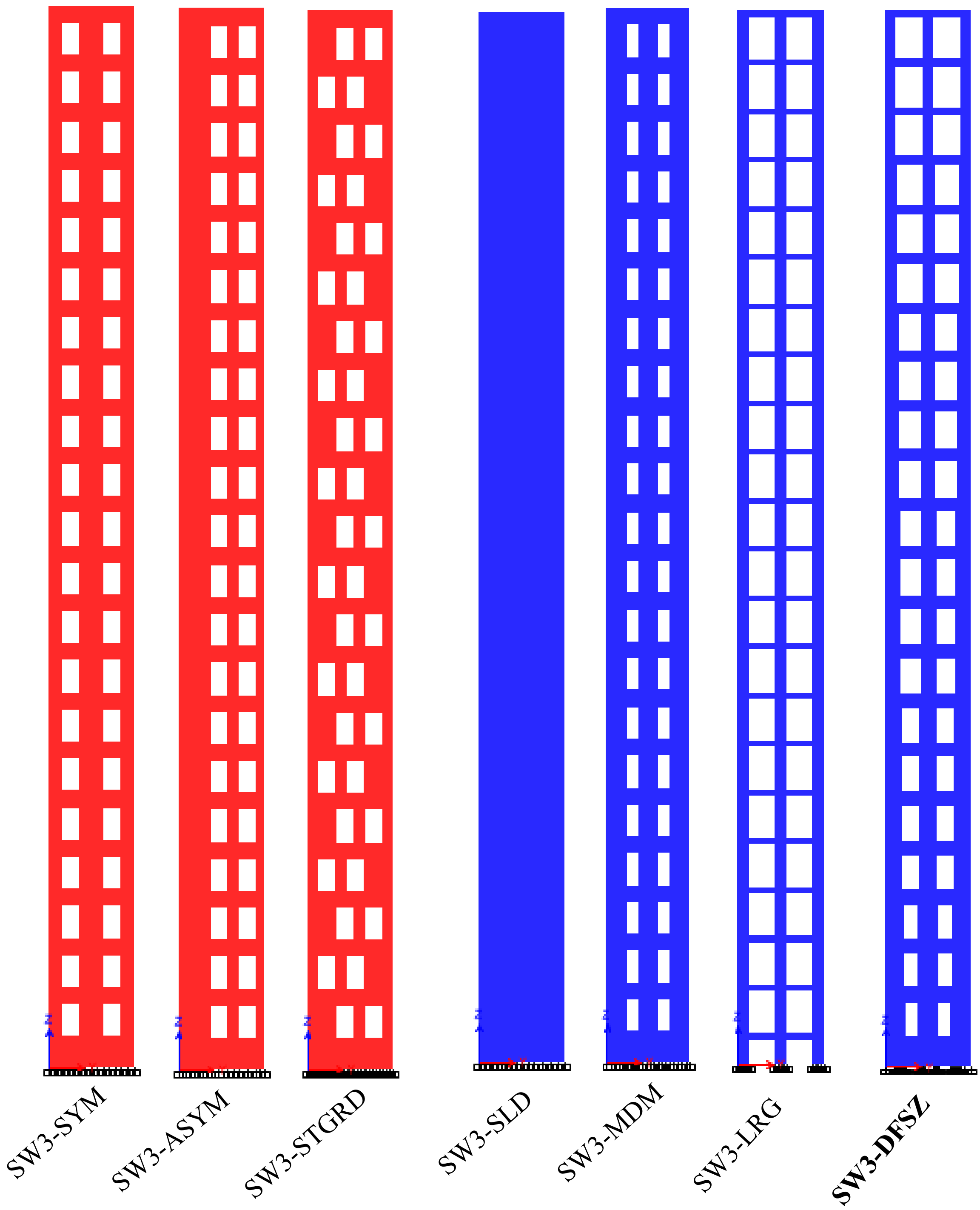
Figure 4.3: Sample models of the 22-storied SW1



a) Sample models of 22-storied SW2 with different location of openings

b) Sample shear wall models of 22-storied SW2 with different sizes of openings

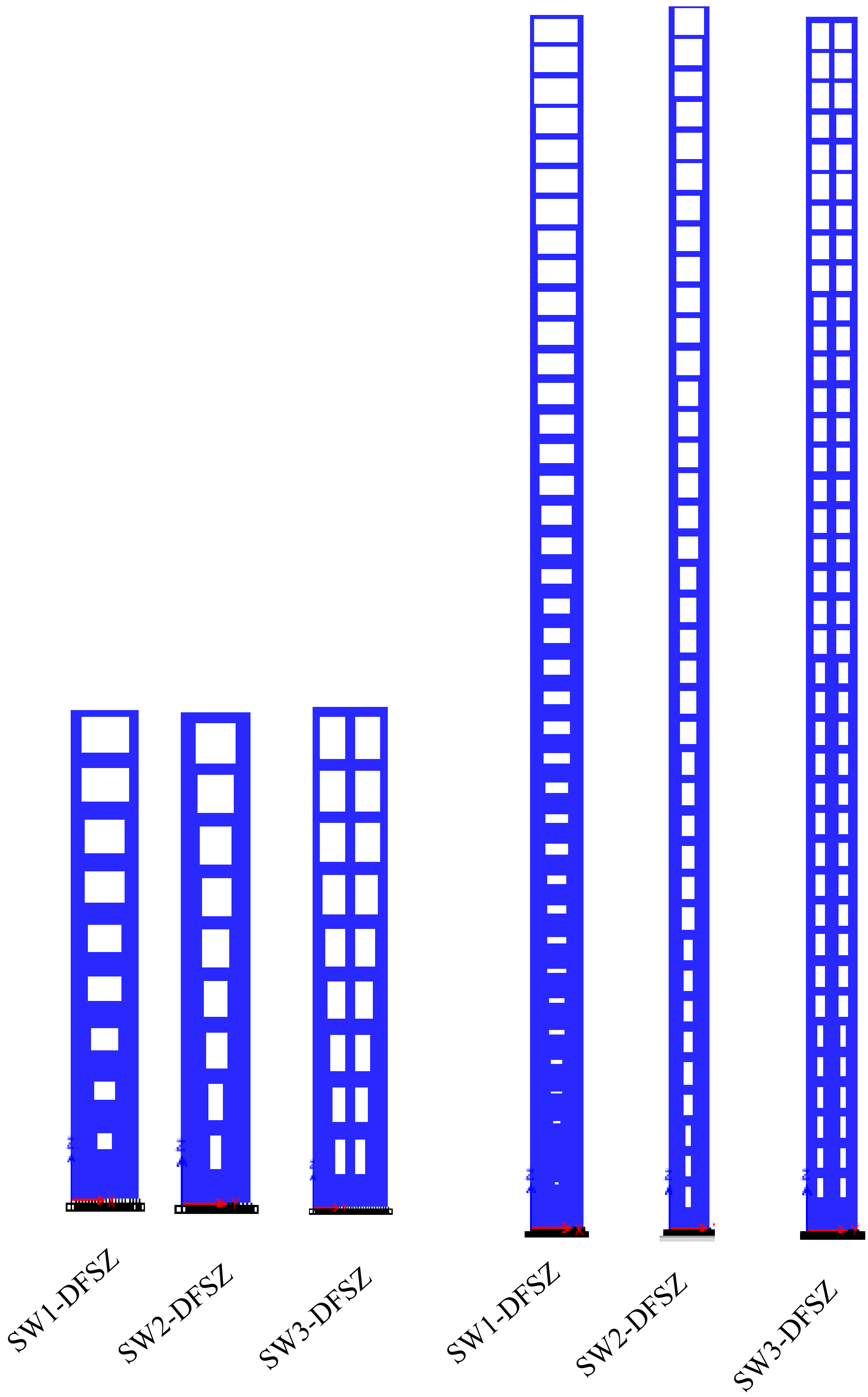
Figure 4.4: Sample models of the 22-storied SW2



a) Sample models of 22-storied SW3 with different location of openings

b) Sample shear wall models of 22-storied SW3 with different sizes of openings

Figure 4.5: Sample models of the 22-storied SW3



a) 10-Storied DFSZ models

b) 40-Storied DFSZ models

Figure 4.6: DFSZ models for 10-Storied and 40-storied SWs

Table 4.3: Sizes of openings for **SW1 –DFSZ, SW2-DFSZ** and **SW3-DFSZ**

Storey level	% of Size of openings per storey wall area								
	10-Storied walls			22-Storied walls			40-Storied walls		
	SW1	SW2	SW3	SW1	SW2	SW3	SW1	SW2	SW3
1	1.5625	0	0	0.3074	0	0	0	0	0
2	4.5621	11.290	17.213	1.4926	11.290	17.213	0.1537	11.2903	17.213
3	8.2381	14.456	20.541	3.4653	13.287	20.201	0.4918	11.2903	17.213
4	14.943	18.964	27.984	5.1752	18.347	23.541	1.10656	13.652	19.423
5	21.214	24.468	34.294	8.5241	21.984	26.608	1.96721	13.652	19.423
6	34.060	30.257	40.349	11.256	24.264	29.213	3.07377	15.864	21.345
7	43.950	36.463	46.287	14.586	27.982	32.854	4.42623	15.864	21.345
8	52.607	40.651	48.449	18.256	27.982	33.694	5.16393	17.151	23.653
9	64.652	40.652	51.643	21.264	30.154	36.284	6.88525	17.151	23.653
10	59.017	44.038	52.878	26.124	30.154	39.871	7.7459	20.257	25.641
11				30.090	31.234	42.605	9.83607	20.257	25.641
12				36.568	31.234	42.605	10.8197	23.262	27.241
13				40.906	35.941	45.981	13.2787	23.262	27.241
14				44.505	35.941	45.981	14.3852	26.198	27.241
15				48.021	37.824	47.214	15.4918	26.198	30.507
16				51..610	37.824	47.214	18.4426	29.254	30.507
17				52.651	39.971	49.293	19.6721	29.254	30.507
18				55.238	39.971	49.293	20.9016	33.871	32.213
19				61.091	41.205	51.198	24.3443	33.871	32.213
20				62.244	41.205	51.198	25.6967	36.291	32.213
21				62.244	43.774	53.89	27.0492	36.291	34.826
22				56.481	44.261	54.50	30.9836	39.404	34.826
23							32.459	39.404	34.826
24							33.9344	42.114	36.351
25							38.3607	42.114	36.351
26							39.959	45.406	36.351
27							41.5574	45.406	39.021
28							46.4754	48.144	39.021
29							48.1967	48.144	39.021
30							49.918	51.273	41.138
31							55.3279	51.273	41.138
32							56.4805	51.273	41.138
33							57.6332	53.651	43.294
34							61.4754	53.651	43.294
35							61.4754	53.651	43.294
36							62.7049	56.422	48.871
37							63.9344	56.427	48.871
38							67.9303	58.068	55.303
39							69.2367	58.064	55.303
40							64.0113	61.692	55.303

The study was first carried out on 22-storied shear wall models. The study was then conducted on 10 storied and 40 storied models of all shear walls (keeping the length and thickness of each shear wall model the same) in order to have more comprehensive conclusions. Generally, 69 shear wall models were used to conduct this study.

4.4 Structural Modelling

When analyzing a structural wall, it is important to model appropriately the cracked section stiffness of the wall and any coupling elements, as this stiffness determines the building periods, base shear, story drifts, and internal force distributions. Earthquake actions strongly depend on deformation behavior and effective stiffness of structural members.

According to ES EN 1998-1-1: 2015 clause 4.3.1(1), the model of the building shall adequately represent the distribution of stiffness and mass in it so that all significant deformation shapes and inertia forces are properly accounted for under the seismic action considered. Clause 4.3.1 (6) of this code also states that, the stiffness of the load bearing elements should, in general, be evaluated taking into account the effect of cracking. According to ES EN 1992-1-1:2015 clause 3.1.3 (4), the Poisson's ratio may be taken equal to 0.2 for uncracked concrete and 0 for cracked concrete.

The main parameters affecting the stiffness of the cracked concrete elements are modulus of elasticity and effective moment of inertia of the section. As mentioned in Chapter 3, C20/25 concrete material was used during modeling the sample shear walls. Based on ES EN 1992-1-1:2015 Clause 3.1.3(3) provisions, the modulus of elasticity of concrete at an age of 28 days can be estimated as:

$$E_{cm} = 22\left(\frac{f_{cm}}{10}\right)^{0.3} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (4.1)$$

Where E_{cm} is in GPa and f_{cm} is in MPa. For concrete < C50/60, the mean compressive strength of the concrete at 28 days can be taken as, $f_{cm} = f_{ck} + 8$ (in MPa), Where f_{ck} is the characteristic compressive cylinder strength of concrete at 28 days (i.e. the value is 20 MPa for C20/25 concrete according to Table 3.1 of the code). Therefore, the modulus of elasticity for C20/25 concrete will be;

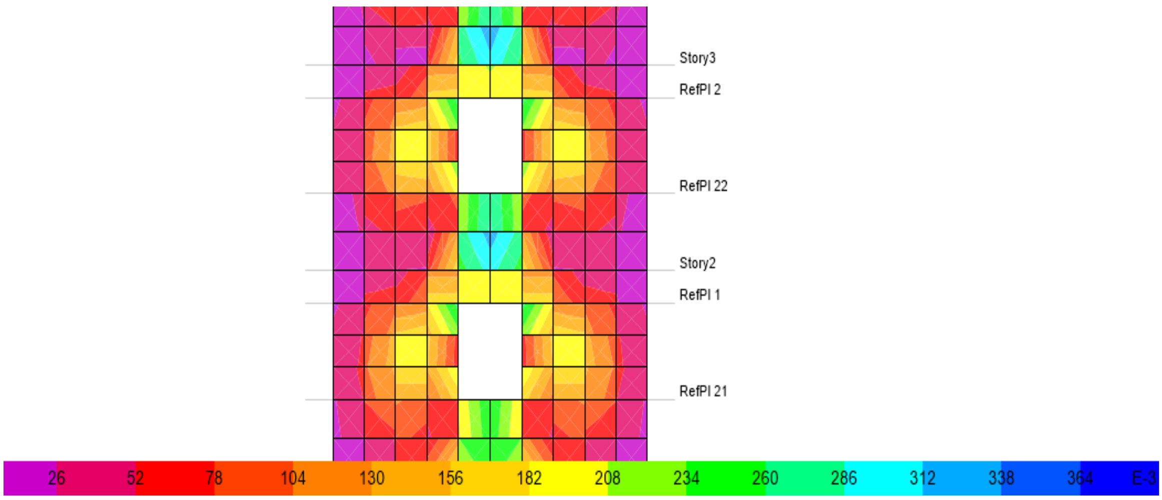
$$E_{cm} = 22\left(\frac{f_{ck} + 8}{10}\right)^{0.3} = 22\left(\frac{20 + 8}{10}\right)^{0.3} = 29.962 \approx 30 \text{ GPa}$$

According to ES EN 1998-1:2015 Clause 4.3.1(7), unless a more accurate analysis of the cracked elements is performed, the elastic flexural and shear stiffness properties of concrete and masonry elements may be taken to be equal to one-half of the corresponding stiffness of the uncracked elements. The effective stiffness of pier elements can be taked as $0.5I_g$ as recommended by ES EN 1998-1-1:2015. However, coupling beams needs further reduction in stiffenss due to their squat behavour.

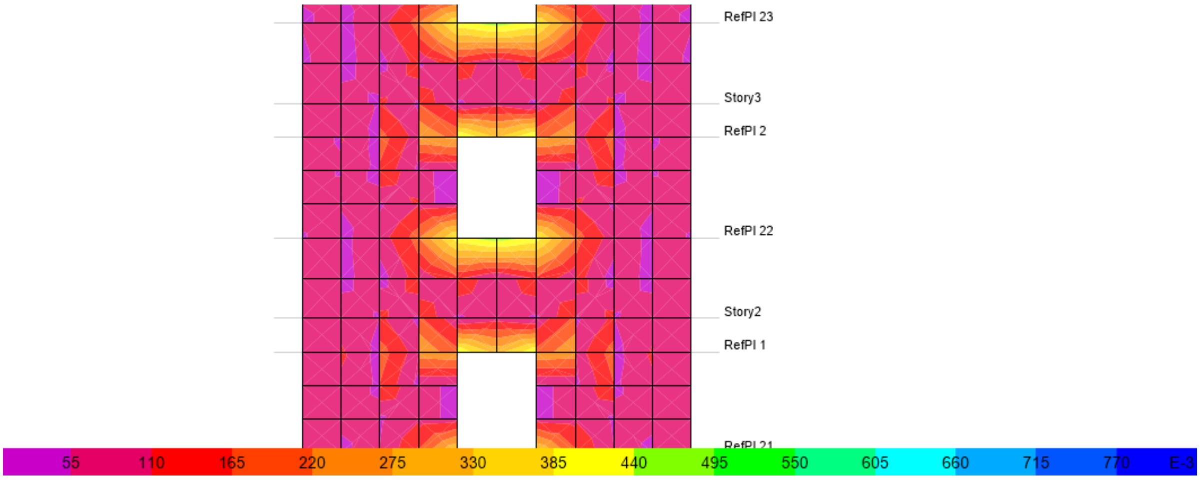
Emilio Gonzalez (1998) states that coupling beams are expected to sustain damage before significant yielding occurs in walls, leading to further stiffness reduction. The Canadian standard, CSA-A23.3-04 (2005), states that effective stiffness of coupling beams should further be reduced because of concentrated end rotations associated with reinforcement slip from anchorage zones within the wall boundary.

4.4.1 Effective Stiffness of coupling Beams

The coupling beam stiffness is an important parameter that defines the overall behaviour of a coupled wall system in a building. In this kind of system, axial forces in the coupled walls resist a significant portion of the overturning moment at the base. The shear transfer between the interconnected walls makes this possible. The coupling beams are the elements that transfer these shear forces between the structural walls. Hence, it can be said that the stiffness of the coupling beam determines how effective this shear force transfer is and is subjected to high shear deformations and shear stresses due to its squat behaviour as shown in Figure 4.7(a) and 4.7(b).



a) Shear stresses, Mpa (, x 10^{-3})



b) Bending stresses, Mpa (x10^{-3})

Figure 4.7: Typical stress distributions of laterally loaded coupled walls

The importance of the coupling beam stiffness is critical in medium to low-rise buildings. In these structures the axial loading in the walls due to gravitational forces is negligible compared to the axial forces produced by seismic forces. If the assumed stiffness is higher than the actual value, axial forces obtained from this analysis will be not conservative for the design of the structural walls. This kind of problem will affect considerably the mode of failure of the structure. Most of the time coupling beams are modeled as slender flexural elements. But in the case of squat beam elements (such as Coupling Beams), it is very important to take in to account their shear deformations due to the concentrated end rotations and high shear forces they inhibited, especially when they are subjected to seismic (i.e. reversal) loads, which leads to further reduction in stiffness. These shear deformations are very important in the behaviour of squat beam elements, such as coupling beams, when the structure is subjected to seismic loads.

Various formulas exist for determining the effective stiffness of coupling beams as discussed in Section 2.8. The recommendations for main parameters vary significantly mainly due to different interpretations of test data and different behavior models. For example, the equation used to evaluate the effective uncracked moment of inertia of a reinforced concrete coupling beam recommended by the Canadian Concrete Standard, CSA A23.3 (2005) and proposed by Paulay and Priestley (1992) is given by the following expression:

$$\mathrm{I_e} = \frac{\mathrm{I_g}}{1 + 3\left(\frac{h}{l_n}\right)^2} \quad \ldots \ldots (4.2)$$

Where I_g is the gross inertia of the beam, h is its overall depth and l_n is its clear span between end of the walls (piers).

Most of the formulas discussed in Section 2.8 depend on the aspect ratio of the coupling beams. In this section the effective stiffness of coupling beams is derived using the basic principles of mechanics by taking into account both flexural and shear deformations.

If both flexural and shear deformations are considered, total deformation of a given coupling beam can be expressed as:

$$\Delta_{\text{total}} = \Delta_{\text{shear}} + \Delta_{\text{flexure}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (4.3)$$

Where; $\Delta_{\text{shear}} =$ shear deformation of coupling beam

$\Delta_{\text{flexure}} =$ flexural defromation of coupling beam

$\Delta_{\text{total}} =$ total defromation of coupling beam

From mechanics of materials: $\Delta = \dfrac{V}{K}$

Where V is the maximum shear force acting on the coupling beam and K is the total stiffness of the coupling beam. Assuming that the coupling beam is fixed at its ends (Figure 4.8), the flexural and shear stiffness of coupling beams can be expressed as;

$$\text{Flexural Stiffness} \qquad k_{fl} = \frac{12EI}{l^3}$$

$$\text{Shear stiffness} \qquad k_{sh} = \left(\frac{GA}{\alpha_s L}\right)$$

Where;

k_{fl} = flexural stiffness of the coupling beam

k_{sh} = shear stiffness of coupling beam

G = Shear modulus (will be defined later)

E = Modulus of elasticity of the concrete

I = Moment of inertia of the section

A = Cross sectional area of the coupling beam ($i.e.\, bh$)

α_s = shear coefficient (recommended value is 1.5 for solid rectangular sections)

l = length of coupling beam

b = overall thickness of coupling beam

h or d = overall depth of coupling beam

The total deformation of the coupling beam can then be obtained by adding both shear and flexural deformations which is expressed as:

$$\Delta_{total} = \Delta_{fl} + \Delta_{sh} = \frac{V}{\left(\frac{12EI}{l^3}\right)} + \frac{V}{\left(\frac{GA}{\alpha_s L}\right)} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (4.4)$$

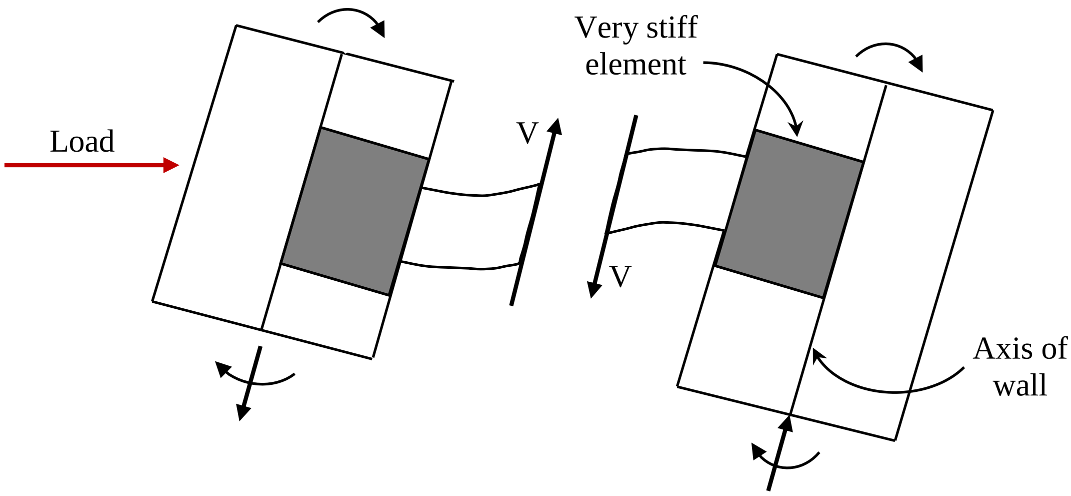


Figure 4.8: Typical deformation of coupling beams due to lateral loads

If shear deformation is taken into account, the total stiffness of the coupling can also be expressed as:

$$k_T = k_{fl} + k_{sh} = \frac{12EI}{l^3} + \left(\frac{GA}{\alpha_s L}\right) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . \dots \dots \dots . \dots . (4.5)$$

For normal or slender beams, the contribution of shear deformations may not be significant and thus the rigidity of coupling beams is almost equal to its flexural rigidity. However, for short or squat beams such as coupling elements of reinforced concrete coupled walls, due to their squat behaviour, the contribution of shear deformation to the total deformation of the coupling beams was found to be significant as shown in Figure 4.9. Therefore, the flexural rigidity of the coupling beams must be reduced by a factor which takes into account the effect of shear deformations.

$$k_T = \frac{Total\ shear\ acting\ in\ coupling\ beam}{Total\ defromation\ exprienced\ in\ coupling\ beams}$$

$$k_T = \frac{V}{\Delta_{fl} + \Delta_{sh}} = \frac{V}{\left(\frac{Vl^3}{12EI}\right) + \alpha_s \left(\frac{VL}{GA}\right)} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . \dots \dots \dots \dots \dots (4.6)$$

The total stiffness of the coupling beam, which is derived by taking into account its shear and flexural deformation, can then be derived by multiplying the flexural rigidity of the coupling beam by a factor which takes into account the effect of shear deformation.

$$k_T = \gamma_{sh} * k_{fl} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (4.7)$$

Where γ_{sh} is called shear factor, which takes into account the effect of shear deformations (i.e. is always less than or equal to 1) and k_T is the total stiffness of coupling beam.

$$\gamma_{sh} = \frac{k_T}{k_{fl}}$$

$$\gamma_{sh} = \frac{k_T}{k_{fl}} = \frac{\dfrac{V}{\dfrac{Vl^3}{12EI} + \alpha_s\left(\dfrac{VL}{GA}\right)}}{\dfrac{12EI}{l^3}} = \left(\frac{1}{\dfrac{l^3}{12EI} + \alpha_s\left(\dfrac{L}{GA}\right)}\right) * \left(\frac{l^3}{12EI}\right)$$

$$\gamma_{sh} = \left(\frac{l^3}{l^3 + 12EI\left(\dfrac{\alpha_s L}{GA}\right)}\right) = \left(\frac{1}{1 + 12EI\left(\dfrac{\alpha_s}{GAL^2}\right)}\right)$$

Substituting the values if *I* and *A* as $bh^3/12$ and bh respectively in to the above equation gives;

$$\gamma_{sh} = \frac{1}{1 + 12\left(\dfrac{bh^3}{12}\right)\left(\dfrac{\alpha_s E}{G(bh)l^2}\right)} = \frac{1}{1 + \dfrac{\alpha_s E}{G}\left(\dfrac{h}{l}\right)^2}$$

The shear modulus, G, can be expressed as a function of Poisson's ratio (ν) and modulus of elasticity of the concrete (E) as;

$$G = \frac{E}{2(1+\nu)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (4.8)$$

$$\gamma_{sh} = \frac{1}{1 + \dfrac{\alpha_s E}{\left(\dfrac{E}{2(1+\nu)}\right)}\left(\dfrac{h}{l}\right)^2} = \frac{1}{1 + \dfrac{2(1+\nu)}{E} * \alpha_s E\left(\dfrac{h}{l}\right)^2}$$

$$\gamma_{sh} = \frac{1}{1 + \alpha_s * 2(1+\nu)\left(\dfrac{h}{l}\right)^2} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (4.9)$$

Equation (4.9) above is called shear factor which takes into account the effect of shear deformation and now is used to determine the un-cracked effective stiffness of coupling beams by multiplying with the total flexural rigidity of the coupling beam.

$$k_e = \gamma_{sh} * k_{fl} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (4.10)$$

$$k_e = \frac{12E_eI_e}{l^3} \qquad and \qquad k_{fl} = \frac{12E_cI_g}{l^3}$$

Where; I_e = Un-cracked effective moment of inertia of coupling beam

I_g = Un-cracked gross moment of inertia of coupling beam

Substituting the values of gross and effective stiffness of the coupling beams into Equation (4.9) above gives:

$$\frac{12E_eI_e}{l^3} = \gamma_{sh} * \frac{12E_cI_g}{l^3}$$

Assuming $E_e = E_c$, the remaining parameter used in comparing both sides of the equation will be the bending moment of inertia of the reinforced concrete coupling beam.

$$\mathrm{I_e} = \gamma_{\mathrm{sh}} * \mathrm{I_g}$$

Substituting the value of shear factor γ_{sh} in to the above equation gives;

$$\mathrm{I_e} = \frac{1}{1 + \alpha_s * 2(1 + \nu)\left(\frac{h}{l}\right)^2} * \mathrm{I_g} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots... (4.11)$$

The above formula agrees with most of the formulas predicted by different international codes and different books discussed in Chapter 2 (Section 2.8). Substituting poisons ratio (υ) and shear coefficient *(α_s)* in the above formula will leave the equation to depend only on the aspect ratio (length/depth) of the coupling beam. Having the above formula at hand, different values of the unknown parameters (poisons ratio (υ) and shear coefficient (α_s)) can be used depending on the recommendations provided by different international codes in order to obtain a formula used to predict the cracked or uncracked effective stiffness of coupling beams.

For example, substituting poisons ratio, $v = 0$ and shear coefficient, α_s =1.5 (recommended shear coefficient value for rectangular solid concrete cross sections) in to Equation (4.11) will give a formula which is exactly similar to the uncracked effective stiffness formula of coupling beams recommended by CSA and Paulay and Priestley as shown on Equation (4.12) below.

$$I_e = \frac{I_g}{1 + 1.5 * 2(1+0)\left(\frac{h}{l}\right)^2}$$

$$\mathrm{I_e} = \frac{\mathrm{I_g}}{1 + 3\left(\frac{h}{l}\right)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.12)$$

Equation (4.12), however, does not include reduction in stiffness that takes in to account the effect of cracking. The factor used to take into account the effect of cracking varies from code to code (it is based on laboratory test results and it is not easy to estimate the exact cracking effects using analytical procedures). For example, ACI uses $0.35E_CI_g$ for beams and $0.7E_CI_g$ for columns. Euro code and the new Ethiopian Building Code Standard (ES EN 1998-1:2015) uses $0.5\ E_CI_g$ for both beams and columns. But, the behaviour of coupling beams is somewhat different from those of slender beams. Due to low length/depth ratio, high amount of shear force is inhibited in those beams and those coupling beams makes the coupled walls to act together and hence subjected to reversal loads too. The Canadian standard (CSA) and Paulay & Priestley use $0.4E_CI_g$ for coupling beams. According to the ES EN 1998-1:2015's provisions, the effective Stiffness of bracing elements can also be taken as $0.4\mathrm{E_CI_g}$. The factor 0.4 can be used for coupling beams if they are treated as bracing elements. Multiplying *Equation (4.12)* by this factor will therefore give a complete formula used to determine the cracked effective stiffness of coupling beams which is exactly similar to the formula recommended by CSA and Paulay and Priestley.

$$I_e = \frac{0.4I_g}{1 + 3\left(\frac{h}{l}\right)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.13)$$

<u>*Note that*</u>: According to ES EN 1998-1:2015 provisions, poisons ratio, ν = 0 for cracked concrete, and ν = 0.2 for un-cracked concrete.

With respect to the cracked stiffness, the above Equation can be modified by introducing the factor which takes into account the effect of cracking. Using the factor recommended by ES EN 1998-1-1:2015 which is used to take into account the effect of cracking for flexural members (i.e. beams and columns), the formula used to estimate the effective stiffness of coupling beams on Equation (4.13) can be rewritten as follows:

$$I_e = \frac{0.5I_g}{1 + 3\left(\frac{h}{l}\right)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.14)$$

The doniminator on the above equation is the contribution of shear deformation to total deformation of the coupling beams and this number gets higher and higher when the aspect ratio*(h/l)* of the coupling beams becomes larger and larger. This indicates that, for short or squat beam elements (such as coupling beams), the contribution of shear deformation to total deformations of the coupling beams may become very significant and even greater in percent than the contribution of flexural deformations as shown in Figure 4.9.

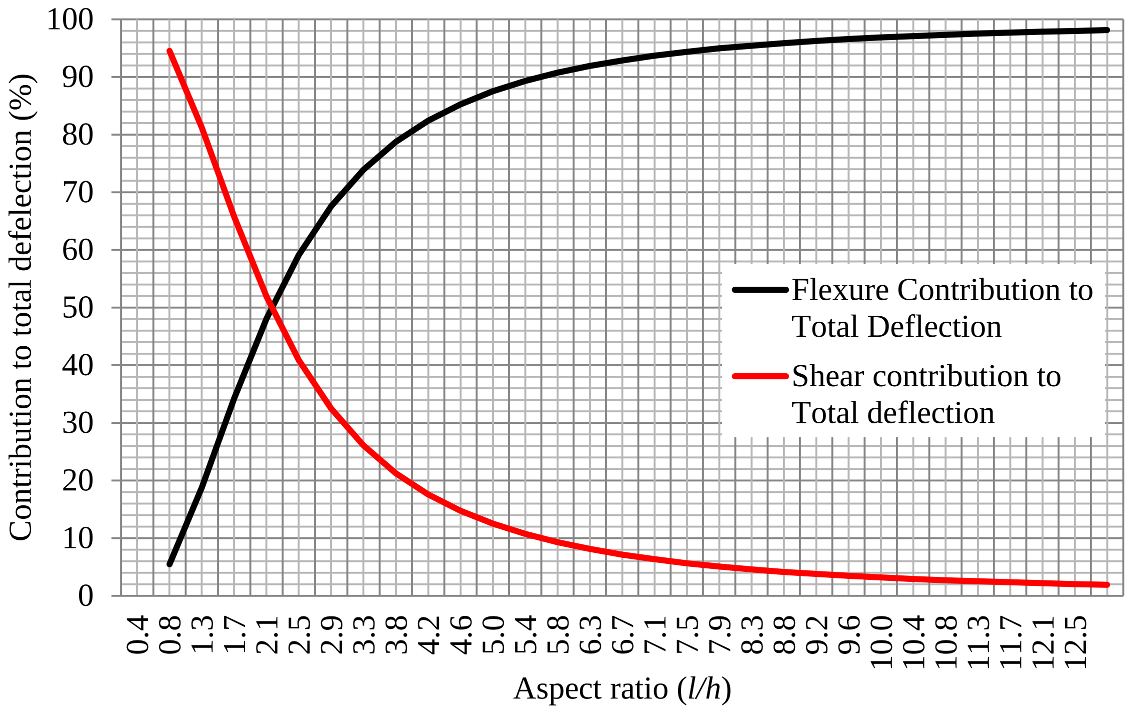


Figure 4.9: Flexure and shear contribution to the total deformation of a coupling beams

Table 4.4 below shows dimensions of the existing coupling beams of SW1, SW2 and SW3 of the 22-storied shear walls on 40/60 saving house projects. The aspect ratio (*l/d*) of the coupling beams for SW1, SW2 and SW3 are 0.73529, 0.72727 and 1.09091 respectively.

Table 4.4: Dimensions of the three existing coupling beams

Coupling beam Parameters	**SW1**	**SW2**	**SW3**
Length, *l*(mm)	1250	800	1200
Height, *h*(mm)	1700	1100	1100
Aspect ratio, *l/h*	**0.73529**	**0.72727**	**1.09091**
Thickness, *b* (mm)	300	300	300

It can be clearly observed from Figure 4.9 and Table 4.4 above that the contribution of shear deformations to the total deformations of the coupling beams of all shear walls is very significant. As a result, shear deformation contribution is **85.8**%, **85.2** % and **76.4** % for coupling beams of SW1, SW2 and SW3 respectively. The contribution of shear deformation to total deformation of coupling beams become small when aspect ratio (*l/h*) of the coupling beam is large. For example, for normal beams having span length of, *l* = 5m and overall depth of, *h* = 400mm, the aspect ratio of the beam will be; *l/h* = 5/0.4 = 12.5 and the contribution of shear deformation to the total deformation of this beam is only 2% as shown from Figure 4.2. This indicates that there is significant difference in assigning the stiffness modification factors for normal conventional beams and squat beams such as coupling beams.

This shows that the effective stiffness of coupling beams highly depends on the aspect ratio (length to depth ratio) of the coupling beams and hence on the sizes of openings provided. The length of opening has direct relationship with the length of the coupling beam while the depth of openings has reverse relationship with the depth the coupling beams. Large length of openings gives large length of coupling beams whereas large depth of openings will yield shallow depth of coupling beams

Example: The variation between Equation (4.14) above and the formulas predicted by different international codes and books as discussed in Chapter 2, in estimating the effective stiffness of coupling beam of the predefined SW1with *thickness* of *300 mm* and aspect ratio, *h/l= 1700/1250= 1.36* is shown in Figure 4.10.

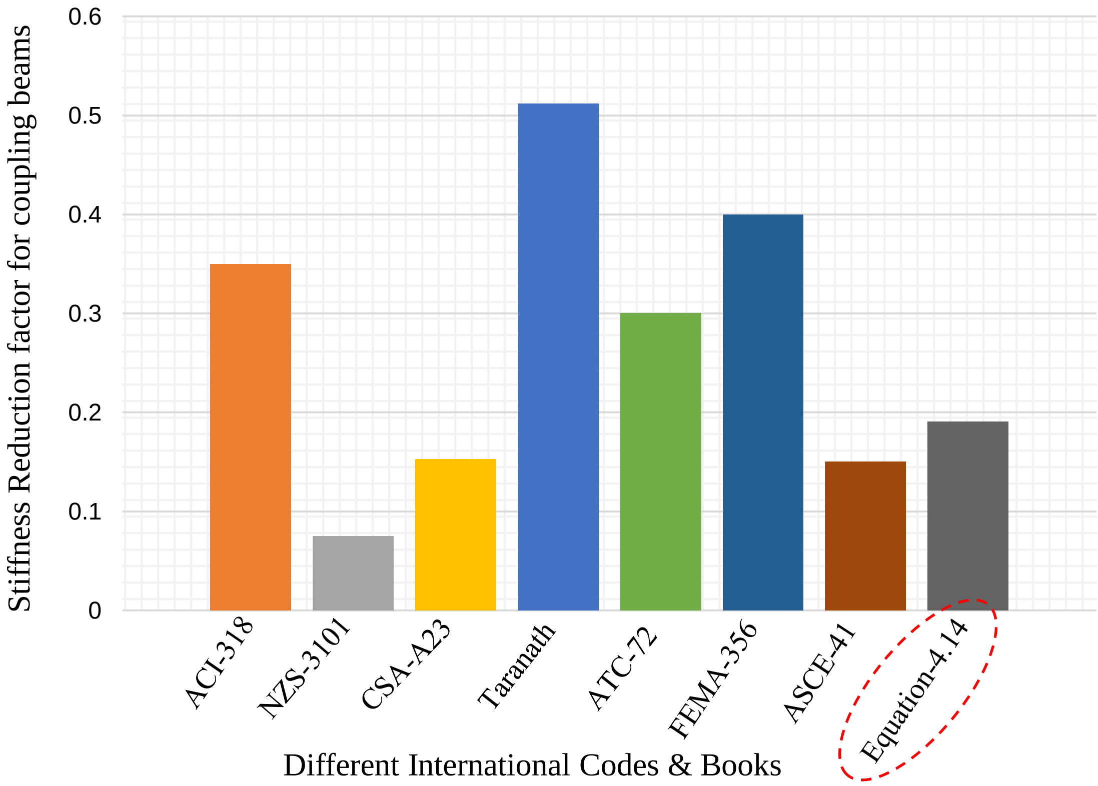


Figure 4.10: Stiffness modification factor for coupling beam of SW1

4.5 Modal Response Spectrum Analysis

In this study, analysis of all sample shear wall models was done using elastic modal Response Spectrum Analysis with the help of ETABS15.2.2, finite element software package. The following parameters were used as an input in addition to material and section properties discussed earlier.

First, ground type B was selected by assuming that all shear walls are located in soils which are characterized by a gradual increase of mechanical properties with depth. Soil factor, S=1.2 was used for ground type B and response spectrum type 1 as recommended by ES EN 1998-1-1:2015. An importance factor $\gamma_I = 1.0$ was used for importance class II (ordinary buildings). Within the scope of ES EN 1998:2015, the earthquake motion at a given point on the surface is represented by an elastic ground acceleration response spectrum, henceforth called an "elastic response spectrum". The lateral loads were applied based on Eurocode 8:2004, due to the fact that, for the horizontal component of the seismic action , the formula used to determine the design spectrum $\mathrm{S_d(T)}$ recommended by ES EN 1998-1-1:2015 is similar to the formula used in EN 1998-1:2004. The values of T_B, T_C and T_D describing the shape of elastic response spectrum depends upon the ground type and are 0.15, 0.5 and 2.0 respectively for response spectrum type 1 and ground type B, as recommended by ES EN 1998-1-1:2015. The peak ground acceleration (a_g) was also taken as 0.2g regarding the assumption that the shear walls are located in the most seismic zone of country, Ethiopia.

The damping correction factor (η) can be determined using the following formula.

$$\eta = \sqrt{\frac{10}{5+\xi}} \geq 0.55 \quad \ldots (4.16)$$

where ξ =damping ratio

For 5% constant viscous damping the reference value of η = 1.

4.5.1 Behavior Factor

The upper limit value of the behaviour factor q, to account for energy dissipation capacity, shall be derived for each design direction as follows:

$$q = q_0 k_w \geq 1.5 \quad \ldots (4.17)$$

Where;

q_o is the basic value of the behaviour factor, dependent on the type of the structural system and on its regularity in elevation.

k_w is the factor reflecting the prevailing failure mode in structural systems with walls.

For coupled wall systems of buildings which are not regular in elevation, the basic value of the behavior factor can be estimated as (ES EN 1998-1-1:2015 Clause 4.2.3.1(7));

$$q_0 = 0.8\left(3.0\left(\frac{\alpha_u}{\alpha_1}\right)\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.18)$$

Where;

α_1: is the value by which the horizontal seismic design action is multiplied in order to first reach the flexural resistance in any member in the structure, while all other design actions remain constant;

α_u: is the value by which the horizontal seismic design action is multiplied, in order to form plastic hinges in a number of sections sufficient for the development of overall structural instability, while all other design actions remain constant. The factor α_u may be obtained from a nonlinear static (pushover) global analysis.

The approximate value of α_u/α_1 can be taken as 1.2 for coupled wall systems and the factor k_w, reflecting the prevailing failure mode in structural systems with walls, shall be taken as follows:

$$k_w = 0.5 \leq \frac{1+\alpha_o}{3} \leq 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.19)$$

Where; α_o is the prevailing aspect ratio of the walls of the structural system.

If the aspect ratios h_{wi}/l_{wi} of all walls i of a structural system do not significantly differ, the prevailing aspect ratio α_o may be determined from the following expression:

$$\alpha_o = \frac{\sum h_{wi}}{\sum l_{wi}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.20)$$

Where;

h_{wi} is the height of wall i; and

l_{wi} is the length of the section of wall i.

For example, for the 10-storied SW1 on which the height of the shear wall is 30.8m and the length of the wall is 6.1m, the prevailing aspect ratio (α_o) is:

$$\alpha_o = \frac{\sum h_{wi}}{\sum l_{wi}} = \frac{30.8}{6.1} = 5.05$$

$$k_w = 0.5 \leq \frac{1 + \alpha_o}{3} = \frac{1 + 5.05}{3} = 2.02 \leq 1$$

$$k_w = 1$$

Substituting the values of q_0 and k_w in equation (4.11) gives:

$$q = 0.8\left(3.0\left(\frac{a_u}{a_1}\right)\right) * k_w \geq 1.5$$

$$q = 0.8(3.0(1.2) * 1 \geq 1.5$$

$$q = 2.88$$

Using the same procedures above, the behaviour factor was determined and used as an input, in addition to the other parameters discussed above, during defining the modal response spectrum analysis of the shear wall models as per ES EN 1998-1-1: 2015.

4.5.2 Number of Modes

The new Ethiopian Building Code Standard, ES EN 1998-1-1: 2015, states that the response of all modes of vibration contributing significantly to the global response shall be taken into account if the sum of the effective modal masses for the modes taken into account amounts to at least 90% of the total mass of the structure and all modes with effective modal masses greater than 5% of the total mass are taken into account for each relevant direction. However, if the above condition is not satisfied, the minimum number of modes (k) to be taken into account in a spatial analysis should satisfy the following two conditions:

$$\begin{cases} k \geq 3\sqrt{n} \\ T_k \leq 0.20 \text{ s} \end{cases}$$

Where;

k is the number of modes taken into account;

n is the number of storyes above the foundation or the top of a rigid basement;

T_k is the period of vibration of mode k.

Therefore, the minimum number of modes that should be taken in to account for the 10-storied, 22-storied and 40-storied shear walls can be determined as;

For 10-storied shear wall, $k \geq 3\sqrt{n} \geq 3\sqrt{10} = 9.487 \qquad k = 10$

For 22-storied shear wall, $k \geq 3\sqrt{n} \geq 3\sqrt{22} = 14.07 \qquad k = 15$

For 40-storied shear wall, $k \geq 3\sqrt{n} \geq 3\sqrt{40} = 18.97 \qquad k = 19$

For all of the 10-Storied, 22-Storied and 40-Storied shear wall models, the period of vibration of the 10^{th}, 15^{th}, 19^{th}, modes were found to be less than 0.2 second respectively and hence the values, k=10, k = 15 and k = 19 are adopted during defining the number of modes of the 10-Storied, 22-Storied and 40-Storied shear wall models.

4.5.3 Combination of Modal Responses

The response of a structure can be defined as a combination of many mode shapes, resulting due to the vibratory motion of the building. But for seismic analysis, the first mode or the fundamental time period is the most significant, which is the inherent property of the building. According to ES EN 1998-1-1:2015 clause 4.3.3.3.2 (1), *SRSS* shall be used for combining the results of modal analysis for both horizontal directions if the response in two consecutive modes *i* and *j* are independent to each other (i.e. $T_j \leq 0.90 * T_i$). If this is not satisfied, the code recommends to use more accurate procedures such as *"Complete Quadratic Combination"* (CQC) for the combination of the modal maxima. In this study "Complete Quadratic Combination" was used for combining the responses of each mode.

As mentioned earlier, modeling and analysis of all shear wall models is done using Modal Response Spectrum Analysis (RSA) with the help of ETABS15.2.2, finite element software package, and using the procedures mentioned in Chapter 3. The analysis results obtained are presented in Chapter 5 and Appendix A of this thesis.

CHAPTER 5: RESULTS AND DISCUSSIONS

5.1 General

In this thesis, the effects of size and location of openings on seismic behaviour of reinforced concrete shear walls was studied using Response Spectrum Analysis and with the help of ETABS15.2.2, finite element software. The study was first carried out on the 22-Storied three shear walls of the selected case study: shear wall with single bands of window openings (SW1), shear wall with single bands of door openings (SW2) and shear wall with two bands of door openings (SW3). The study was then conducted on 10-storied and 40-storied models of the above mentioned reinforced concrete shear walls in order to get more comprehensive conclusions. Analysis results of all shear wall models were compared relative to the seismic response parameters (i.e. Story drift, Story Displacement, Base shear and Shell's Internal Force Distributions). For each seismic response, the discussions are categorized in to two main groups to identify the effects of openings on seismic behaviour of reinforced concrete shear walls. The first discussion deals with the effects of size of openings and the second discussion deals with the effects of location of openings. The discussions were supported by graphs and tables for more clarity.

5.2 Base Shear

5.2.1 Effect of size of Openings

Base shear is an estimate of the maximum expected lateral force at the base of a structure that is caused due to seismic ground motion. The maximum base shear for all shear wall models with different size of openings is shown in Table 5.1.

Table 5.1: Maximum base shear (kN) of all walls with different sizes of openings

Model		Sizes of shear wall openings					
		Solid	Small	Medium	Large	Very large	Different size
10-Storied	SW1	174.429	170.377	151.012	98.775	46.143	116.0287
	SW2	132.178		118.7659	60.7734		88.5269
	SW3	174.429		152.7691	98.844		103.1014
22-Storied	SW1	183.8201	180.744	162.5787	99.1674	48.7872	150.1958
	SW2	121.8539		111.4054	52.656		86.82
	SW3	183.8201		156.826	90.3732		123.6065
40-Storied	SW1	217.5782	213.139	177.2881	108.7821	55.6965	148.2458
	SW2	148.9121		135.2756	62.7634		106.4384
	SW3	217.5782		161.2107	103.4189		150.1836

It can be observed from Table 5.1 that, for all shear wall models, the base shear is decreased with increasing size of openings. Moreover, using different sizes of symmetric openings which gradually increases from the bottom storey to the uppermost storey (DFSZ) gives reduced base shear than the solid wall and corresponding wall with small and medium openings. Figure 5.1 and 5.2 shows the maximum base shear of 10-storied SW1 and 10-Storied SW2 with different sizes of openings respectively.

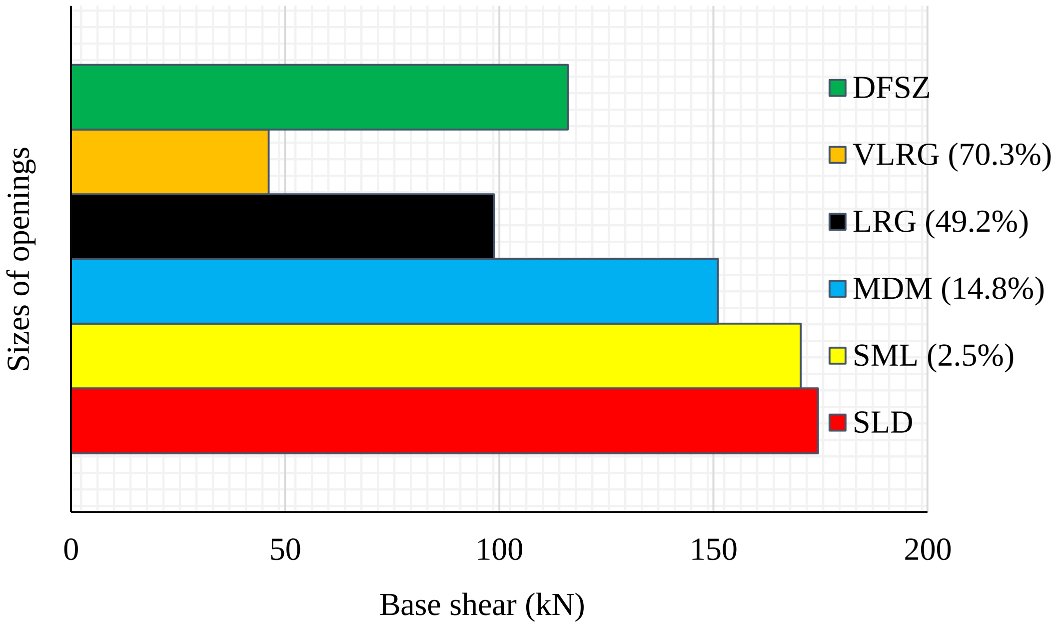


Figure 5.1: Base shear of 10-storied SW1 with different sizes of openings

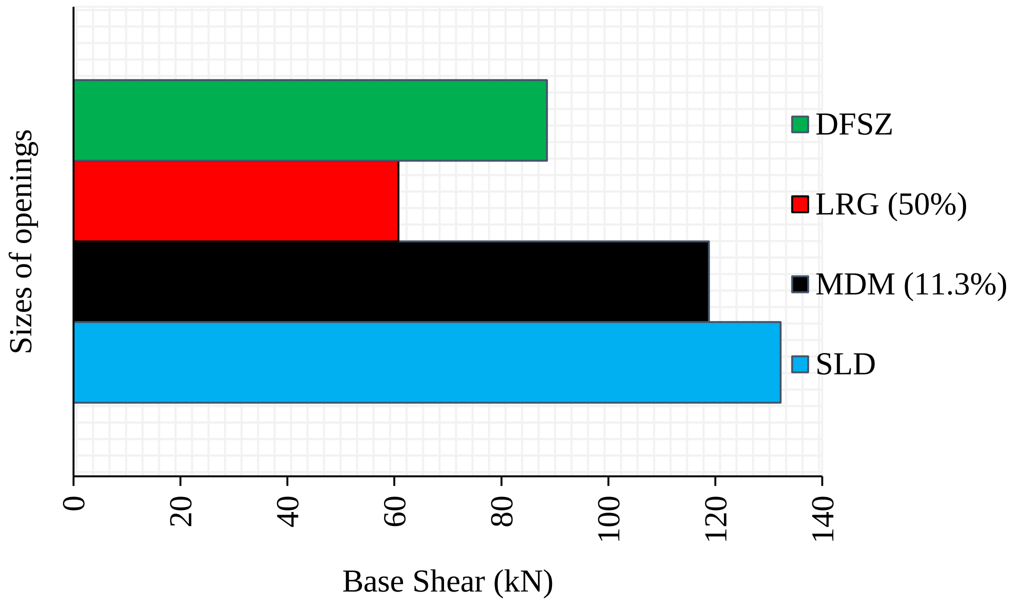


Figure 5.2: Base shear of 10-storied SW2 with different sizes of openings

As a result, the solid wall without opening (SLD) obviously give larger base shear than shear wall with any size of opening. For example, for the 10-storied SW1, the model with different size of symmetric openings which gradually increases from the bottom storey to the topmost storey gives 33.48% less shear at the base of the shear wall than the solid wall without opening which implies the potential damage to the bottom level of the shear wall is reduced.

5.2.2 Effects of Location of Openings

Though introducing openings into shear walls reduces the shear at base of the shear wall, the asymmetric, symmetric and staggered location of openings having similar sizes have no significant effect on base shear of the shear walls as shown in Table 5.2.

Table 5.2: Max. Base shear (kN) of walls with different location of openings

Model		Location of shear wall openings				
		SLD	ASYM	SYM	STGRD	DFSZ
10-Storied	SW1	174.429	155.7478	158.9796	157.3197	116.0287
	SW2	132.1779	116.9038	118.7659	117.7884	88.5269
	SW3	174.429	136.8824	136.5171	138.4814	103.1014
22-Storied	SW1	183.8201	159.0037	171.4293	166.0466	150.1958
	SW2	121.8539	105.5121	111.4054	109.3414	86.82
	SW3	183.8201	137.1174	137.1865	137.91	127.9289
40-Storied	SW1	217.5782	190.4493	200.0796	196.1335	148.2458
	SW2	148.9121	129.9489	135.2756	133.1599	106.4384
	SW3	217.5782	160.7249	161.2107	162.0888	150.1836

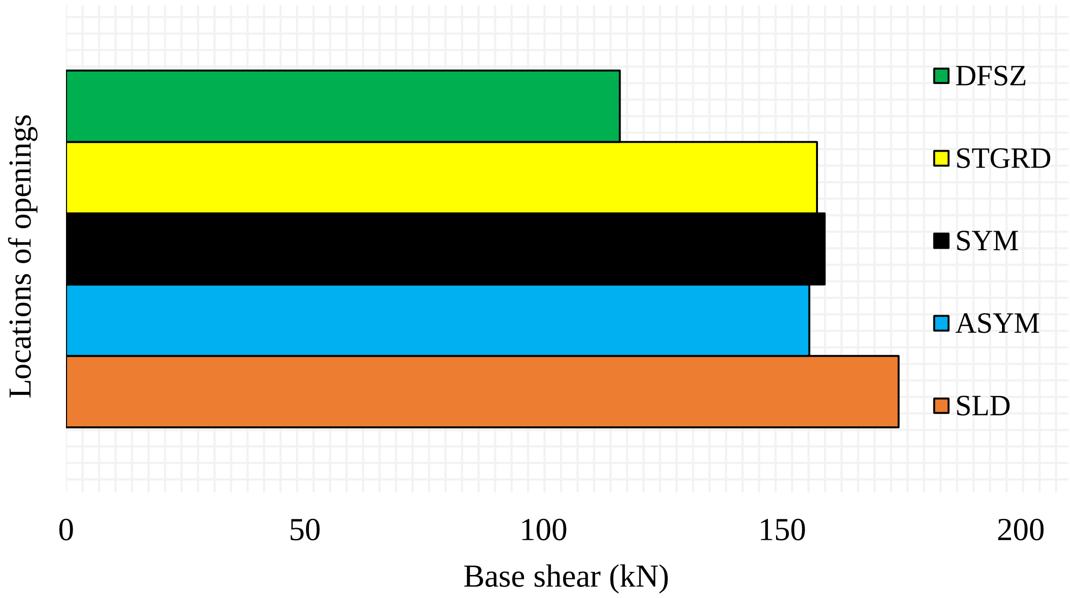


Figure 5.3: Base shear of 10-storied SW1 with different location of openings

But, using different size of symmetric openings which gradually increases from the bottom storey to the top most storey again gives lesser displacement than the solid wall without openings and shear wall with asymmetric, symmetric and staggered location of openings.

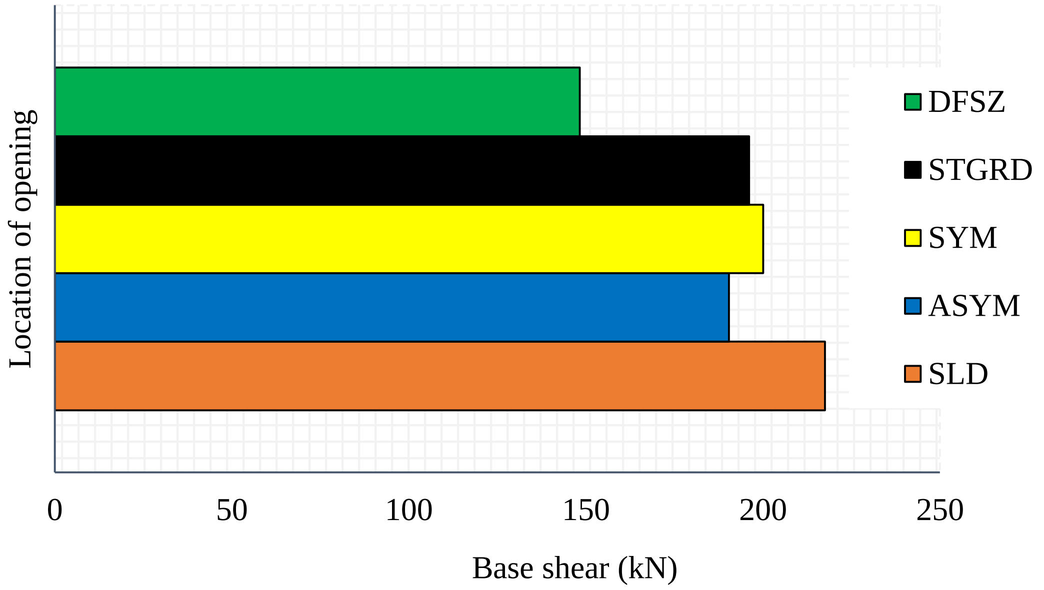


Figure 5.4: Base shear of 40-storied SW1 with different location of openings

5.3 Lateral Displacement at the Top

5.3.1 Effect of Size of Openings

Lateral displacement refers to the distance that points on a structural element are moved from their initial locations by the seismic waves. The lateral displacement at the top is thus the roof or uppermost story displacement of the shear walls considered. The lateral displacement at the top of all shear wall models with deferent sizes of openings is shown in Table 5.3.

Table 5.3: Lateral displacement at the top (mm) of walls with different sizes of openings

Model		Sizes of shear wall openings					
		Without opening	Small size	Medium size	Large size	Very large	Different size
10-Storied	SW1	6.379	6.257	6.04	9.066	24.203	4.725
	SW2	10.804		10.063	20.318		8.419
	SW3	6.379		6.325	12.168		5.372
22-Storied	SW1	55.698	55.099	52.95	51.295	64.211	46.212
	SW2	72.794		68.79	69.161		59.809
	SW3	55.698		53.952	56.134		48.084
40-Storied	SW1	364.275	355.706	325.267	271.17	342.953	200.877
	SW2	606.765		542.496	427.049		352.882
	SW3	364.275		365.889	323.00		258.456

It can be observed from Table 5.3 that introducing openings into shear walls may reduce the lateral displacement at the top of the walls. However, using very large sizes of openings gives larger lateral displacement at the top than even the solid walls without openings. Figure 5.5 shows comparison of lateral displacement at the top of the 10-storied SW1 with different sizes of openings.

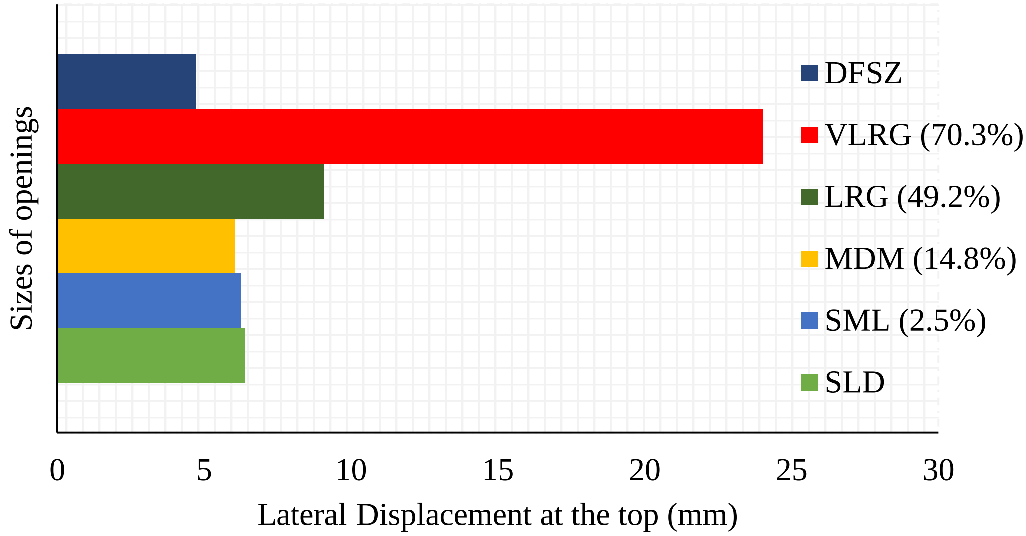


Figure 5.5: Displacement at the top of 10-storied SW1 with different sizes of opening

The lateral displacement at the top of the 10-storied SW1 with large (49.2%) and very large (70.3%) size of openings is 42.1% and 276.6% larger than the lateral displacement of the corresponding solid wall without openings respectively whereas the shear walls with different sizes of symmetric openings, which gradually increases from the bottom story to the top most storey, gives 26% less lateral displacement at the top than the corresponding solid walls and the trend is similar in both 10-storied SW2 and SW3.

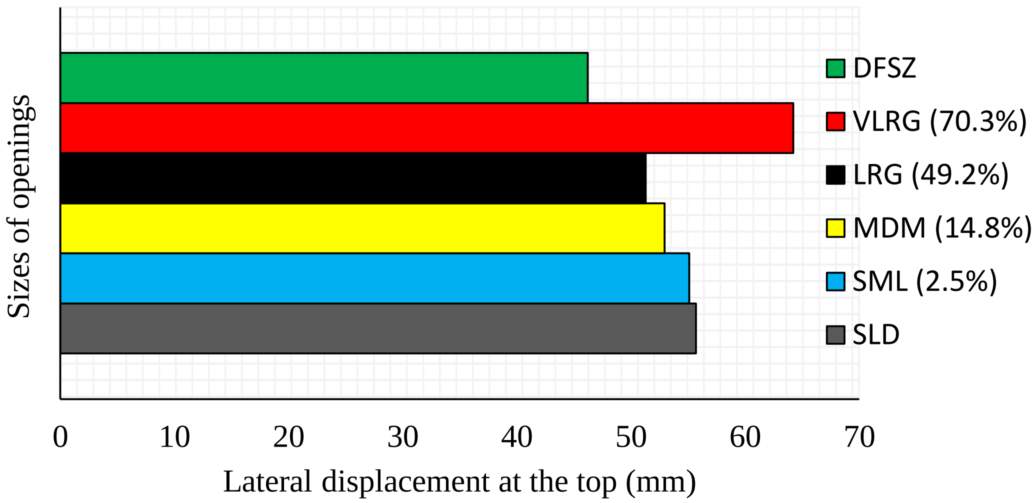


Figure 5.6: Displacement at the top of 22-storied SW1 with different sizes of opening

Figure 5.6 shows the lateral displacement at the top of 22-storied SW1 with different sizes of openings. It can be clearly observed from the figure that the shear walls with very large (70.3%) size of openings gives 15.8% larger lateral displacement at the top than the solid wall (SW1-SLD), while SW1-DFSZ gives 28.03% less lateral displacement at the top than SW1-ASYM and the trend is similar for both 22-storied SW2 and 22-storied SW3.
The same is true for the 40-storied SW1 (Figure 5.7) as the shear wall with different sizes of symmetric openings, which gradually increases from the bottom storey to top most story, gives 44.86 % less lateral displacement at the top than the corresponding solid shear wall without opening.

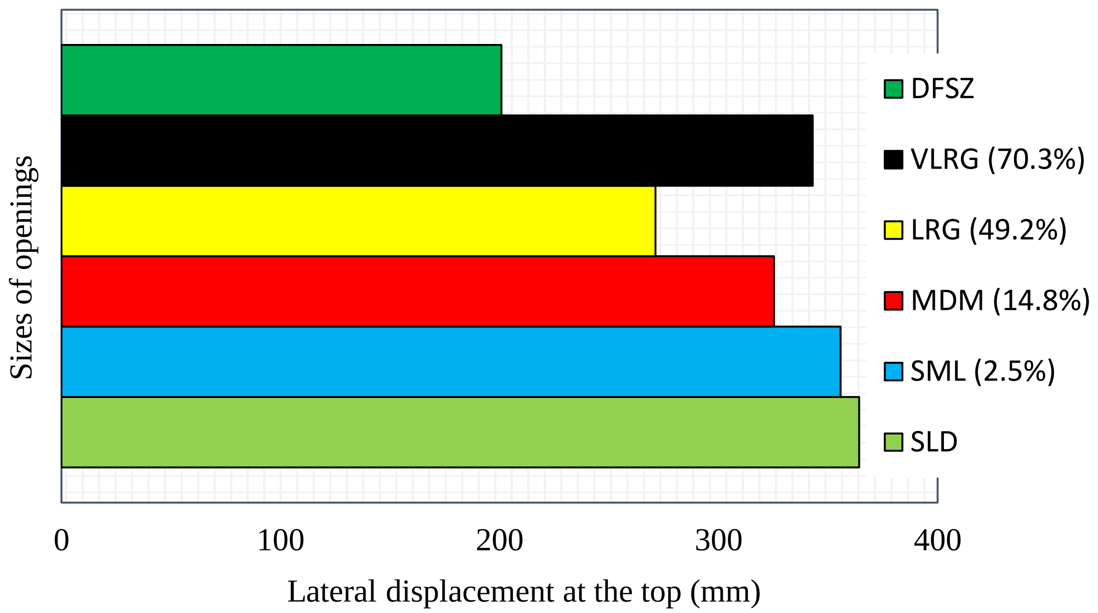


Figure 5.7: Displacement at the top of 40-storied SW1 with different sizes of opening

The trend is again similar for both 40-storied shear wall models with single bands of door openings (SW2) and two bands of door opening (SW3) as shown in Table 5.3. For all shear walls, it is observed that the shear walls with different sizes of symmetric openings, which gradually increases from the bottom storey to the top most storey, gives less lateral displacement at the top than shear walls without openings or with any sizes of openings.

5.3.2 Effects of Location of Openings

The location (Asymmetric, Symmetric and Staggered) of openings also affects the lateral displacement at the top of the walls. The lateral displacement of all the models with different location of openings are also tabulated in Table 5.4.

Table 5.4: Lateral displacement at the top (mm) of walls with different location of openings

Model		Location of shear wall openings				
		Without Opening	Asymmetric	Symmetric	Staggered	Different size
10-Storied	SW1	6.379	7.189	6.004	6.385	4.725
	SW2	10.804	11.964	10.063	10.513	8.419
	SW3	6.379	7.785	6.723	6.566	5.372
22-Storied	SW1	55.698	59.324	53.298	55.81	46.212
	SW2	72.794	76.642	68.79	71.36	59.809
	SW3	55.698	56.183	55.914	55.843	48.084
40-Storied	SW1	364.275	424.49	331.61	366.919	200.877
	SW2	606.765	682.072	542.496	583.956	352.882
	SW3	364.275	370.932	365.889	357.627	258.456

It was discussed in Section 5.3.1 that introducing small and medium openings into shear walls gives less lateral displacement at the top than the solid shear walls without opening. However, for all shear wall models, using asymmetric location of those openings gives larger lateral displacement at the top than even the solid shear walls without openings as shown in Table 5.4 which indicates that the location of openings also significantly affects the lateral displacement at the top of the walls. For example, the lateral displacement at the top of 10-storied SW1, 22-storied SW1 and 40-storied SW1 with asymmetric location of openings is 52.15%, 28.37% and 111.32% larger than lateral displacement of the corresponding SW1-DFSZ model respectively. The lateral displacement at the top of 40-storied SW1 with different locations of openings is shown in Figure 5.8 below.

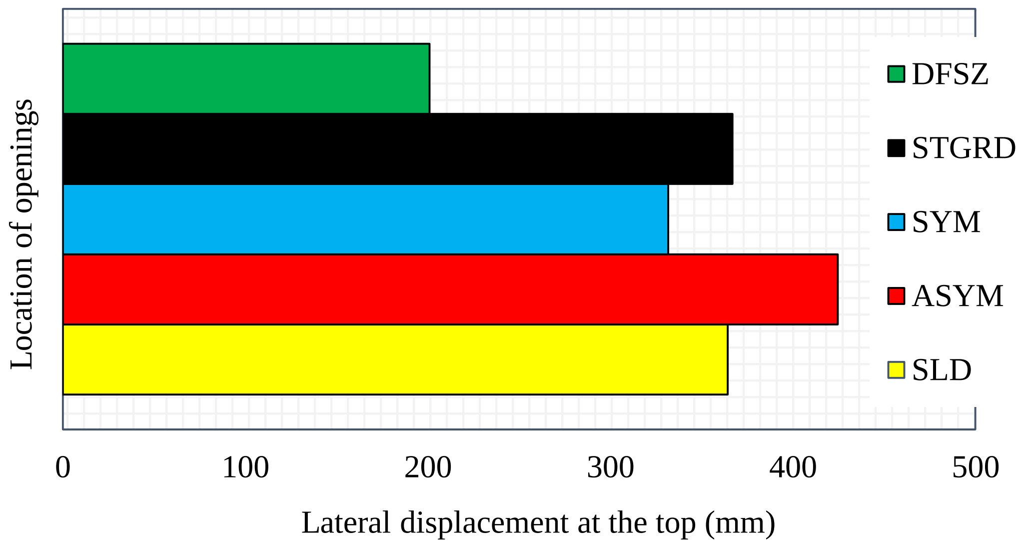


Figure 5.8: Displacement at the top 40-storied SW1 with different location of opening

For all shear wall models with single bands of window openings (SW1) and single band of door openings (SW2), using symmetric location of openings gives less lateral displacement at the top than the asymmetric and staggered location of openings. For all shear wall models with two bands of door openings (SW3), staggered location of openings gives slightly less lateral displacement at the top than symmetric location of openings as shown in Table 5.4. However, for all shear wall models, using different sizes of symmetric openings which gradually increases from the bottom storey to the top most storey (model DFSZ) is more effective in reducing the lateral displacement at the top than all other types of openings. For example, for the 40-storied shear wall models, SW1-DFSZ gives 44.86% less lateral displacement at the top than SW1-SLD as shown in Figure 5.8 and SW2-DFSZ gives 41.84% less lateral displacement at the top than SW2-SLD as shown in Figure 5.9.

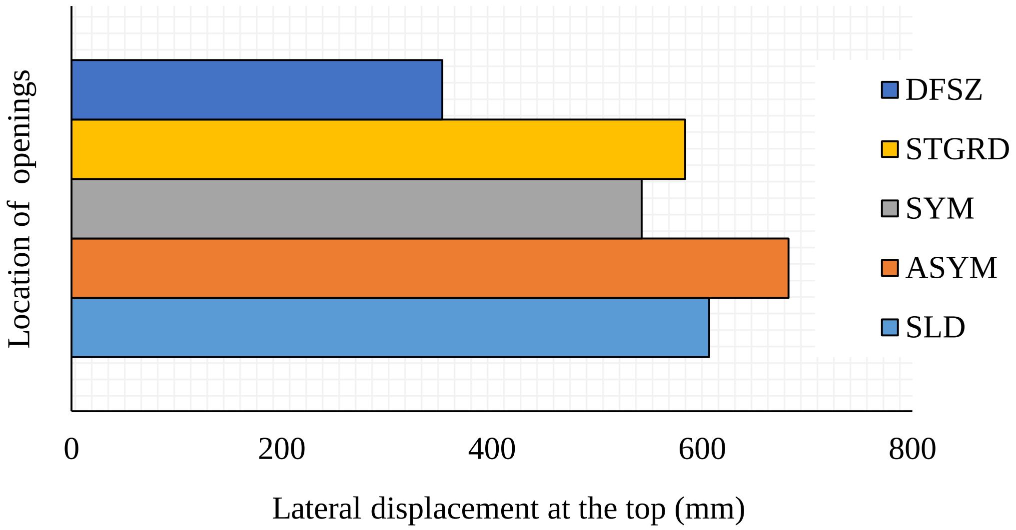


Figure 5.9: Displacement at the top of 40-storied SW2 with different location of opening

For all models, the shear walls with different sizes of openings which gradually increases from the bottom storey to the uppermost story is more effective in reducing the lateral displacement at the top and experiences a lower period of vibration than all other shear wall models with any sizes of openings due to the fact that, in the case of structures with a long natural period, the buildings will experience lower accelerations but larger displacements.

5.4 Story Drift

5.4.1 Effect of Size of Openings

Story drift is defined as the displacement of one storey level relative to the other storey level above or below. The storey drifts have been usually used to calculate expected damage to the structure during earthquake events. The story drifts of all the models with different size of openings are presented on Table A1 to Table A6 of Appendix A. Figure 5.10 shows the story drift of the 22-storied SW1 with different sizes of openings. As can be clearly observed from the figure, using relatively larger size of openings gives higher storey drift for bottom stories and lower storey drift for upper stories than using smaller openings.

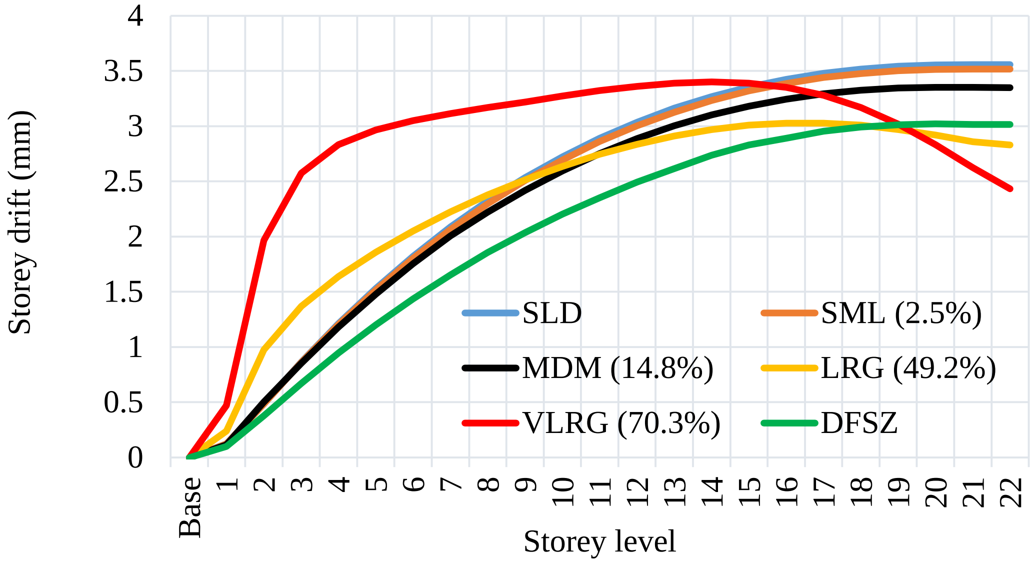


Figure 5.10: Story drift of 22-storied SW1 with different sizes of openings

However, using different sizes of openings which gradually increases from the bottom storey to the uppermost storey of the wall (DFSZ) is more effective in reducing the storey drift than the wall without opening or with smaller and larger openings. For the 10-Storied SW1 (Figure 5.11), using large (49.2%) size of openings leads to significant increases in storey drift. For the 40-Storied SW1(Figure 5.12), using DFSZ model significantly reduces the story drift throughout the height of the wall. The same is true for both SW2 and SW3 as shown on Table A2 to Table A6 of appendix A.

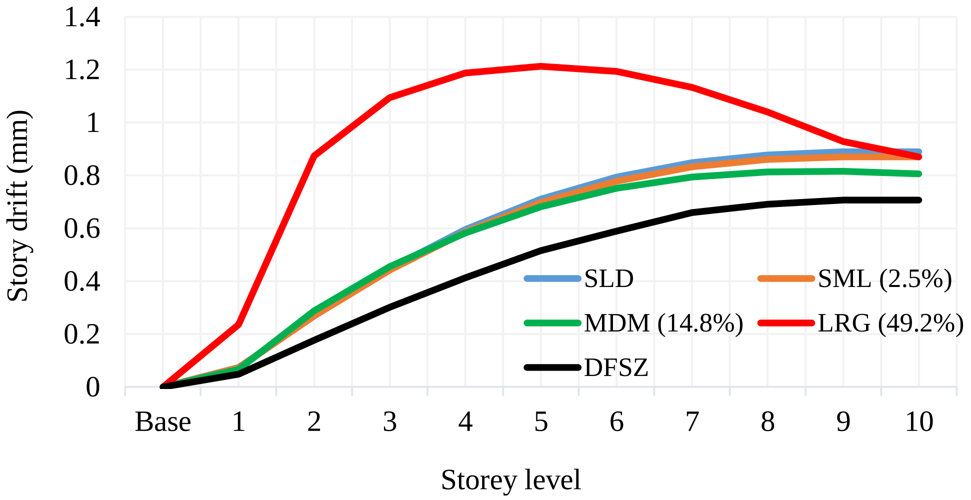


Figure 5.11: Storey drift of 10-storied SW1 with different sizes of openings

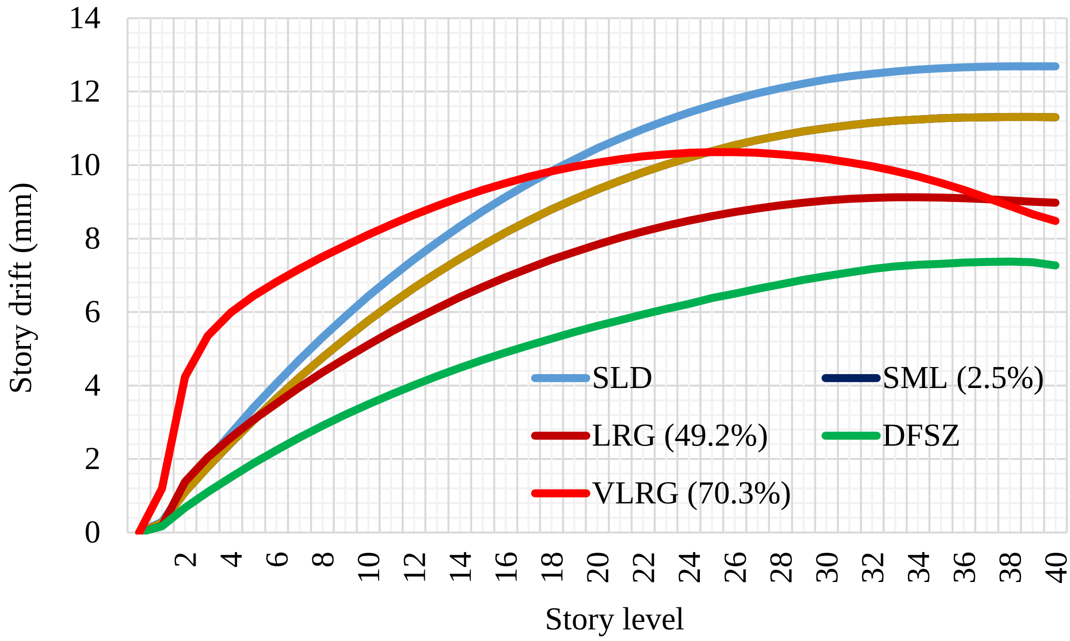


Figure 5.12: Story drift of 40-storied SW1 with different sizes of openings

5.4.2 Effects of Location of Openings

The storey drift of all models with different location of openings is shown on Table A.13 to Table A.15 of appendix A. For all models, the wall with different sizes of symmetric openings, which gradually increases from the bottom storey to the uppermost storey, gives less storey drift than the walls with ASYM, STGRD and even the SYM location of uniform size openings.

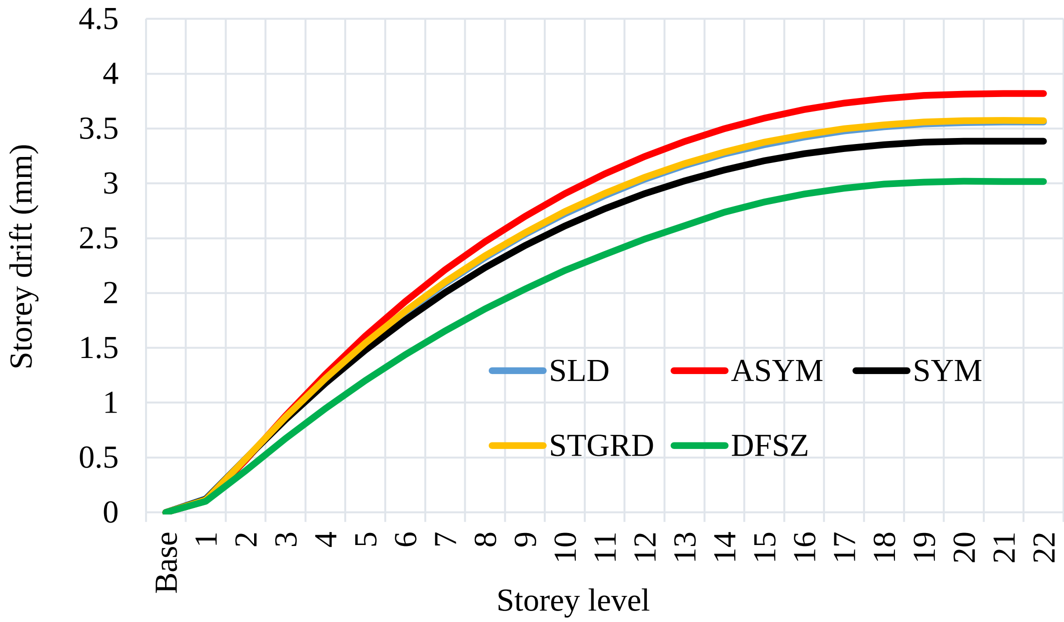


Figure 5.13: Story drift of 22-storied SW1 with different location of openings

Figure 5.13 shows that the storey drift of the 22-storied SW1 with different location of openings. Similarly, for all shear wall models, the response of shear walls with staggered location of openings is almost similar to corresponding solid walls without openings as far as story drift is considered. The results are similar for the 10-storied SW1 as shown in Figure 5.14.

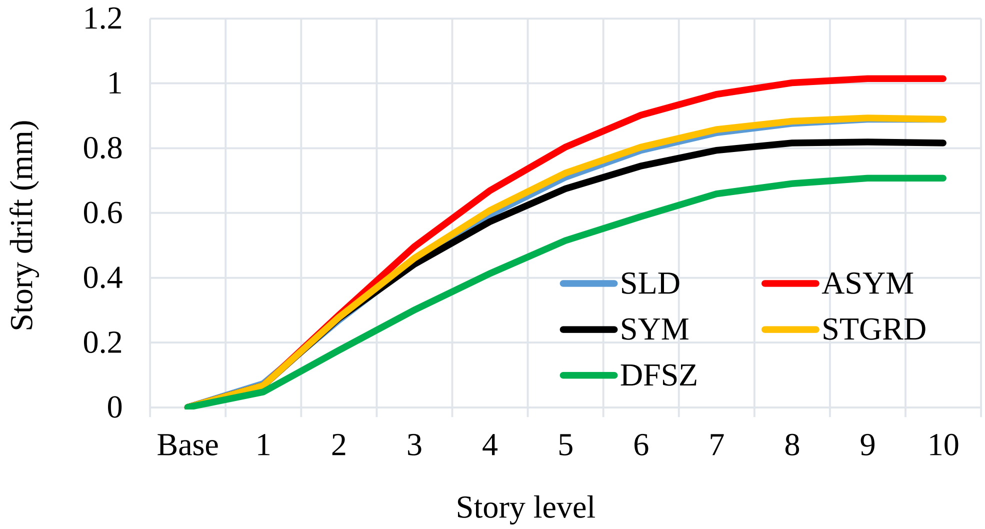


Figure 5.14: Story drift of 10-storied SW1 with different location of openings

The result is again similar for the 40-storied SW1 (Figure 5.15) except the effect is significant in the 40-storied shear walls as DFSZ model reduces the story drift of shear wall with asymmetric location of openings by more than half (*i.e. the average decrease is 51.55%).* The trend is found to be the similar for the 10-storied, 22 storied and 40 storied SW2s'.

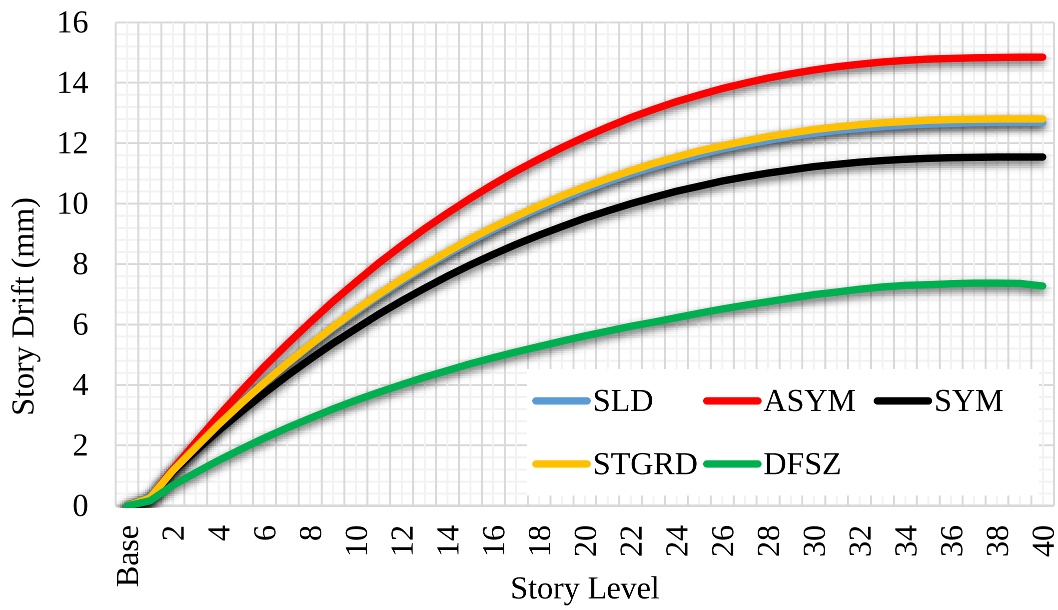


Figure 5.15: Story drift of 40-storied SW1 with different location of openings

For the shear wall with two bands of door openings (SW3), the asymmetric, symmetric and staggered locations of opening show no significant difference in story drift. However, using different sizes of symmetric openings which gradually increases from bottom storey to uppermost storey (DFSZ) again gives less storey drift than the asymmetric, symmetric and staggered location of openings as shown on Table A.13 to Table A.15 of Appendix A. Figure 5.16 and 5.17 show the story drift of the 22-storied SW1 and 40-storied SW1 with different locations of openings respectively.

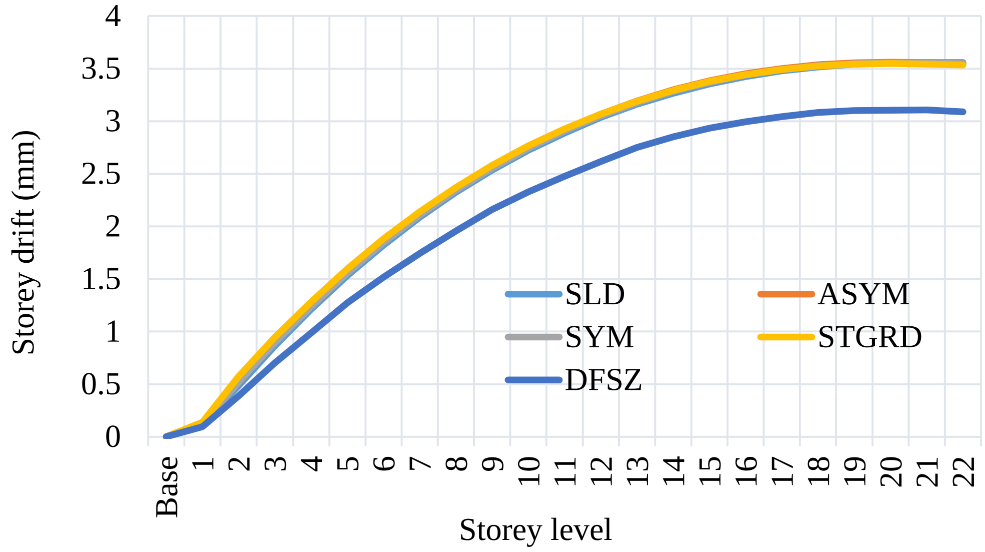


Figure 5.16: Story drift of 22-storied SW3 with different location of openings

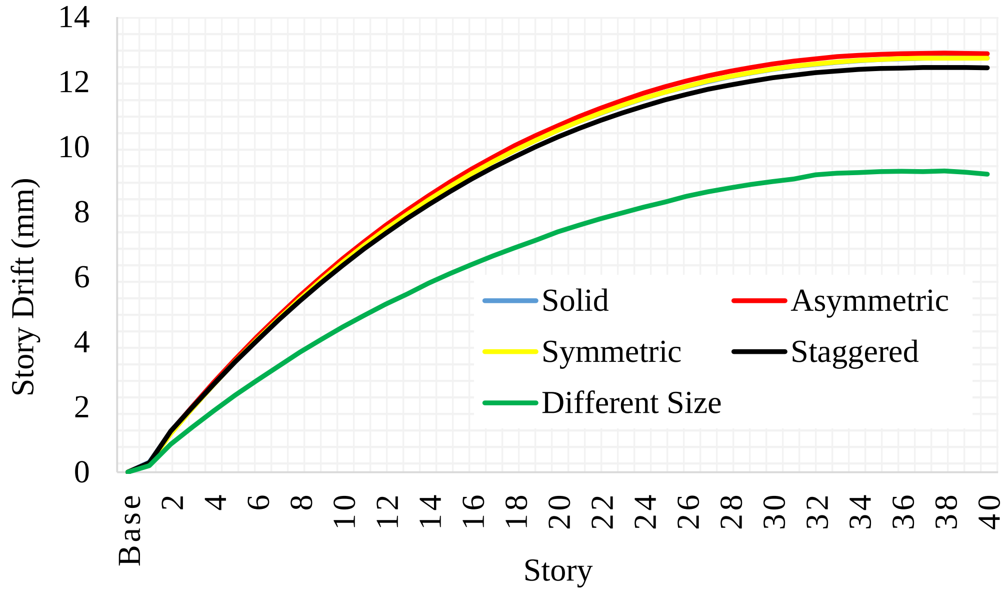


Figure 5.17: Storey drift of 40-storied SW3 with different location of openings

5.5 Story Displacement

5.5.1 Effect of size of Openings

Story displacement refers to the distance that points on a storey level are moved from their initial locations by the seismic waves. The maximum storey displacements for all models are shown in Table A7 to Table A12 of Appendix A. Figure 5.18 and 5.19 show the storey displacement of 10-storied and 22-storied SW1 with different sizes of openings respectively.

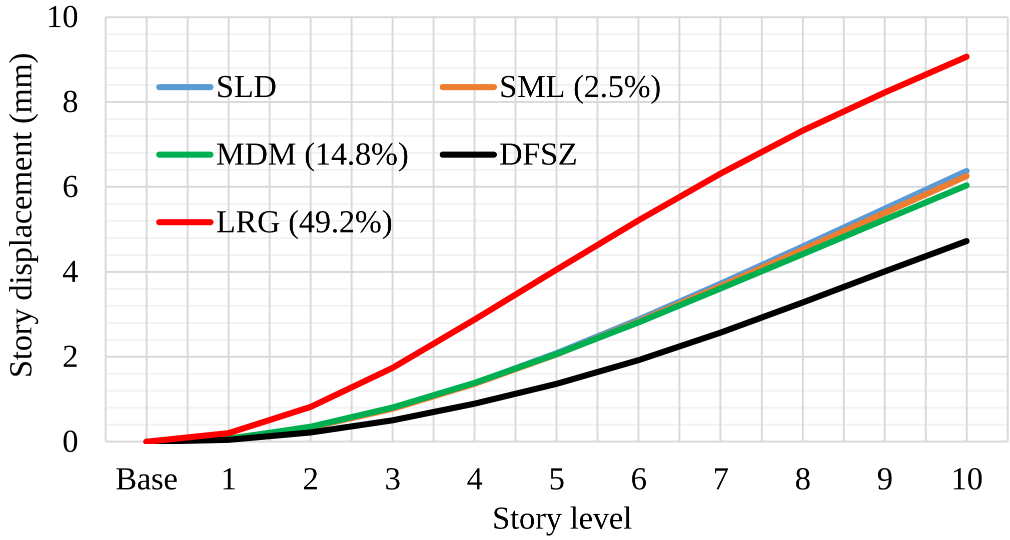


Figure 5.18: Story Displacement of 10-storied SW1 with different size of openings

For all shear wall models, the models with VLRG openings experiences higher storey displacement than the walls with smaller openings while the model with DFSZ openings gives less storey displacement than the solid shear walls without opening and the shear wall with small, medium, large or very large openings.

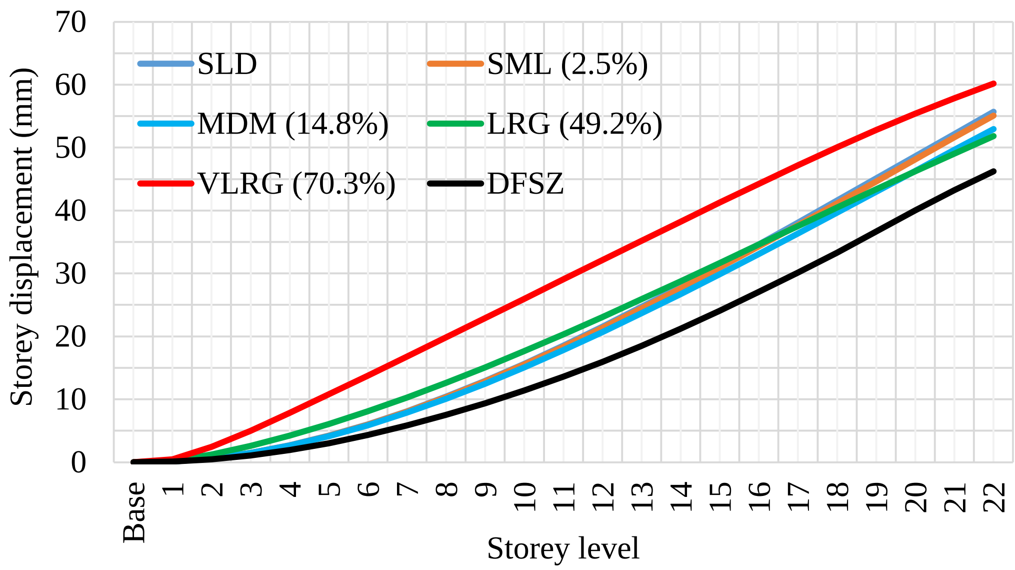


Figure 5.19: Story Displacement of 22-storied SW1 with different size of openings

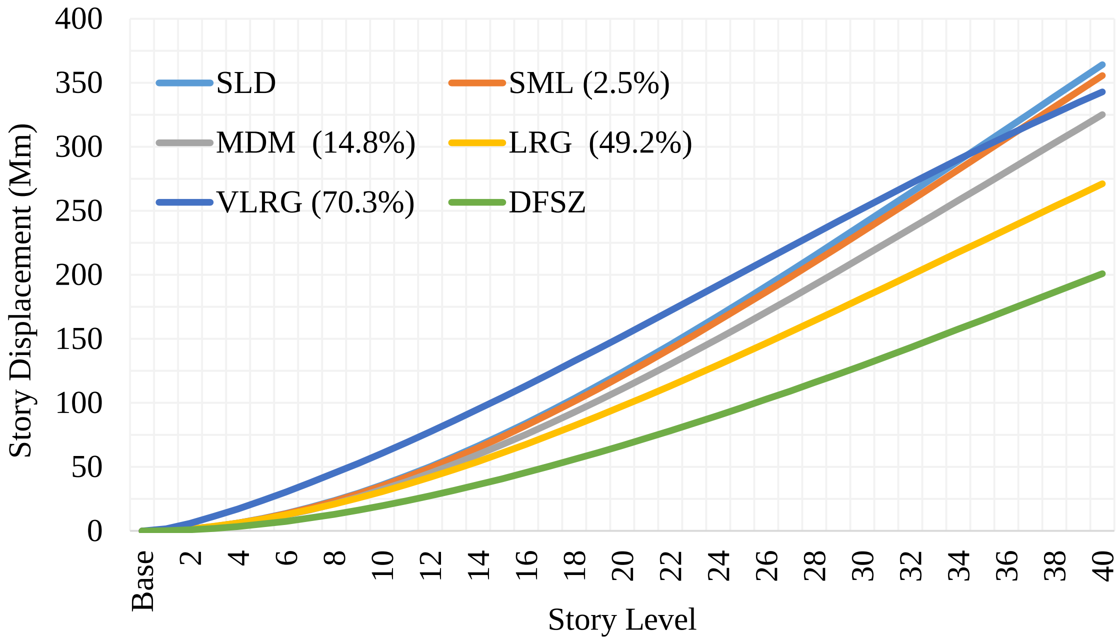


Figure 5.20: Story displacement of 40-storied SW1 with different size of openings

5.5.2 Effects of Location of Openings

The effects of location of openings on storey displacement of all models are shown in Table A.16 to Table A.18 of Appendix A. It can be clearly observed that, for all models, different sizes of openings which gradually increases from the bottom storey to the uppermost storey gave less storey displacement than asymmetric, symmetric and staggered location of openings and even the solid wall without opening. Figure 5.21 and 5.22 show the storey displacement of the 22-storied and 40-storied SW1 with different location of openings respectively.

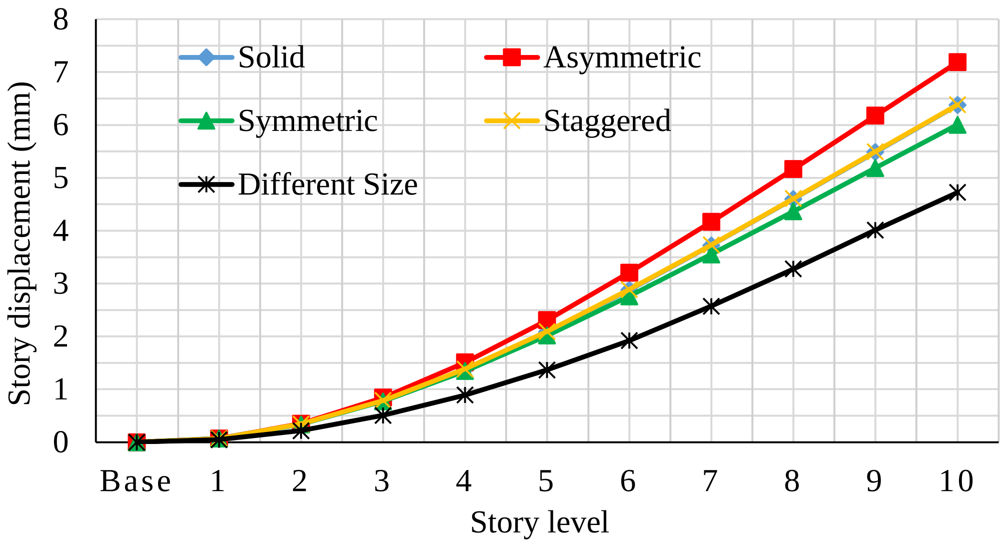


Figure 5.21: Story displacement of 10-storied SW1 with different location of openings

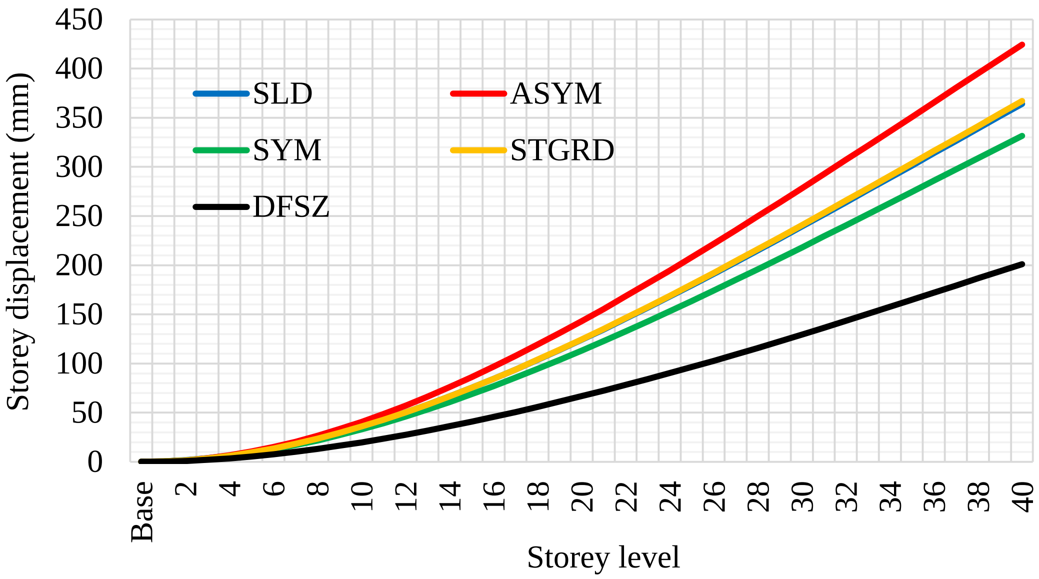


Figure 5.22: Storey displacement of 40-storied SW1 with different location of openings

For all models of SW1 and SW2, the storey displacement of shear wall with Staggered location of opening is almost equal to the storey displacement of solid wall without openings. For the wall with two bands of door openings (SW3), the difference in storey displacements of the models with symmetric, asymmetric and staggered location of openings is not significant. However, using different sizes of openings which gradually increases from the bottom storey to the uppermost storey again gives less storey displacement than all other location of openings as shown in Figure 5.23.

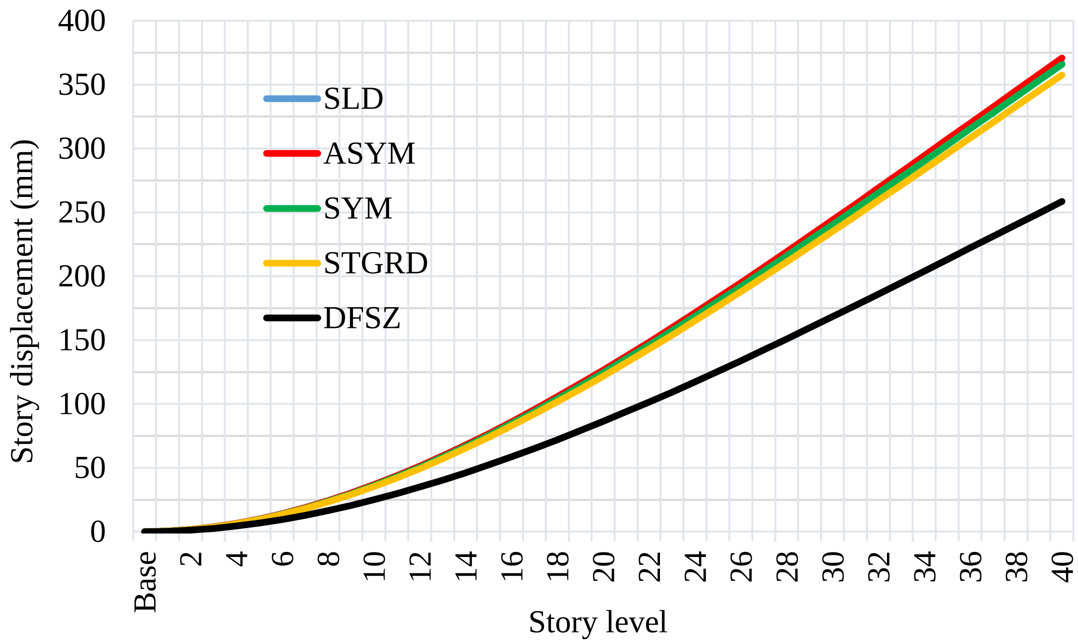


Figure 5.23: Story displacement of 40-storied SW3 with different location of openings

5.6 Shell's Internal Force Distributions

5.6.1 Effect of size of Openings

It can be clearly observed from Table 5.5 that introducing openings may slightly decrease the shell's internal forces in walls. However, using large or very large openings dramatically increase internal forces of the walls as in the case of 10-storied SW1 shown in Figure 5.24. For all shear wall models, using shear wall with different sizes of openings which gradually increases from the bottom storey to the uppermost story of the wall is more effective in reducing the internal forces experienced in walls as compared to solid shear wall without opening or walls with any uniform size of openings.

Table 5.5: Maximum shell force (kN) of all walls with different sizes of openings

Model		Sizes of shear wall openings					
		Solid	Small	Medium	Large	Very large	Different size
10-Storied	SW1	779.83	724.88	672.03	1062.48	1982.69	415.426
	SW2	959.33		893.94	2154.79		634.83
	SW3	779.83		698.73	1571.36		471.97
22-Storied	SW1	1313.01	1346.79	1251.11	1370.94	1652.40	973.969
	SW2	1279.60		1257.02	2032.67		1027.04
	SW3	1313.01		1265.92	1542.18		895.01
40-Storied	SW1	2474.47	2526.76	2201.99	1889.00	2745.56	1304.257
	SW2	3168.78		2915.05	2673.51		2059.80
	SW3	2474.47		1620.98	2549.03		1630.89

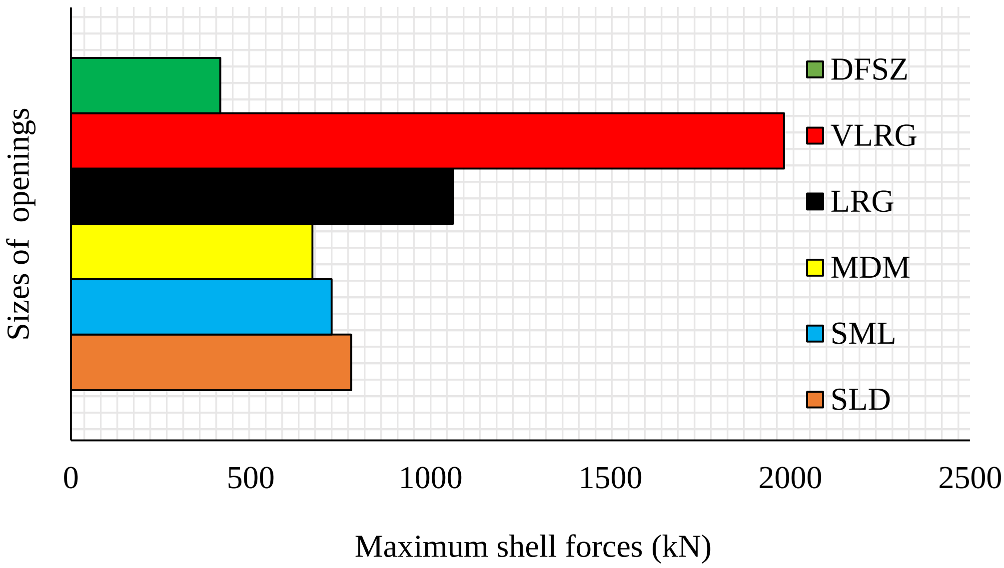


Figure 5.24: Max. shell forces of 10-storied SW1 with different size of openings

5.6.2 Effects of Location of Openings

For the different location of openings, using symmetric openings is more effective in reducing the shell's internal forces than staggered and asymmetric openings. However, for all shear wall models, using different sizes of openings which gradually increases from the bottom storey to the uppermost story of the wall was again found to be more effective in reducing the internal forces experienced by the walls compared to all other location of openings as shown in Table 5.6. For example, for the 10-storied SW1 (Figure 5.25), DFSZ model gives 57.01% less shell's internal force than the corresponding shear with asymmetric location of openings. The reduction is 63.66% in the 40-stoired SW1 and the trend is similar for almost all shear wall models as shown in Table 5.6.

Table 5.6: Maximum Shell force (kN) of walls with different location of openings

Model		Location of shear wall openings				
		SLD	ASYM	SYM	STGRD	DFSZ
10-Storied	SW1	779.83	962.655	723.782	720.503	415.426
	SW2	959.331	1050.533	893.935	883.263	634.826
	SW3	779.83	949.262	627.35	743.673	471.968
22-Storied	SW1	1313.012	1620.697	1230.12	1232.834	973.969
	SW2	1279.595	1479.82	1257.019	1254.428	1027.041
	SW3	1313.012	1463.817	1159.094	1532.583	895.012
40-Storied	SW1	2474.474	3589.65	2334.955	2458.32	1304.257
	SW2	3168.783	3983.906	2915.049	2971.543	2059.802
	SW3	2474.474	2982.898	2335.243	2782.59	1630.894

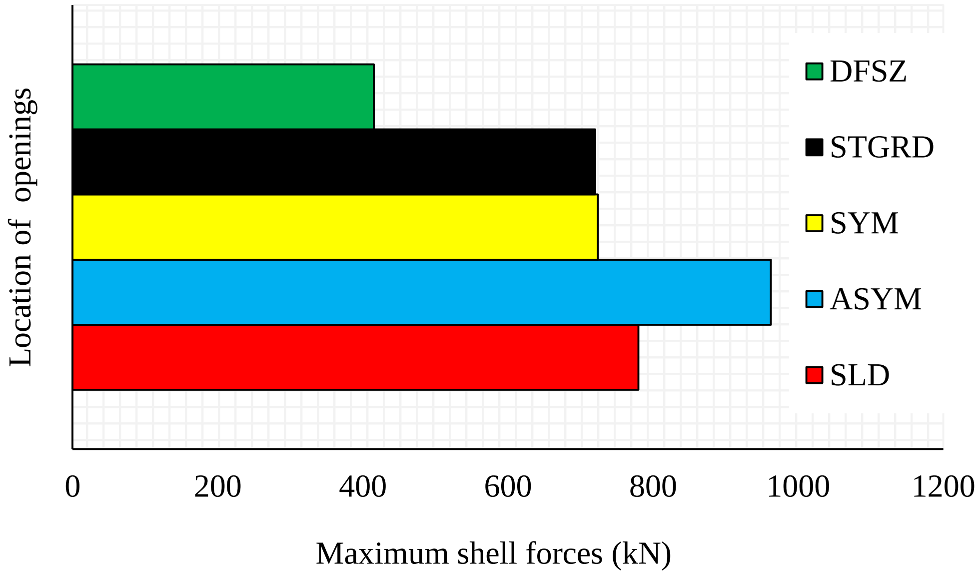


Figure 5.25: Max. shell forces of 10-storied SW1 with different location of openings

It can be observed from Figure 5.25 that, for the 10-storied SW1, the model with different sizes of symmetric openings, which gradually increases from the bottom storey to the top most storey, is very effective in reducing the maximum shell forces experienced in the shear wall as compared to all other location of openings and hence gives 56.85% lesser maximum shell force than the shear wall model with asymmetric location of openings. the trend is similar for both the 22-storied and 40-storied models as shown in Table 5.6. Figure 5.26 shows the maximum shell forces of 40-Storied SW1with different location of openings.

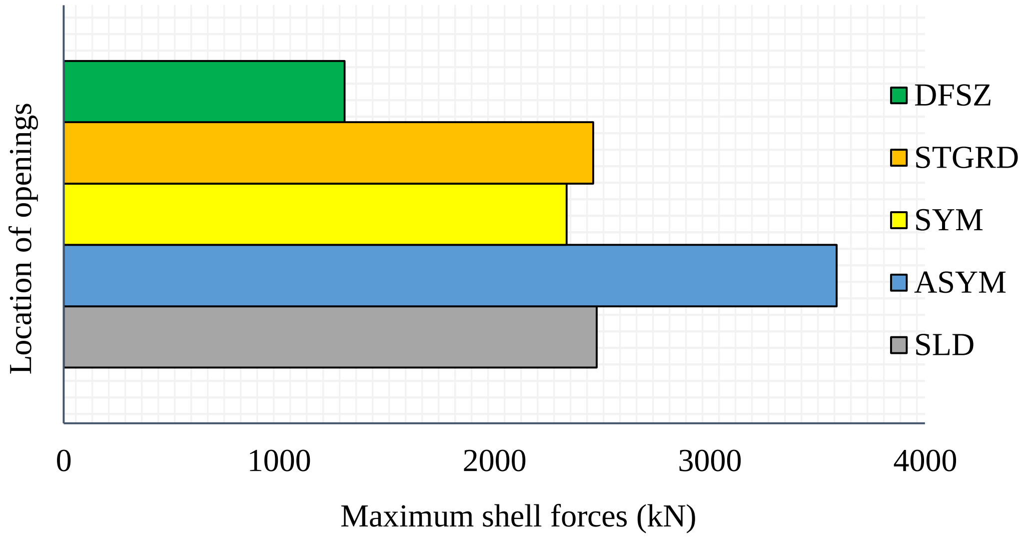


Figure 5.26: Max. shell forces of 40-storied SW1 with different location of openings

CHAPTER 6: CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The objective of this study was to better understand the behaviour of reinforced concrete shear walls with openings subjected to earthquake loading. With the application of finite element software, ETABS15.2.2, this study revealed that stiffness as well as seismic responses (lateral displacement, drift, base shear and shell's internal force distributions) of reinforced concrete shear walls are affected by the size of openings. It is concluded that introducing openings into reinforced concrete shear walls reduces the lateral displacement, story drift, base shear and shell stresses experienced by walls while using larger size of openings dramatically increases the lateral displacement, drift and shell's internal forces of the shear walls considered, which agrees with the finding of Baseer and Farrukh (2015). However, using different size of symmetric openings which gradually increases from the bottom storey of the wall to the top most storey of the wall is more effective in reducing the seismic responses as compared to the corresponding shear wall model with any size of opening or solid wall without openings.

The sizes of opening provided in reinforced concrete coupled walls also affects the effective stiffness of coupling beams due to the fact that the aspect ratio of the coupling beam, which determines its effective stiffness, is directly related to the size of the coupling beams and hence to the size of the openings provided.

The seismic behavior of the reinforced concrete shear walls considered not only depends on the size of openings but also on the location of openings. As far as lateral displacement, drift and shell forces are considered, shear wall with asymmetric location of openings gives significantly higher response than the shear wall with symmetric and staggered location of openings and shear wall models with symmetric location of openings gives reduced seismic responses than shear walls with asymmetric and staggered location of openings. It is, therefore, concluded that asymmetrical location of openings should be avoided as far as possible, which agrees with the findings of Pooja and Dr. SV Itti (2014). Moreover, using shear wall with different sizes of symmetric openings which gradually increases from the bottom storey to the top most storey is again more effective in reducing the seismic responses experienced by the wall as compared to all other location of uniform size openings and this trend increases with increasing story level. Generally, it is advisable to say that before introducing opening in reinforced concrete shear walls, proper analysis should be made so that unfavorable openings can be avoided.

6.2 Recommendation

As it was presented, symmetric location of opening is more efficient in reducing the seismic responses than asymmetric and staggered location of openings. However, two of the three shear walls used on 40/60 saving house projects have asymmetrical openings. It is therefore recommended to avoid asymmetric location of openings in those shear walls. Indeed, if practically feasible, it is recommended to use openings which increases from the bottom storey to the topmost storey, as this model gives less seismic responses than even the shear walls with any size of uniform symmetric openings. The advantage of using this type of shear wall over corresponding solid shear wall without opening is not limited to structural safety only but obviously reduces the amount of material to be used which tends to be more economic.

Due to the unavailability of testing machines (i.e. such as cyclic loading testing machine) and economic constraints, laboratory works required for this particular study are not covered in this paper. Therefore, if it seems economically feasible, it is recommended if this study is supported with laboratory works.

As it was presented, this study was carried out using response spectrum analysis with the help of ETABS15.2.2, finite element software. Non-linear time history analysis and Non-linear static (pushover) analysis for such area of interest should be studied in future work to get more comprehensive comments.

Though door openings usually start at the base of a story, there may sometimes be window openings located either at the top or bottom of the storey. Consequently, the findings from this study may or may not vary when the openings are located either at the top or bottom of the storey and therefore is suggested for future research. The effect of using boundary elements (Thickening wall around the window and/or door openings) on the seismic responses of reinforced concrete coupled shear walls is also suggested for future study.

In this study, the effective stiffness of coupling beams of all reinforced concrete coupled walls are determined by considering both shear and flexural deformations and was found to be dependent on the aspect ratio of the coupling beam. The effect of other parameters, such as reinforcement ratio and the way of reinforcing is suggested for future studies so that shear walls with openings can be understood in a better way.

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APPENDIX A: Displacement and Drift Results of all Models

Table A.1: Story drift of 10-storied SW1 with different sizes of openings

Story	Solid	Small	Medium	Large	Very large	Different size
Base	0	0	0	0	0	0
1	0.074	0.072	0.066	0.236	0.64	0.048
2	0.2688	0.2688	0.288	0.8736	2.6592	0.176
3	0.448	0.4416	0.4544	1.0944	3.3984	0.3008
4	0.5952	0.5856	0.5824	1.1872	3.5232	0.4128
5	0.7104	0.6976	0.6816	1.2128	3.3888	0.5152
6	0.7936	0.7776	0.752	1.1936	3.1008	0.5888
7	0.848	0.832	0.7936	1.1328	2.7104	0.6592
8	0.8768	0.8608	0.8128	1.04	2.2368	0.6912
9	0.8896	0.8704	0.816	0.928	1.7088	0.7072
10	0.8896	0.8704	0.8064	0.8704	1.216	0.7072

Table A.2: Story drifts of 22-storied SW1 with different sizes of openings

Story	Solid	Small	Medium	Large	Very large	Different size
Base	0	0	0	0	0	0
1	0.124	0.122	0.114	0.238	0.472	0.1
2	0.4864	0.4864	0.5024	0.976	1.9648	0.3776
3	0.864	0.8608	0.8544	1.3696	2.576	0.672
4	1.2128	1.2032	1.1808	1.6384	2.832	0.9472
5	1.5328	1.5168	1.4784	1.8592	2.9664	1.2
6	1.8208	1.8048	1.7536	2.0512	3.0496	1.4368
7	2.0864	2.064	2.0064	2.224	3.1136	1.6544
8	2.3232	2.2976	2.2208	2.3776	3.168	1.856
9	2.5344	2.5088	2.4192	2.5152	3.2192	2.0352
10	2.7232	2.6944	2.5952	2.6368	3.2736	2.2048
11	2.8896	2.8608	2.752	2.7456	3.3216	2.352
12	3.0368	3.0048	2.8864	2.8352	3.36	2.4928
13	3.1616	3.1264	3.0048	2.912	3.3888	2.6144
14	3.2672	3.232	3.1008	2.9696	3.4016	2.736
15	3.3536	3.3184	3.1808	3.008	3.3888	2.8288
16	3.424	3.3856	3.2448	3.0272	3.3504	2.8907424
17	3.4784	3.44	3.2928	3.0272	3.28	2.9542848
18	3.5168	3.4752	3.3248	3.008	3.168	2.9929056
19	3.5424	3.5008	3.344	2.9696	3.0176	3.0116
20	3.5552	3.5136	3.3504	2.9184	2.832	3.0202848
21	3.5584	3.5168	3.3504	2.8576	2.624	3.0164544
22	3.5584	3.5168	3.3472	2.8288	2.432	3.0162016

Table A.3: Story drifts of 40-storied SW1 with different sizes of openings

Story	Solid	Small	Medium	Large	Very large	Different size
Base	0	0	0	0	0	0
1	0.292	0.254	0.254	0.176	1.2	0.17
2	1.1936	1.1008	1.1008	1.376	4.24	0.672
3	1.9616	1.776	1.776	2.0448	5.3504	1.0976
4	2.6944	2.432	2.432	2.5824	5.984	1.5008
5	3.3984	3.056	3.056	3.0656	6.4416	1.8816
6	4.064	3.6544	3.6544	3.5168	6.8256	2.2432
7	4.7008	4.2208	4.2208	3.9456	7.1744	2.5824
8	5.3088	4.7616	4.7616	4.3552	7.5008	2.9024
9	5.8816	5.2736	5.2736	4.7424	7.8112	3.2064
10	6.4288	5.76	5.76	5.1104	8.1056	3.488
11	6.944	6.2208	6.2208	5.4624	8.3872	3.76
12	7.4336	6.656	6.656	5.792	8.6496	4.0128
13	7.8976	7.0688	7.0688	6.1056	8.8928	4.2528
14	8.336	7.456	7.456	6.4032	9.12	4.48
15	8.7456	7.8208	7.8208	6.6816	9.3248	4.6944
16	9.136	8.1632	8.1632	6.944	9.5104	4.8992
17	9.4976	8.4864	8.4864	7.1904	9.68	5.0912
18	9.84	8.7904	8.7904	7.424	9.8272	5.2736
19	10.1568	9.072	9.072	7.6384	9.9584	5.4528
20	10.4544	9.3344	9.3344	7.8368	10.0672	5.6192
21	10.7296	9.5808	9.5808	8.0224	10.1632	5.7792
22	10.9824	9.808	9.808	8.192	10.2368	5.936
23	11.216	10.016	10.016	8.3488	10.2944	6.08
24	11.4304	10.208	10.208	8.4864	10.3328	6.2272
25	11.6256	10.3808	10.3808	8.6144	10.352	6.3776
26	11.8016	10.5408	10.5408	8.7264	10.352	6.5056
27	11.9584	10.6816	10.6816	8.8224	10.3328	6.6368
28	12.096	10.8064	10.8064	8.9088	10.2944	6.7584
29	12.2208	10.9152	10.9152	8.9792	10.24	6.8736
30	12.3264	11.008	11.008	9.0336	10.1696	6.9856
31	12.416	11.088	11.088	9.0784	10.0768	7.0752
32	12.4896	11.152	11.152	9.1072	9.968	7.1712
33	12.5504	11.2032	11.2032	9.1232	9.8368	7.2448
34	12.5984	11.2448	11.2448	9.1264	9.6864	7.2896
35	12.6336	11.2736	11.2736	9.12	9.5136	7.312
36	12.6592	11.2928	11.2928	9.1008	9.3216	7.3504
37	12.6752	11.3056	11.3056	9.072	9.1104	7.3664
38	12.6848	11.3088	11.3088	9.0336	8.8864	7.3728
39	12.688	11.3088	11.3088	8.9984	8.6656	7.36
40	12.6848	11.3056	11.3056	8.976	8.48	7.2704

Table A.4: Story drifts of 10-storied SW2 and SW3 with different sizes of openings

Story	Shear wall 2 (SW2)				Shear wall 3 (SW3)			
	Without opening	Medium size	Large size	Different size	Without opening	Medium size	Large size	Different size
Base	0	0	0	0	0	0	0	0
1	0.106	0.102	0.44	0.074	0.074	0.076	0.278	0.05
2	0.4416	0.4448	1.8784	0.3296	0.2688	0.3104	1.1136	0.2208
3	0.7488	0.7264	2.5216	0.56	0.448	0.4768	1.4272	0.3584
4	1.0016	0.9536	2.7392	0.7648	0.5952	0.6112	1.5424	0.48
5	1.2	1.1264	2.7488	0.928	0.7104	0.7168	1.568	0.576
6	1.344	1.2544	2.6208	1.0592	0.7904	0.7872	1.5328	0.6432
7	1.44	1.3344	2.4	1.152	0.848	0.8352	1.4464	0.6784
8	1.4976	1.3792	2.0992	1.2096	0.8768	0.8544	1.312	0.7072
9	1.52	1.392	1.7568	1.2128	0.8896	0.8544	1.1424	0.70112
10	1.5232	1.3824	1.44	1.1584	0.8896	0.8416	0.9696	0.6976

Table A.5: Story drifts of 22-storied SW2 and SW3 with different sizes of openings

Story	Shear wall 2 (SW2)				Shear wall 3 (SW3)			
	Without opening	Medium size	Large size	Different size	Without opening	Medium size	Large size	Different size
Base	0	0	0	0	0	0	0	0
1	0.142	0.138	0.408	0.11	0.124	0.124	0.28	0.094
2	0.6368	0.6304	1.776	0.5088	0.4864	0.5184	1.1616	0.3872
3	1.136	1.1008	2.4896	0.9056	0.864	0.8704	1.6	0.7008
4	1.5936	1.5296	2.8544	1.264	1.2128	1.2064	1.8784	0.9888
5	2.0096	1.92	3.0784	1.6064	1.5328	1.5104	2.1024	1.2736
6	2.3872	2.272	3.2352	1.8976	1.8208	1.7856	2.2944	1.5168
7	2.7296	2.592	3.3568	2.16	2.0864	2.0384	2.464	1.744
8	3.0368	2.88	3.4688	2.4096	2.3232	2.2624	2.6144	1.9552
9	3.312	3.136	3.5712	2.6592	2.5344	2.4672	2.752	2.16
10	3.5584	3.3664	3.6736	2.848	2.7232	2.6464	2.8768	2.3264
11	3.776	3.5712	3.7696	3.0208	2.8896	2.8064	2.9856	2.4768
12	3.968	3.7504	3.8592	3.1904	3.0368	2.944	3.0816	2.6176
13	4.1344	3.904	3.936	3.3472	3.1616	3.0624	3.1616	2.752
14	4.2784	4.0384	3.9936	3.488	3.2672	3.1616	3.2224	2.8512
15	4.3968	4.1504	4.0256	3.5904	3.3536	3.2448	3.264	2.9344
16	4.4928	4.2368	4.0288	3.6864	3.424	3.3088	3.2832	2.9952
17	4.5696	4.3072	3.9904	3.7888	3.4784	3.3568	3.28	3.0432
18	4.624	4.3552	3.9136	3.8592	3.5168	3.392	3.2512	3.0816
19	4.6624	4.3872	3.792	3.8784	3.5424	3.4112	3.2032	3.1008
20	4.6816	4.4032	3.6352	3.8976	3.5552	3.4176	3.1328	3.104
21	4.6912	4.4096	3.4592	3.8592	3.5584	3.4176	3.0496	3.1072
22	4.6912	4.4064	3.3056	3.7536	3.5584	3.4112	2.9664	3.088

Table A.6: Story drifts of 40-storied SW2 and SW3 with different sizes of openings

Story	Shear wall 2 (SW2)				Shear wall 3 (SW3)			
	Without opening	Medium size	Large size	Different size	Without opening	Medium size	Large size	Different size
Base	0	0	0	0	0	0	0	0
1	0.336	0.308	0.57	0.206	0.306	0.27	0.572	0.202
2	1.5552	1.4368	2.6048	0.9568	1.2448	1.1872	1.9808	0.8608
3	2.8608	2.6048	3.9104	1.7216	2.0128	1.9552	2.6848	1.3824
4	4.112	3.7216	4.8256	2.448	2.7488	2.6944	3.2768	1.888
5	5.3088	4.7904	5.5776	3.1488	3.4496	3.4016	3.824	2.3648
6	6.4512	5.8112	6.2496	3.8048	4.1184	4.0736	4.3392	2.8192
7	7.5456	6.784	6.8736	4.4288	4.7552	4.7168	4.832	3.2512
8	8.5856	7.712	7.4656	5.0272	5.36	5.3248	5.3024	3.6864
9	9.5744	8.5952	8.0288	5.5872	5.936	5.9072	5.7472	4.0832
10	10.5184	9.4336	8.5632	6.1216	6.4832	6.4544	6.1728	4.464
11	11.4112	10.2304	9.072	6.6336	7.0016	6.976	6.576	4.8224
12	12.2592	10.9824	9.5552	7.1104	7.4912	7.472	6.9568	5.1616
13	13.0624	11.696	10.0128	7.5648	7.952	7.936	7.3216	5.4848
14	13.8208	12.3712	10.4416	8	8.3904	8.3776	7.664	5.8144
15	14.5344	13.0048	10.8448	8.4	8.8032	8.7936	7.9872	6.1088
16	15.2032	13.6032	11.2192	8.784	9.1904	9.184	8.288	6.3872
17	15.8336	14.1632	11.5648	9.1552	9.5552	9.552	8.5728	6.6528
18	16.4224	14.6848	11.888	9.4912	9.8976	9.8944	8.8384	6.8992
19	16.9696	15.1744	12.1824	9.8144	10.2144	10.2144	9.0848	7.136
20	17.4784	15.6256	12.4512	10.1248	10.512	10.5152	9.312	7.3888
21	17.9488	16.0448	12.6944	10.4	10.7872	10.7904	9.52	7.5968
22	18.3808	16.432	12.912	10.6656	11.04	11.0464	9.712	7.792
23	18.7776	16.784	13.104	10.9216	11.2736	11.2832	9.8848	7.9776
24	19.136	17.1072	13.2736	11.1424	11.488	11.4976	10.0416	8.1472
25	19.4624	17.3984	13.4176	11.3536	11.6832	11.6928	10.1792	8.3072
26	19.7568	17.6608	13.5392	11.5584	11.8592	11.8688	10.3008	8.4896
27	20.0192	17.8944	13.6384	11.728	12.016	12.0288	10.4096	8.624
28	20.2496	18.1024	13.7152	11.888	12.1568	12.1664	10.4992	8.7392
29	20.4512	18.2816	13.7696	12.0448	12.2784	12.2912	10.5728	8.8512
30	20.624	18.4384	13.8016	12.1664	12.384	12.3936	10.6304	8.9408
31	20.7712	18.5696	13.8112	12.2752	12.4736	12.4832	10.6752	9.0208
32	20.8928	18.6784	13.8016	12.384	12.5472	12.5568	10.7008	9.1424
33	20.9888	18.7648	13.7728	12.4512	12.608	12.6176	10.7136	9.1936
34	21.0656	18.832	13.7216	12.5024	12.656	12.6624	10.7104	9.2192
35	21.1232	18.8832	13.648	12.5536	12.6912	12.6976	10.6944	9.2448
36	21.1648	18.9184	13.5584	12.56	12.7168	12.72	10.6656	9.2544
37	21.1904	18.9408	13.4496	12.5472	12.7328	12.7328	10.624	9.2416
38	21.2064	18.9504	13.3344	12.5376	12.7424	12.736	10.576	9.2608
39	21.2128	18.9536	13.2128	12.4704	12.7456	12.736	10.5216	9.2224
40	21.2128	18.9504	13.1136	12.3936	12.7456	12.7296	10.4704	9.168

Table A.7: Story displacement of 10-storied SW1 with different size of openings

Story	Solid	Small	Medium	Large	Very large	Different size
Base	0	0	0	0	0	0
1	0.075	0.073	0.067	0.2	0.64	0.048
2	0.342	0.338	0.352	0.821	3.299	0.218
3	0.788	0.778	0.803	1.743	6.695	0.506
4	1.381	1.361	1.384	2.88	10.203	0.893
5	2.088	2.055	2.064	4.057	13.543	1.367
6	2.878	2.83	2.813	5.215	16.565	1.922
7	3.723	3.659	3.606	6.314	19.17	2.572
8	4.6	4.518	4.418	7.322	21.287	3.279
9	5.489	5.387	5.232	8.222	22.882	4.012
10	6.379	6.257	6.04	9.066	24.023	4.725

Table A.8: Story displacement of 22-storied SW1 with different size of openings

Story	Solid	Small	Medium	Large	Very large	Different size
Base	0	0	0	0	0	0
1	0.124	0.123	0.115	0.24	0.471	0.09
2	0.608	0.606	0.612	1.213	2.435	0.438
3	1.47	1.462	1.464	2.58	5.01	1.057
4	2.68	2.662	2.642	4.211	7.833	1.926
5	4.207	4.175	4.118	6.056	10.772	3.023
6	6.025	5.975	5.869	8.088	13.772	4.332
7	8.104	8.033	7.868	10.284	16.804	5.831
8	10.418	10.324	10.081	12.624	19.855	7.514
9	12.942	12.822	12.489	15.09	22.916	9.362
10	15.653	15.504	15.071	17.666	25.983	11.386
11	18.527	18.348	17.806	20.337	29.055	13.571
12	21.543	21.322	20.673	23.089	32.127	15.956
13	24.682	24.437	23.653	25.907	35.194	18.506
14	27.923	27.643	26.727	28.777	38.247	21.21
15	31.25	30.933	29.88	31.683	41.276	24.087
16	34.645	34.29	33.094	34.61	44.265	27.095
17	38.092	37.699	36.355	37.543	47.194	30.164
18	41.579	41.146	39.649	40.464	50.04	33.287
19	45.092	44.618	42.965	43.359	52.778	36.64
20	48.621	48.106	46.291	46.214	55.384	40.004
21	52.158	51.601	49.62	49.025	57.841	43.216
22	55.698	55.099	52.95	51.814	60.163	46.212

Table A.9: Story displacement of 40-storied SW1 with different size of openings

Story	Solid	Small	Medium	Large	Very large	Different size
Base	0	0	0	0	0	0
1	0.439	0.43	0.381	0.264	1.799	0.255
2	1.627	1.596	1.473	1.594	6.038	0.915
3	3.584	3.513	3.247	3.638	11.385	2.009
4	6.276	6.147	5.675	6.217	17.36	3.505
5	9.669	9.466	8.729	9.274	23.782	5.383
6	13.729	13.436	12.378	12.779	30.573	7.62
7	18.425	18.026	16.595	16.708	37.695	10.198
8	23.724	23.204	21.35	21.039	45.123	13.093
9	29.596	28.942	26.616	25.751	52.838	16.289
10	36.011	35.209	32.366	30.823	60.824	19.766
11	42.939	41.978	38.572	36.236	69.067	23.51
12	50.353	49.219	45.211	41.972	77.551	27.503
13	58.225	56.908	52.255	48.011	86.261	31.732
14	66.529	65.017	59.683	54.337	95.18	36.18
15	75.238	73.522	67.47	60.933	104.291	40.834
16	84.329	82.399	75.594	67.781	113.576	45.686
17	93.777	91.624	84.034	74.868	123.016	50.719
18	103.558	101.174	92.768	82.175	132.593	55.925
19	113.65	111.027	101.778	89.689	142.289	61.298
20	124.03	121.162	111.042	97.393	152.085	66.824
21	134.678	131.558	120.543	105.274	161.964	72.494
22	145.573	142.194	130.262	113.317	171.909	78.308
23	156.694	153.051	140.182	121.507	181.901	84.252
24	168.022	164.11	150.286	129.83	191.923	90.328
25	179.538	175.353	160.557	138.274	201.959	96.535
26	191.224	186.762	170.979	146.824	211.989	102.858
27	203.062	198.319	181.538	155.469	221.998	109.294
28	215.036	210.009	192.217	164.194	231.968	115.862
29	227.13	221.815	203.003	172.988	241.882	122.536
30	239.327	233.722	213.881	181.84	251.725	129.332
31	251.613	245.717	224.839	190.736	261.48	136.269
32	263.975	257.786	235.863	199.666	271.132	143.302
33	276.399	269.915	246.943	208.619	280.665	150.426
34	288.874	282.095	258.067	217.584	290.064	157.619
35	301.389	294.313	269.225	226.552	299.313	164.819
36	313.934	306.56	280.409	235.512	308.399	172.053
37	326.501	318.829	291.611	244.458	317.307	179.313
38	339.084	331.113	302.824	253.381	326.03	186.56
39	351.676	343.406	314.043	262.281	334.568	193.755
40	364.275	355.706	325.267	271.17	342.953	200.877

Table A.10: Story displacement of 10-storied SW2 & SW3 with different sizes of openings

Story	Shear wall 2 (SW2)				Shear wall 3 (SW3)			
	Without opening	Medium size	Large size	Different size	Without opening	Medium size	Large size	Different size
Base	0	0	0	0	0	0	0	0
1	0.106	0.102	0.441	0.075	0.075	0.076	0.278	0.051
2	0.545	0.543	2.317	0.404	0.342	0.377	1.391	0.271
3	1.292	1.268	4.837	0.962	0.788	0.851	2.817	0.629
4	2.291	2.218	7.567	1.725	1.381	1.46	4.351	1.108
5	3.487	3.342	10.286	2.653	2.088	2.171	5.903	1.693
6	4.827	4.591	12.861	3.712	2.878	2.955	7.411	2.369
7	6.265	5.922	15.198	4.864	3.723	3.784	8.827	3.119
8	7.76	7.295	17.228	6.068	4.6	4.634	10.105	3.921
9	9.28	8.682	18.919	7.272	5.489	5.484	11.216	4.686
10	10.804	10.063	20.318	8.419	6.379	6.325	12.168	5.372

Table A.11: Story displacement of 22-storied SW2 & SW3 with different sizes of openings

Story	Shear wall 2 (SW2)				Shear wall 3 (SW3)			
	Without opening	Medium size	Large size	Differen t size	Without opening	Medium size	Large size	Differen t size
Base	0	0	0	0	0	0	0	0
1	0.142	0.139	0.408	0.108	0.124	0.125	0.281	0.095
2	0.775	0.766	2.184	0.596	0.608	0.629	1.443	0.478
3	1.908	1.865	4.669	1.454	1.47	1.498	3.04	1.171
4	3.499	3.39	7.514	2.653	2.68	2.699	4.91	2.159
5	5.505	5.304	10.565	4.165	4.208	4.204	6.995	3.424
6	7.887	7.57	13.745	5.965	6.025	5.984	9.26	4.938
7	10.608	10.151	17.014	8.026	8.104	8.014	11.682	6.677
8	13.631	13.016	20.351	10.329	10.418	10.268	14.242	8.628
9	16.923	16.133	23.745	12.85	12.943	12.721	16.922	10.775
10	20.455	19.474	27.19	15.575	15.653	15.352	19.706	13.089
11	24.198	23.012	30.684	18.485	18.527	18.137	22.583	15.55
12	28.126	26.722	34.222	21.573	21.544	21.058	25.539	18.148
13	32.212	30.581	37.8	24.825	24.682	24.093	28.56	20.875
14	36.436	34.567	41.41	28.243	27.924	27.226	31.634	23.698
15	40.774	38.659	45.037	31.809	31.251	30.439	34.744	26.601
16	45.205	42.837	48.666	35.522	34.646	33.714	37.875	29.576
17	49.711	47.083	52.275	39.314	38.093	37.038	41.009	32.618
18	54.272	51.379	55.838	43.268	41.58	40.396	44.127	35.694
19	58.874	55.709	59.327	47.325	45.093	43.775	47.213	38.794
20	63.502	60.061	62.715	51.528	48.622	47.166	50.248	41.91
21	68.144	64.424	65.989	55.759	52.159	50.56	53.221	45.007
22	72.794	68.79	69.161	59.809	55.699	53.952	56.134	48.074

Table A.12: Story displacement of 40-storied SW2 & SW3 with different sizes of openings

Story	Shear wall 2 (SW2)				Shear wall 3 (SW3)			
	Without opening	Medium size	Large size	Different size	Without opening	Medium size	Large size	Different size
Base	0	0	0	0	0	0	0	0
1	0.336	0.307	0.57	0.206	0.439	0.432	0.917	0.325
2	1.888	1.742	3.174	1.16	1.627	1.559	2.896	1.162
3	4.746	4.344	7.08	2.878	3.584	3.512	5.572	2.543
4	8.854	8.063	11.896	5.325	6.276	6.203	8.834	4.426
5	14.158	12.849	17.454	8.47	9.669	9.599	12.637	6.788
6	20.606	18.655	23.671	12.27	13.729	13.668	16.95	9.598
7	28.144	25.433	30.5	16.693	18.425	18.377	21.749	12.843
8	36.721	33.135	37.904	21.712	23.724	23.694	27.008	16.514
9	46.286	41.718	45.855	27.289	29.596	29.587	32.706	20.587
10	56.79	51.136	54.325	33.396	36.011	36.028	38.818	25.034
11	68.185	61.347	63.289	40.009	42.939	42.985	45.325	29.836
12	80.423	72.306	72.721	47.093	50.353	50.432	52.204	34.969
13	93.459	83.974	82.596	54.624	58.225	58.34	59.435	40.422
14	107.246	96.311	92.888	62.581	66.529	66.682	66.999	46.193
15	121.741	109.275	103.571	70.932	75.238	75.434	74.875	52.256
16	136.9	122.83	114.62	79.658	84.329	84.57	83.045	58.587
17	152.681	136.938	126.007	88.742	93.777	94.066	91.49	65.175
18	169.043	151.562	137.708	98.154	103.558	103.897	100.19	71.998
19	185.946	166.666	149.695	107.878	113.65	114.042	109.129	79.049
20	203.351	182.216	161.944	117.898	124.03	124.478	118.286	86.335
21	221.218	198.177	174.428	128.186	134.678	135.183	127.645	93.825
22	239.511	214.517	187.124	138.729	145.573	146.137	137.188	101.498
23	258.193	231.204	200.007	149.512	156.694	157.318	146.898	109.346
24	277.229	248.206	213.052	160.509	168.022	168.708	156.757	117.351
25	296.586	265.494	226.237	171.706	179.538	180.286	166.75	125.507
26	316.231	283.038	239.539	183.094	191.224	192.036	176.861	133.83
27	336.132	300.811	252.936	194.646	203.062	203.938	187.074	142.281
28	356.259	318.786	266.406	206.349	215.036	215.976	197.375	150.841
29	376.584	336.938	279.929	218.196	227.13	228.133	207.748	159.504
30	397.08	355.243	293.484	230.159	239.327	240.394	218.18	168.253
31	417.721	373.678	307.053	242.226	251.613	252.743	228.657	177.082
32	438.484	392.221	320.616	254.39	263.975	265.167	239.165	186.016
33	459.346	410.853	334.156	266.623	276.399	277.652	249.692	195.004
34	480.288	429.557	347.655	278.91	288.874	290.186	260.226	204.026
35	501.292	448.314	361.097	291.245	301.389	302.758	270.754	213.081
36	522.342	467.113	374.467	303.598	313.934	315.358	281.267	222.152
37	543.423	485.939	387.751	315.951	326.501	327.978	291.754	231.229
38	564.526	504.782	400.941	328.307	339.084	340.61	302.207	240.329
39	585.642	523.636	414.034	340.62	351.676	353.248	312.621	249.408
40	606.765	542.496	427.049	352.882	364.275	365.889	323.00	258.456

Table A.13: Story drift of 10-storied shear walls with different location of openings

Story	Shear wall 1 (SW1)			Shear wall 2 (SW2)			Shear wall 3 (SW3)		
	Asymmetric	Symmetric	Staggered	Asymmetric	Symmetric	Staggered	Asymmetric	Symmetric	Staggered
B	0	0	0	0	0	0	0	0	0
1	0.068	0.068	0.068	0.11	0.102	0.106	0.078	0.076	0.08
2	0.2848	0.2752	0.2784	0.4736	0.4448	0.448	0.3744	0.32	0.368
3	0.496	0.4416	0.4608	0.8256	0.7264	0.7392	0.6048	0.5024	0.5344
4	0.6688	0.5728	0.608	1.1104	0.9536	0.9856	0.7744	0.6496	0.6656
5	0.8032	0.6752	0.7232	1.3312	1.1264	1.1744	0.8992	0.7616	0.7648
6	0.9024	0.7456	0.8032	1.4944	1.2544	1.312	0.9824	0.8416	0.832
7	0.9664	0.7936	0.8576	1.6032	1.3344	1.4048	1.0304	0.8896	0.8704
8	1.0016	0.816	0.8832	1.6672	1.3792	1.456	1.0464	0.9152	0.8864
9	1.0144	0.8192	0.8928	1.6928	1.392	1.4752	1.0368	0.9152	0.8768
10	1.0144	0.816	0.8896	1.6928	1.3824	1.472	1.0144	0.9024	0.8544

Table A.14: Story drift of 22-storied shear walls with different location of openings

Story	Shear wall 1 (SW1)			Shear wall 2 (SW2)			Shear wall 3 (SW3)		
	Asymmetric	Symmetric	Staggered	Asymmetric	Symmetric	Staggered	Asymmetric	Symmetric	Staggered
B	0	0	0	0	0	0	0	0	0
1	0.104	0.118	0.112	0.148	0.138	0.146	0.13	0.124	0.138
2	0.4736	0.4864	0.4864	0.64	0.6304	0.6368	0.5376	0.5184	0.5728
3	0.88	0.8448	0.8672	1.1776	1.1008	1.12	0.9152	0.8928	0.944
4	1.2608	1.1776	1.2224	1.664	1.5296	1.568	1.264	1.2384	1.2832
5	1.6064	1.4784	1.5424	2.1088	1.92	1.9776	1.5808	1.5584	1.5968
6	1.9232	1.7536	1.8336	2.5088	2.272	2.3456	1.8688	1.8464	1.8816
7	2.2112	2.0032	2.0992	2.8704	2.592	2.6816	2.128	2.1088	2.1376
8	2.4672	2.2304	2.3392	3.1968	2.88	2.9792	2.3648	2.3424	2.3712
9	2.6976	2.432	2.5504	3.488	3.136	3.2512	2.5728	2.5536	2.5792
10	2.9056	2.6112	2.7424	3.7472	3.3664	3.4912	2.7616	2.7424	2.7648
11	3.088	2.768	2.9088	3.9808	3.5712	3.7056	2.9248	2.9088	2.928
12	3.2448	2.9056	3.056	4.1856	3.7504	3.8912	3.0688	3.0528	3.0688
13	3.3824	3.024	3.1808	4.3616	3.904	4.0576	3.1936	3.1776	3.1904
14	3.4976	3.1232	3.2864	4.5152	4.0384	4.1984	3.2992	3.2832	3.2928
15	3.5936	3.2064	3.376	4.6464	4.1504	4.3136	3.3856	3.3696	3.3792
16	3.6736	3.2704	3.4432	4.752	4.2368	4.4096	3.4528	3.44	3.4432
17	3.7312	3.3184	3.4976	4.832	4.3072	4.4832	3.5008	3.4912	3.4912
18	3.7728	3.3536	3.5328	4.8928	4.3552	4.5376	3.536	3.5264	3.5232
19	3.8016	3.376	3.5584	4.9312	4.3872	4.5728	3.5552	3.5456	3.5424
20	3.8144	3.3856	3.5712	4.9536	4.4032	4.592	3.5616	3.5552	3.5488
21	3.8208	3.3856	3.5744	4.9632	4.4096	4.5984	3.5584	3.5552	3.5424
22	3.8208	3.3856	3.5712	4.9632	4.4064	4.5984	3.5488	3.5488	3.5328

Table A.15: Story drift of 40-storied shear walls with different location of openings

Story	Shear wall 1 (SW1)			Shear wall 2 (SW2)			Shear wall 3 (SW3)		
	Asymmetric	Symmetric	Staggered	Asymmetric	Symmetric	Staggered	Asymmetric	Symmetric	Staggered
B	0	0	0	0	0	0	0	0	0
1	0.264	0.266	0.266	0.378	0.308	0.342	0.282	0.27	0.284
2	1.2032	1.1136	1.1584	1.6416	1.4368	1.5232	1.2416	1.1872	1.2608
3	2.0992	1.8144	1.9392	3.1136	2.6048	2.7648	2.0096	1.9552	1.9936
4	2.9728	2.4832	2.688	4.528	3.7216	3.9712	2.7584	2.6944	2.704
5	3.8048	3.12	3.3984	5.8816	4.7904	5.1232	3.4752	3.4016	3.3888
6	4.6016	3.728	4.0768	7.1744	5.8112	6.2272	4.1568	4.0736	4.0448
7	5.3568	4.304	4.7232	8.4096	6.784	7.2768	4.8032	4.7168	4.6688
8	6.08	4.8544	5.3376	9.5904	7.712	8.2784	5.4208	5.3248	5.264
9	6.7648	5.376	5.92	10.7104	8.5952	9.232	6.0064	5.9072	5.8272
10	7.4144	5.8688	6.4736	11.7792	9.4336	10.1376	6.5632	6.4544	6.3616
11	8.032	6.3392	6.9984	12.7904	10.2304	10.9984	7.088	6.976	6.8672
12	8.6144	6.7808	7.4944	13.7536	10.9824	11.8144	7.5872	7.472	7.3472
13	9.168	7.2032	7.9648	14.6624	11.696	12.5856	8.0608	7.936	7.8016
14	9.6896	7.5968	8.4096	15.52	12.3712	13.3152	8.5056	8.3776	8.2304
15	10.1792	7.9712	8.8256	16.3296	13.0048	14.0032	8.9248	8.7936	8.6336
16	10.6432	8.3232	9.2192	17.0912	13.6032	14.6464	9.3216	9.184	9.0144
17	11.0752	8.6528	9.5872	17.8048	14.1632	15.2512	9.6928	9.552	9.3696
18	11.4816	8.96	9.9328	18.4704	14.6848	15.8176	10.0384	9.8944	9.7024
19	11.8624	9.248	10.256	19.0912	15.1744	16.3456	10.3616	10.2144	10.016
20	12.2144	9.5168	10.5568	19.6672	15.6256	16.8352	10.6528	10.5152	10.304
21	12.5408	9.7664	10.8352	20.1984	16.0448	17.2864	10.9408	10.7904	10.5728
22	12.8416	9.9968	11.0912	20.688	16.432	17.7024	11.2	11.0464	10.8224
23	13.1168	10.2112	11.328	21.1328	16.784	18.0832	11.4368	11.2832	11.0496
24	13.3696	10.4064	11.5424	21.5424	17.1072	18.432	11.6544	11.4976	11.2576
25	13.6	10.5824	11.7408	21.9104	17.3984	18.7456	11.8528	11.6928	11.4496
26	13.808	10.7424	11.9168	22.24	17.6608	19.0272	12.0288	11.8688	11.6192
27	13.9936	10.8864	12.0768	22.5344	17.8944	19.28	12.1888	12.0288	11.7728
28	14.1568	11.0112	12.2176	22.7936	18.1024	19.5008	12.3296	12.1664	11.9072
29	14.3008	11.1232	12.3392	23.0208	18.2816	19.696	12.4512	12.2912	12.0256
30	14.4224	11.2192	12.448	23.216	18.4384	19.8656	12.5568	12.3936	12.128
31	14.528	11.3024	12.5376	23.3792	18.5696	20.0064	12.6464	12.4832	12.2144
32	14.6144	11.3696	12.6112	23.5168	18.6784	20.1248	12.7168	12.5568	12.2848
33	14.6848	11.424	12.672	23.6256	18.7648	20.2176	12.7776	12.6176	12.3392
34	14.7392	11.4656	12.72	23.712	18.832	20.2944	12.8192	12.6624	12.384
35	14.7808	11.4976	12.7552	23.776	18.8832	20.3488	12.8512	12.6976	12.4128
36	14.8096	11.52	12.7776	23.8208	18.9184	20.3872	12.8736	12.72	12.432
37	14.8288	11.5328	12.7936	23.8496	18.9408	20.4128	12.8832	12.7328	12.4448
38	14.8384	11.5392	12.8	23.8656	18.9504	20.4256	12.8864	12.736	12.448
39	14.8416	11.5392	12.8032	23.872	18.9536	20.4288	12.8832	12.736	12.4448
40	14.8416	11.5392	12.8032	23.872	18.9504	20.4288	12.8736	12.7296	12.4384

Table A.16: Story displacement of 10-storied SWs with different location of openings

Story	Shear wall 1 (SW1)			Shear wall 2 (SW2)			Shear wall 3 (SW3)		
	Asymmetric	Symmetric	Staggered	Asymmetric	Symmetric	Staggered	Asymmetric	Symmetric	Staggered
B	0	0	0	0	0	0	0	0	0
1	0.067	0.069	0.068	0.111	0.102	0.106	0.079	0.075	0.081
2	0.35	0.337	0.345	0.568	0.543	0.542	0.447	0.377	0.428
3	0.842	0.774	0.79	1.391	1.268	1.271	1.05	0.876	0.936
4	1.508	1.345	1.384	2.5	2.218	2.246	1.822	1.521	1.578
5	2.308	2.017	2.093	3.83	3.342	3.413	2.715	2.278	2.321
6	3.207	2.761	2.886	5.323	4.591	4.719	3.69	3.114	3.133
7	4.169	3.552	3.733	6.923	5.922	6.117	4.71	4.001	3.986
8	5.167	4.367	4.61	8.586	7.295	7.568	5.745	4.911	4.855
9	6.179	5.187	5.497	10.273	8.682	9.04	6.772	5.823	5.718
10	7.189	6.004	6.385	11.964	10.063	10.513	7.785	6.723	6.566

Table A.17: Story displacement of 22-storied SWs with different location of openings

Story	Shear wall 1 (SW1)			Shear wall 2 (SW2)			Shear wall 3 (SW3)		
	Asymmetric	Symmetric	Staggered	Asymmetric	Symmetric	Staggered	Asymmetric	Symmetric	Staggered
B	0	0	0	0	0	0	0	0	0
1	0.104	0.117	0.112	0.147	0.139	0.146	0.131	0.124	0.138
2	0.564	0.598	0.599	0.766	0.766	0.769	0.636	0.612	0.671
3	1.44	1.44	1.448	1.938	1.865	1.874	1.549	1.502	1.571
4	2.696	2.614	2.649	3.599	3.39	3.431	2.808	2.738	2.809
5	4.3	4.089	4.173	5.702	5.304	5.396	4.384	4.291	4.366
6	6.218	5.839	5.988	8.204	7.57	7.729	6.245	6.132	6.205
7	8.422	7.837	8.068	11.064	10.151	10.395	8.365	8.232	8.305
8	10.881	10.059	10.385	14.244	13.016	13.358	10.717	10.565	10.635
9	13.568	12.48	12.915	17.71	16.133	16.585	13.275	13.107	13.173
10	16.457	15.078	15.632	21.428	19.474	20.048	16.017	15.833	15.893
11	19.524	17.83	18.515	25.369	23.012	23.718	18.919	18.721	18.775
12	22.745	20.717	21.541	29.505	26.722	27.569	21.96	21.749	21.795
13	26.099	23.719	24.69	33.811	30.581	31.577	25.121	24.898	24.937
14	29.566	26.818	27.943	38.262	34.567	35.718	28.382	28.149	28.179
15	33.126	29.997	31.281	42.836	38.659	39.972	31.727	31.484	31.505
16	36.76	33.239	34.689	47.51	42.837	44.318	35.136	34.885	34.895
17	40.453	36.529	38.149	52.265	47.083	48.736	38.595	38.337	38.337
18	44.189	39.854	41.648	57.081	51.379	53.209	42.089	41.825	41.813
19	47.954	43.203	45.172	61.94	55.709	57.72	45.605	45.337	45.312
20	51.737	46.564	48.713	66.827	60.061	62.256	49.131	48.861	48.821
21	55.529	49.93	52.261	71.731	64.424	66.805	52.658	52.389	52.333
22	59.324	53.298	55.811	76.642	68.79	71.36	56.183	55.914	55.843

Table A.18: Story displacement of 40-storied SWs with different location of openings

Story	Shear wall 1 (SW1)			Shear wall 2 (SW2)			Shear wall 3 (SW3)		
	Asymmetric	Symmetric	Staggered	Asymmetric	Symmetric	Staggered	Asymmetric	Symmetric	Staggered
B	0	0	0	0	0	0	0	0	0
1	0.395	0.4	0.4	0.378	0.307	0.341	0.452	0.432	0.456
2	1.585	1.507	1.559	1.968	1.742	1.825	1.626	1.559	1.653
3	3.679	3.317	3.465	5.076	4.344	4.55	3.628	3.512	3.569
4	6.647	5.795	6.118	9.598	8.063	8.487	6.381	6.203	6.203
5	10.448	8.91	9.485	15.473	12.849	13.577	9.849	9.599	9.527
6	15.043	12.632	13.53	22.641	18.655	19.769	13.997	13.668	13.507
7	20.394	16.93	18.22	31.044	25.433	27.012	18.792	18.377	18.112
8	26.465	21.775	23.524	40.623	33.135	35.257	24.2	23.694	23.311
9	33.218	27.139	29.41	51.321	41.718	44.455	30.193	29.587	29.073
10	40.618	32.996	35.848	63.084	51.136	54.557	36.738	36.028	35.369
11	48.631	39.317	42.808	75.855	61.347	65.517	43.806	42.985	42.169
12	57.225	46.078	50.261	89.583	72.306	77.29	51.368	50.432	49.447
13	66.365	53.253	58.179	104.215	83.974	89.831	59.397	58.34	57.175
14	76.021	60.818	66.536	119.699	96.311	103.096	67.865	66.682	65.327
15	86.163	68.751	75.306	135.987	109.275	117.042	76.746	75.434	73.879
16	96.76	77.028	84.463	153.028	122.83	131.628	86.016	84.57	82.805
17	107.783	85.629	93.982	170.775	136.938	146.814	95.649	94.066	92.083
18	119.205	94.53	103.841	189.182	151.562	162.56	105.622	103.897	101.688
19	130.998	103.713	114.015	208.202	166.666	178.827	115.908	114.042	111.599
20	143.136	113.157	124.482	227.79	182.216	195.576	126.479	124.478	121.795
21	155.592	122.843	135.221	247.903	198.177	212.772	137.328	135.183	132.253
22	168.342	132.753	146.21	268.499	214.517	230.378	148.43	146.137	142.953
23	181.361	142.867	157.429	289.535	231.204	248.36	159.763	157.318	153.876
24	194.626	153.17	168.859	310.973	248.206	266.683	171.306	168.708	165.003
25	208.114	163.642	180.479	332.772	265.494	285.316	183.04	180.286	176.314
26	221.803	174.269	192.271	354.898	283.038	304.226	194.945	192.036	187.792
27	235.672	185.034	204.218	377.313	300.811	323.384	207.003	203.938	199.419
28	249.7	195.923	216.303	399.983	318.786	342.76	219.198	215.976	211.179
29	263.869	206.919	228.508	422.876	336.938	362.328	231.512	228.133	223.055
30	278.159	218.01	240.818	445.961	355.243	382.06	243.93	240.394	235.033
31	292.553	229.182	253.219	469.209	373.678	401.934	256.435	252.743	247.097
32	307.034	240.423	265.696	492.593	392.221	421.925	269.015	265.167	259.235
33	321.588	251.72	278.235	516.088	410.853	442.012	281.655	277.652	271.432
34	336.2	263.063	290.826	539.672	429.557	462.177	294.343	290.186	283.677
35	350.858	274.442	303.457	563.324	448.314	482.401	307.067	302.758	295.959
36	365.55	285.848	316.118	587.026	467.113	502.669	319.818	315.358	308.268
37	380.266	297.274	328.801	610.763	485.939	522.968	332.586	327.978	320.595
38	394.998	308.712	341.499	634.522	504.782	543.287	345.364	340.61	332.934
39	409.741	320.158	354.206	658.294	523.636	563.618	358.147	353.248	345.279
40	424.49	331.61	366.919	682.073	542.496	583.956	370.932	365.889	357.627

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