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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Parametric Assessment of the Effect of Shear Deformation in Concrete Shear Wall with and without Openings for Lateral Action using Simplified Hand Procedure

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A Thesis in Structural Engineering

By Dagmawi Girma

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A Thesis

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The undersigned have examined the thesis entitled ‘**Parametric Assessment of the Effect of Shear Deformation in Concrete Shear Wall with and without Openings for Lateral Action using Simplified Hand Procedure**’ presented by **DAGMAWI GIRMA**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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UNDERTAKING

I certify that research work titled "**Parametric Assessment of the Effect of Shear Deformation in Concrete Shear Wall with and without Openings for Lateral Action using Simplified Hand Procedure**" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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ABSTRACT

Shear wall, a continuous vertical member, is an important element in high-rise building, which provides the lateral stability and resistance to lateral force. Lateral load resistance capacity of shear wall is controlled by two parameters, the strength and the ductility; it is better to have the shear strength somewhat greater than the compressional to prevent shear failure, which is brittle, sudden and of serious consequence. Due to the architectural and functionality reasons, openings are providing in this important structural part.

The main objective of this study is to investigate the effects of shear deformation on shear wall with different type of openings and wall dimension for later action using simplified hand procedure. To investigate the effect of shear deformation, parametric study presents for shear wall deformation. A total of thirty-two cases of systematically random selected input variables namely: height of shear wall (H), length wall (L), opening height (h_o), opening length (l_o) and thickness for shear wall with window and door type of opening. For solid shear wall (without opening) input variables are height of wall (H) length of wall (L) and thickness (t). The systematically selection random variables is done using Latin Hypercube Sampling method (LHS). Those random variables distribution follow normal distribution. And then by taking the shear deformation of thirty-two cases of shear wall with and without opening from simplified hand procedure, verified by illustrative example and ANSYS, a statistical data analysis is performed using regression analysis in order to identify the most influential input parameter on the shear wall deformation of shear wall.

Results of statistical data analysis demonstrates the significance of five input variables on two cases, shear wall with and without opening and three input variables on solid shear wall. Height of opening most influential parameter for shear wall with and without opening. But for shear wall without opening thickness of wall is influential parameter for the determination of shear deformation. On other hand, this paper provides some support to identify which parameter increase and which parameter decrease shear deformation to reduce brittle failure in of shear wall. This will enable to consider factor of safety for the uncertain input parameters on shear deformation equations. It is helpful to construct empirical equation using large set of data.

Key words: *shear deformation, parametric study, simplified hand procedure, Latin Hypercube Sampling Method (LHS)*

TABLE OF CONTENTS

ACKNOWLEDGEMENT…………………………………………………………………… i

ABSTRACT……………………………………………………………………………... ii

TABLE CONTENTS …………………………………………………………………… iii

LIST OF FIGURES ……………………………………………………………………. v

LIST OF TABLE ……………………………………………………………………. vii

CHAPTER ONE: INTRODUCTION……………………………………………. -1-

1.1 Background ………………………………………………………………... **-1-**

1.2 Statement of Problem ……………………………………………………… **-2-**

1.3 Objective ……………………………………………………………………... **-3-**

1.4 Methodology ……………………………………………………………………. **-3-**

1.5 Scope and Limitation of the Study ……………………………………………… **-4-**

1.6 Organization of the thesis **-4-**

CHAPTER TWO: LITERATURE REVIEW -5-

2.1 General **-5-**

2.1.1 Beam Theory……………………………………………………………….

2.1.1.1 Euler Bernoulli Beam Theory ………………………………… **-5-**

2.1.1.2 Timoshenko Beam Theory…………………………………… **-5-**

2.1.2 Shear Wall Deformation ………………………………………………... **-7-**

2.1.3 Shear Deformation ……………………………………………………… **-9-**

2.2 Previous researches on shear wall deformation ……………………………. **-10-**

2.3 Summary of the Previous researches Works………………………………… **-21-**

CHAPTER THREE: INVESTIGATION OF THE BEHAVIOUR OF SHEAR WALL DEFORMATION WITH DIFFERENT OPENINGS SIZE -22-

3.1 General ……………………………………………………………………. **-22-**

3.2 Determination of Shear Wall Deformation………………………………… **-22-**

3.2.1 Pier Analysis ……………………………………………………… **-22-**

3.2.2 Method For Calculating The Deformation Of Wall (One Over Rigidity Of Wall) With Opening……………………………………. -25-

3.3 Introduction for Simplified Hand Method ………………………………………. -25-

3.3.1 Solid Rectangular Shear Wall ………………………………………… -25-

3.3.2 Shear Wall With Opening……………………………………………… -26-

3.3.3 Deep Beam Concept …………………………………………………… -28-

3.4 Description of Sample Shear Wall Model ………………………………………… -29-

3.4.1 Analysis of Effect of Location of Opening in Shear Wall ………….. -32-

3.5 Sampling Method ……………………………………………………………….. -34-

3.6 Deformation Analysis ………………………………………………………… -37-

3.7 Validation of Simplified Hand Method on Shear Wall Deformation ……………… -42-

3.7.1 Illustrative Example …………………………………………………… -42-

CHAPTER FOUR: PARAMETRIC STUDY …………………………………………… -46-

4.1 Introduction ……………………………………………………………………… -46-

4.2 Statically Data Analysis ……………………………………………………….. -46-

4.2.1 The XLSTAT Approach ……………………………………….………….. -46-

4.2.2 Sensitivity Analysis ………………………………………………………. -46-

4.2.2.1 Uncertainty of Import Variable on Wall Deformation ……………………. -47-

4.2.3 Variable Import in the Project VIP …………………………………………… -50-

CHAPTER FIVE: SUMMARY OF RESULTS AND DISCUSSION……………….…... -54-

CHAPTER SIX: CONCLUSIOS AND RECOMMENDATIONS …………………….. -58-

5.1 Conclusion ……………………………………………………………………….. -58-

5.2 Recommendation ……………………………………………………………….. -59-

REFERENCES…………………………………………………………………………... -60-

APPENDICES A: SIMPLIFIED HAND METHOD RESULT …………………….… -61-

APPENDICES B: ELEMENT USED FOR MODELING IN ANSYS…...……………. -71-

APPENDICES C: OUTLIERS ANALYSIS……………………………………………. -76-

LIST OF FIGURES

Fig. 2.1 Euler-Bernoulli and Timoshenko beam Deformation………………………. 6

Fig. 2.2 Infinitesimal length of beam showing Banding and shear deformation ….. 7

Fig. 2.3 Shear and Flexural Deformation……………………………………………. 8

Fig. 2.4 Deformation shear wall with opening……………………………………… 8

Fig. 2.5 Instrumentation of U-Shaped wall ………………………………………… 11

Fig. 2.6 Variation of length of shear panel diagonals………………………………. 12

Fig. 2.7 Element Model (MVLEM element and Coupled Model Element) 15

Fig.2.8 Proposed instrumentation Schemes (Wall without opening and Wall with Opening)…………………………………………………………………….. 16

Fig. 2.9 Calculation of flexural deformation (Wall without opening and Wall with opening) ………………………………………………………………… 17

Fig.2.10 Calculation of shear deformation: (a) Wall without opening (b) Wall with opening……………………………………………………………………. 19

Fig. 3.1 wall pier displacement at top and cantilevering from fixed bottom and deflection of wall due to bending and shear deformation (Amrhein, 1998)….. 23

Fig. 3.2 wall pier displacement at top displacement, fixed at top and bottom of wall due to bending, and shear deformation (Amrhein, 1998) …………………….. 24

Fig. 3.3 (a) Horizontal combination of wall segment (b) vertical combination of wall segment (Drydale,Hamid and Baker, 1994) ………………………………….. 24

Fig. 3.4 Deflection of Cantilever shear Wall ……………………………………….. 26

Fig. 3.5 Wall Element Fixed at Both End …………………………………………… 27

Fig. 3.6 Cantilever Shear Wall ……………………………………………………… 28

Fig. 3.7 Probability Distribution of *Ratio of shear Deformation for* Shear wall without Opening………………………………………………………………………… 39

Fig. 3.8 Probability Distribution of *Ratio of shear Deformation for* Shear wall with Window Type Opening ………………………………………………………………… 40

Fig. 3.9 Probability Distribution of *Ratio of shear Deformation for* Shear wall with Door type Opening……….. 41

Fig. 4.1 Uncertainty of random Variable for window type of opening……………… 48

Fig. 4.2 Uncertainty of random Variable for door type of opening…………………. 49

Fig. 4.3 Uncertainty of random Variable for solid wall type (without opening)……... 50

Fig. 4.4 Variable Importance of Window Type of Opening…………………………. 51

Fig. 4.5 Variable Importance of Door Type of Opening…………………………….. 52

Fig. 4.6 Variable Importance of Solid Shear Wall Type (without opening) ……….. 53

Fig. 5.1 Uncertainty of random variable and VIP for Window type of opening …..... 56

Fig. 5.2 Uncertainty of random variable and VIP for Door type of opening ……….. 56

Fig. 5.3 Effect of Aspect ratio and percentage of opening in ratio of shear deformation to total deformation of shear wall……………………………… 57

Fig. 5.4 Effect of Aspect ratio and wall thickness in ratio of shear deformation to total deformation of shear wall…………………………………………… 57

Fig. A.1 Effect of different parameters in shear wall with Window type of opening… 65

Fig. A.2 Effect of different parameters in shear wall with Door type of opening….. 68

Fig. A.3 Ratio of shear deformation vs Aspect ratio for shear wall without opening… 69

Fig. A.4 Ratio of shear deformation vs percentage of opening for shear wall with window type opening……………………………………………………… 70

Fig. A.5 Ratio of shear deformation vs percentage of opening for shear wall with door type opening……………………………………………………………… 71

Fig. B.1 BAME189 Geometry………………………………………………………… 73

Fig. B.1 SHELL181Geometry………………………………………………………… 75

Fig. C.1 Outlier Analysis with respect to input Variable for Shear wall with window type of opening ………………………………………………………….... 78

Fig. C.2 Outlier Analysis with respect to Dependent Variable for Shear wall with window type of opening ……………………………………………………… 78

Fig. C.3 Outlier Analysis with respect to input Variable for Shear wall with Door type of opening ………………………………………………………….... 79

Fig.C.4 Outlier Analysis with respect to Dependent Variable for Shear wall with Door type of opening ……………………………………………………….. 79

Fig. C.5 Outlier Analysis with respect to input Variable for Shear wall without opening ……………………………………………………………………….... 80

Fig. C.6 Outlier Analysis with respect to Dependent Variable for Shear wall without opening …………………………………………………………… 80

LIST OF TABLE

Table 3.1 Description of Five Parameters……………………………………………………... 33

Table 3.2 ANSYS Verification Analysis……………………………………………………. 36

Table 3.3 Statistical Variations of Random Variables for SW without Opening…………….. 38

Table 3.4 Statistical Variations of Random Variables for SW with Window Type of Opening 39

Table 3.5. Statistical Variations of Random Variables for SW with Door Type of Opening … 39

Table 3.6 32X5 LHS Combination of random variable for shear wall with and without opening 40

Table 3.7 Simplified Hand Method results for 32X5 LHS Combination of random variables for three type of shear wall. ………………………………………………………………. 42

Table 3.8 Confidence Interval for shear wall with without opening……………………. 43

Table 3.9 Confidence Interval for shear wall with window type of opening…………… 44

Table 3.10 Confidence Interval for shear wall with door type of opening……………… 45

Table 4.1 Relative Importance of Input Parameter for the Model: for window type of opening……………………………………………………………………………… 51

Table 4.2 Relative Importance of Input Parameter for the Model: for door type of opening……………………………………………………………………………… 52

Table 4.3 Relative Importance of Input Parameter for Solid Shear Wall without opening……. 53

Table 5.1 Relative importance of input parameter for different type of shear wall…………… 55

Table 5.2 Uncertainty of random variables for different type wall type ……………………… 55

Table A.1 Simplified Hand Method results for LHS combination of random variables for shear wall with Window type of opening……………………………………….. 63

Table A.2 Simplified Hand Method results for LHS combination of random variables for shear wall with Door type of opening………………………………………………. 66

CHAPTER ONE

INTRODUCTION

1.1 Background

Shear walls are generally used to resist lateral loads caused by earthquake or wind acting parallel to the plane of the wall in addition to gravity loads from adjacent floors. These walls can often provide lateral bracing for the structure by reducing lateral displacements and resisting applied forces. In shear wall-frame buildings, lateral loads are resisted in part by the wall and in part by frames which the combination of the two provides lateral stiffness for buildings.

Wall behavior is generally classified according to wall aspect ratio(h_w/l_w), or shear-span-to-depth ratio (M/Vl_w), as either shear-controlled (walls with aspect ratio less than approximately 1.0 to 1.5) or flexure-controlled (aspect ratios greater than 2.5 to 3.0). For walls between these aspect ratios, Herein referred to as moderate aspect ratio walls, although flexural yielding is expected, nonlinear shear deformations may be significant and lead to reduced lateral stiffness, strength and ductility.

On other hand, Experimental results have shown that flexural and shear yielding occur near-simultaneously even when the wall nominal shear strength is as much as twice the shear developed at flexural yielding (Massone and Wallace, 2004) suggesting that there is an interaction between nonlinear flex ural and shear modes of behavior, commonly referred to as shear-flexure interaction (SFI). This interaction has been observed experimentally even in relatively slender RC walls with aspect ratios of 3.0 (Thomsen and Wallace, 1995) and 4.0 (Sayre, 2003), with shear deformations contributing approximately by 30% and 10% to lateral Displacement at the first story and roof-level, respectively (Massone and Wallace, 2004). Recent test results reported by Tran and Wallace (2012) show that the degree of interaction increases for walls with aspect ratios of 1.5 and 2.0, with nonlinear shear deformations constituting as much as 35% and 30% of the wall top displacement, respectively. Previous research has shown that analytical predictions obtained using models that consider uncoupled axial/flexural and shear behavior may underestimate axial compressive strains even in relatively slender RC walls controlled by flexure (Orakcal and Wallace, 2006), and overestimate the lateral load capacity of moderate-aspect-ratio walls (Tran, 2012) and low-aspect-ratio walls (Massone et al, 2006).

1.2 Statement of Problem

Compared to the options that are available to engineers when modeling the flexural response of RC members, the variety of approaches for modeling the shear response is relatively sparse. Most structural engineering programs, the shear stiffness of beam elements that develop a flexural mechanism is assigned a constant value that cannot be updated during the loading process. This modeling approach has been supported by the misconception that because the shear reinforcement is not supposed to yield and the compression strut is not supposed to crush the shear deformations will remain constant once the nominal yield has been reached. Hence, regarding the acknowledgement of the magnitude of the shear deformations, a vicious circle was created, wherein shear deformations in structural analyses are underestimated due to excessively large shear stiffness values. Their contribution to the total deformations are therefore perceived as negligible and their effect on the structural performance is not considered.

On the other hand shear wall in building will be perforated by row of opening that are required for windows external wall or for door way or corridors in internal walls. However, the size and location of opening in the shear wall may have adverse effect on seismic responses of shear wall structures. As an engineer, it is necessary to know the effects of openings size and configuration in shear wall on stiffness (because it is important since lateral force are distributed to individual shear wall according to their relative stiffness) as well as on seismic response and behavior of structural system so that suitable configuration of opening in shear wall can be made.

This thesis aimed to add contribution on the effects of shear deformation in shear wall having opening by using simplified hand procedure and, identify which parameter in determination of shear deformation important, and verified by linear elastic modeling software that included the effect of shear deformation.

1.3 Objective

The main objective of this study is to investigate the effects of shear deformation on shear wall with different type of openings and wall dimension for later action using simplified hand procedure. And also this thesis paper aimed to magnify the effect of shear deformation that undermine and/or underestimate in most analysis software currently used in our country. This investigation implemented by performing a parametric study to identify which input parameter in the determination of deformation of shear wall important and influential in shear deformation of concrete shear wall.

1.4 Methodology

Reviewing the existing literatures for shear deformation in shear wall having opening is the first task in this study. Due to the unavailability of testing machines and financial constraints, experimental(s) required for this particular study is not covered. Instead, simplified hand procedure which is recommended in several design guidelines for calculating the lateral stiffness and deformation of shear wall with and without opening, assess the effect of shear deformation in wall with and without opening was used. To undertake this analysis firstly scaling factor for input variables range established. And then systematical random selection of input variable is done using Latin Hyper Cube Sampling method (LHS). Those input variables follow normal distribution that comprise 32 systematical selected combinations to determine shear deformation using Simplified hand procedure. This simplified method validated using ANSYS SHELL181 Element software that include shear deformation in total wall deformation.

After this, by taking value of shear deformation obtained from simplified hand method a parametric study using partial least square regression analysis has been done. This analysis helped to know the most influential parameters on shear deformation of shear wall. Finally, statistical data evaluation on predicting shear deformation of shear wall is conducted. This statistical data analysis is performed using XLSTAT 2017 tool.

1.5 Scope and Limitation of the Study

The scope of this paper is focused only on linearly elastic concrete shear wall with the point load condition. The input variable data ranges were distributed normal to generate an output data shear deformation. However, it uses limited number of cases for the input data evaluation when modeling wall. The statistical data analysis accuracy will be better when the sample data being large set.

1.6 Organization

There are six chapter in this study. Where, Chapter one deals with introducing the general background, methodology and objective of the thesis work.

In the second chapter, theoretical background regarding deformation of different type of structures will be presented and literature will be reviewed to figure out the basic consideration in determination of wall deformation.

Chapter three deals with investigation mechanisms for behavior of shear wall with and without opening due to shear deformation. Within this chapter Systematic random variable selection using Latin Hypercube Sampling (LHS) and analysis using simplified hand procedure to determine shear deformation presented. And also, validation of simplified hand method explained.

Chapter four presents, parametric study using partial least square regression analysis and sensitivity analysis.

Chapter five presents summary of output with their respective discussion.

The last chapters of this thesis is made to address the conclusion drawn from results and discussion section and recommendation are put forward on the basis of the finding.

CHAPTER TWO

LITERATURE REVIEW

2.1 General

2.1.1 Beam Theories

Two mathematical model, namely the shear-deformable (Timoshenko) model and shear-in deformable (Euler-Bernoulli) model, are presented.

Since the Timoshenko beam theory is higher order than the Euler-Bernoulli theory, it is known to be superior in predicting the transient response of the beam. The superiority of the Timoshenko model is more pronounced for beam with a low aspect ratio. It is shown that use of an Euler-Bernoulli based controller to suppress beam vibration can lead to instability caused by the inadvertent excitation of unmodelled modes.

2.1.1.1 Euler Bernoulli Beam Theory

In Euler – Bernoulli beam theory, shear deformations are neglected, and plane sections remain plane and normal to the longitudinal axis. The difference between the normal to the longitudinal axis and the plane section rotation is the shear deformation. A deformed Euler-Bernoulli beam and its reference configuration in which the centerline is straight and parallel to the x-axis. The cross-sections of the beam remain plane and orthogonal to the centerline after deformation. These relations are shown in Fig. 2.2.It can be seen in Fig. 2.1 that in the Euler-Bernoulli beam the deformation at a section,dvS/dx, is just the rotation due to bending only, since the plane section remains normal to the longitudinal axis.

2.1.1.1Timoshenko Beam Theory

In the Timoshenko beam theory, plane sections still remain plane but are no longer normal to the longitudinal axis. And section deformation is the sum of two contribution: one due to bending, dvb/dx, and the other is the shear deformation, dvS/dx. By considering an infinitesimal length of the beam, as shown in Fig. 2.2, it is seen that the shear deformation in Timoshenko beam theory, dvS/dx, is the same as the shear strain related to pure shear.

In Timoshenko beam theory, the rotary inertia of a differential element of the beam is considered non-negligible and the cross-sections are allowed to rotate relative to the centerline due to shear deformation. The Euler-Bernoulli beam theory may be obtained as a limiting case of Timoshenko beam theory when a particular dimensionless quantity in the forthcoming section is very small.

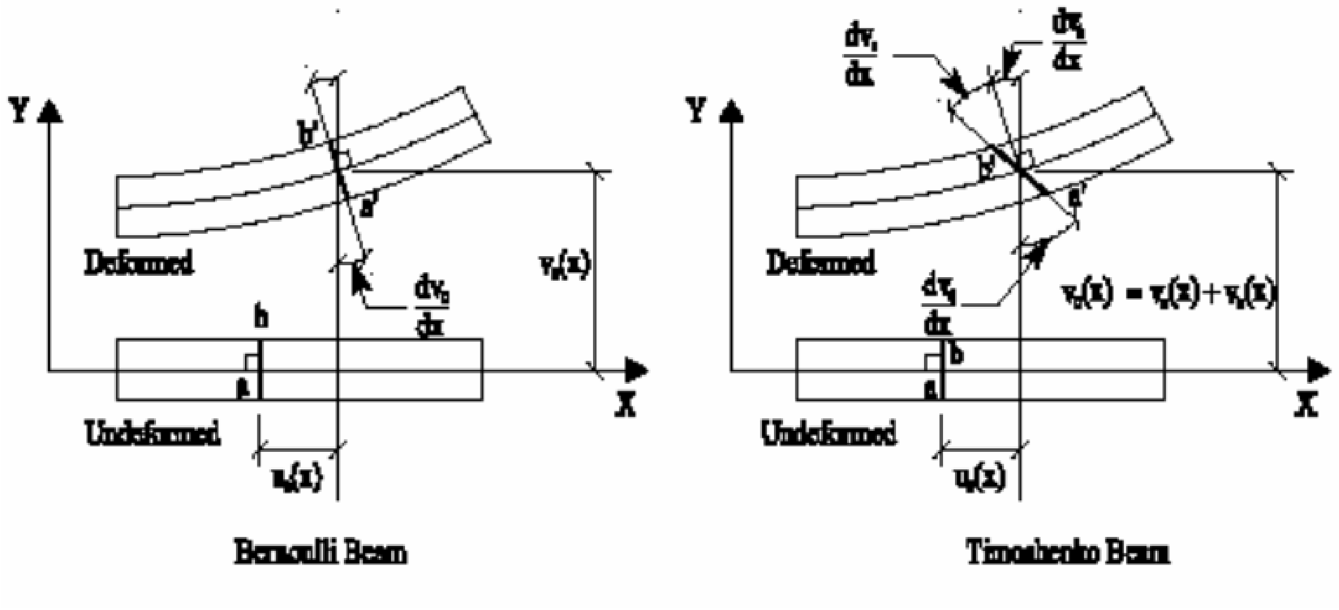


Fig. 2.1 *Euler-Bernoulli and Timoshenko beam Deformation*

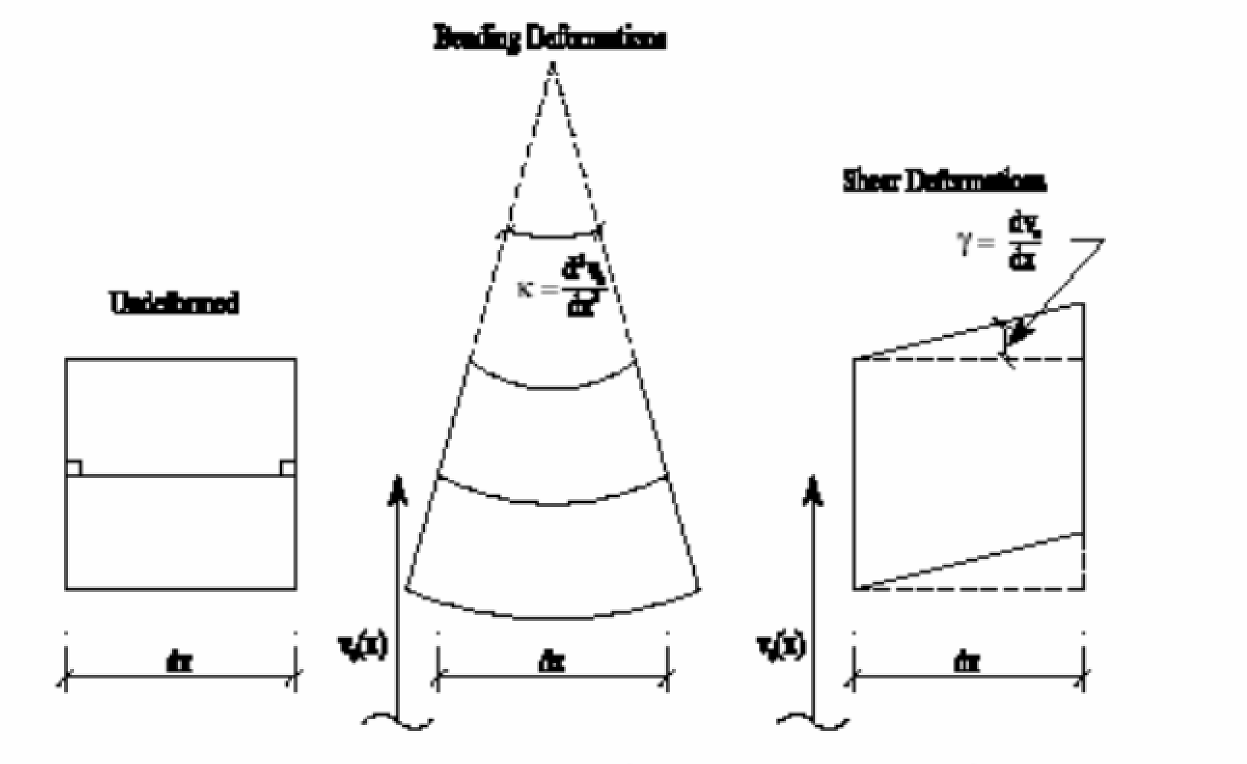
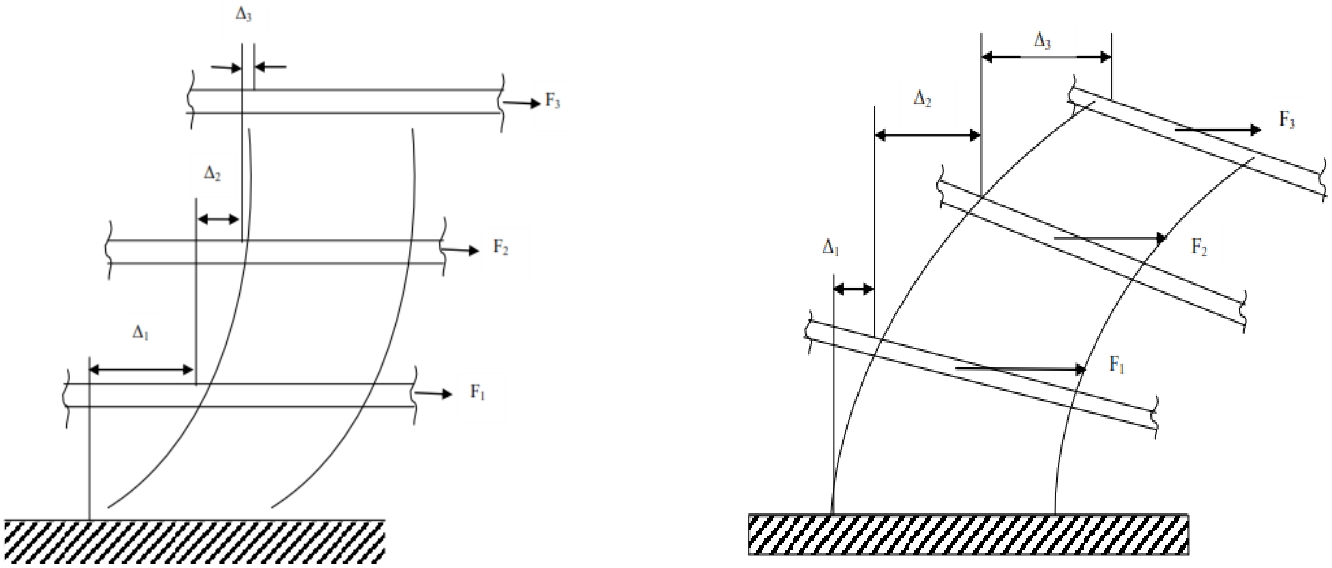


Fig. 2.2 *Infinitesimal length of beam showing Bending and shear deformation*

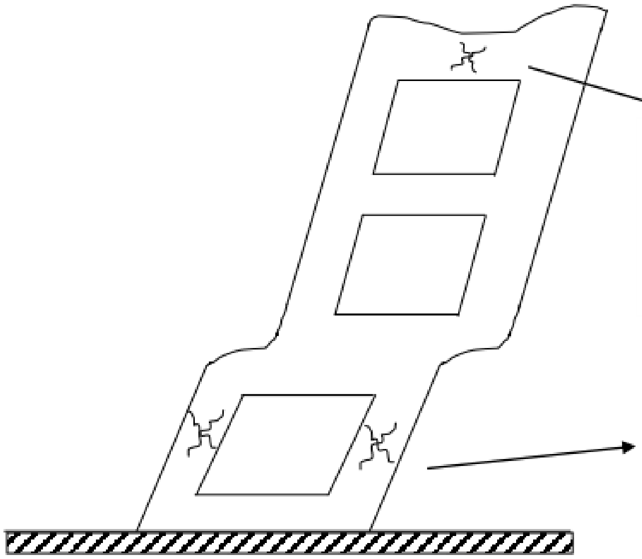
2.1.2 Shear Wall deformation:

The rigidity of a wall is usually defined as the force required causing a unit deflection. Rigidity is expressed in KN/m. The deflection of a concrete shear wall is the sum of the shear (Fig. 2.3a) and flexural deflections (Fig. 2.3b). In case of solid wall with no openings the computations of deflection are quite simple. However when the shear wall has openings as for doors and windows the computations for deflection (Fig. 2.4) and rigidity are much more complex. For this reason several short cut approximate methods have been developed like simplified hand method.



a *Shear Deformation* **b** *Flexural Deformation*

Fig. 2.3 *Shear and Flexural Deformation*



Diagonal tension cracks in spandrels may occur at the top or at other elevations depending on vertical shear distribution.

Diagonal tension cracks in piers usually most severe at bottom where horizontal shear is largest.

Fig. 2.4 Deformation *shear wall with opening*

2.1.3 Shear Deformation

Structural design is based on the forces developed in the members due to the applied loads. The member forces are developed primarily due to deformations in the structures caused by these loads. Thus it is very important to accurately determine the deformations for the design to be adequate. Flexural and axial deformations in structures can be determined to a high level of accuracy. Deformations in multi-story structures are affected by shear deformations in the members. However, shear deformations in structures are, typically, a very low percentage of the total deformation, allowing them to be neglected in most cases. A good amount of research has been done on modeling and predicting the value of shear deformations, but the issue is still far from being resolved. This is because the determination of shear deformation requires the calculation of a quantity referred to as 'Shear Area' of the member cross section. 'Shear Area' is generally understood to be the effective area of the section participating in the shear deformation and as such is a unclear value ranging from the gross cross-sectional area to the area of the web for a wide flange section. For structures involving members having low clear span to member depth ratio, shear deformations could be responsible for as high as 20% of the total drift (Charney, 1990). This necessitates a better understanding of shear deformations. The traditional method of including the effects of shear deformation is also not accurate. Consider a cantilever beam of length L. The deflection of the tip, Δ, under a point load P including the shear deformation is given by the Equation 2.1.

$$\Delta = \frac{PH^3}{3EI} + \alpha \frac{PH}{GA} \tag{2.1}$$

Where E is the modulus of elasticity, G is the shear modulus, I is the moment of inertia of the section about the bending axis and A is the shear area of the section. The first term in Equation 2.1 represents the flexural deformation and the shear deformation is denoted by the second term.

2.2 Previous researches on shear wall deformation

In the subsequent section, a review of previous work on effect of shear deformation in shear walls with and without opening are stated that in chronological order.

Many researchers have develop analytical (numerical method) and experimental to analyzed (mostly to design) shear with and without opening.

A.Neuenhofer, P.E. (Journal of Structural Engineering ASCE/Nov.2006):

He investigates the accuracy of a simplified hand method for calculating the lateral stiffness of shear wall with openings. Parametric studies are performed in which the location and size of the opening as well as the aspect ratio of the wall varied. Overall, this paper is organized in three parts: First part brief review of deep beam theory, Second part discusses the simplified hand procedure to account for openings in shear walls, it also describes the special purpose finite-element procedure. Third part he perform parametric studies of shear wall with opening using both hand procedure and finite-element analysis. Size and location of the opening as well as the aspect ratio of the wall are varied. Results indicate that the recommended hand method consistently underestimates the impact of the opening on the reduction of stiffness, thus producing a lateral stiffness larger than that obtained from detailed finite-element analysis.

This study focused on the accuracy of a popular simplified hand method for calculating the lateral stiffness of shear walls with opening by comparing the results of that procedure to those obtained from finite-element analysis. A special-purpose finite element procedure is implemented into the scientific computing package MATLAB in which shear wall are modeled with the conventional four-node plane stress membrane element.

Parametric studies are carried out in which size and positions of the wall opening as well as the aspect ratio of the wall are varied. This researcher not crate any plat form for selecting size of opening and wall for the parametric study rather he select those parameters randomly. Results estimate the impact of the opening on the reduction of stiffness larger than that obtained from detailed finite-element analysis.

Hisahiro Hiraishi (1983): most penetrating work on the deformation of shear wall originates from this researchers. He prepare paper reports on an evaluation method of distribution of total deformation of a shear wall without opening into the flexural and shear deformations using analytical and experimental (truss model). This paper also mentioned an evaluation method of distributing the total deformation of a shear wall into the flexural and shear deformation. Finally he has been reached the following three conclusions:

Firstly Shear deformation is overestimated, and consequently flexural deformation is underestimated if the shear deformation is determined simply as a difference in length of two diagonals. Secondly flexural and shear deformations are estimated with excellent accuracy by using the rotation at the storey mid height of a shear wall. Thirdly shear deformation increases by the rotational mechanism having a rotation center at the base of the column under compression.

Katrin Beyer, Alessandron Dazio and M. J. Nigel Priestley (March-April 2011)

This paper presented experimental data for shear deformations of slender cantilever wall by examining the data of 34 test units available in the literature with an aspect ratio larger than two that were subjected to quasi-static cyclic loading and to identify parameters that affect the shear deformation. Of particular interest is the ratio of shear-to-flexural deformation when the wall is loaded in the inelastic range to consider in structural analysis. Based on these results, shear displacements can be estimated or the effective stiffness of beam element can be determined.

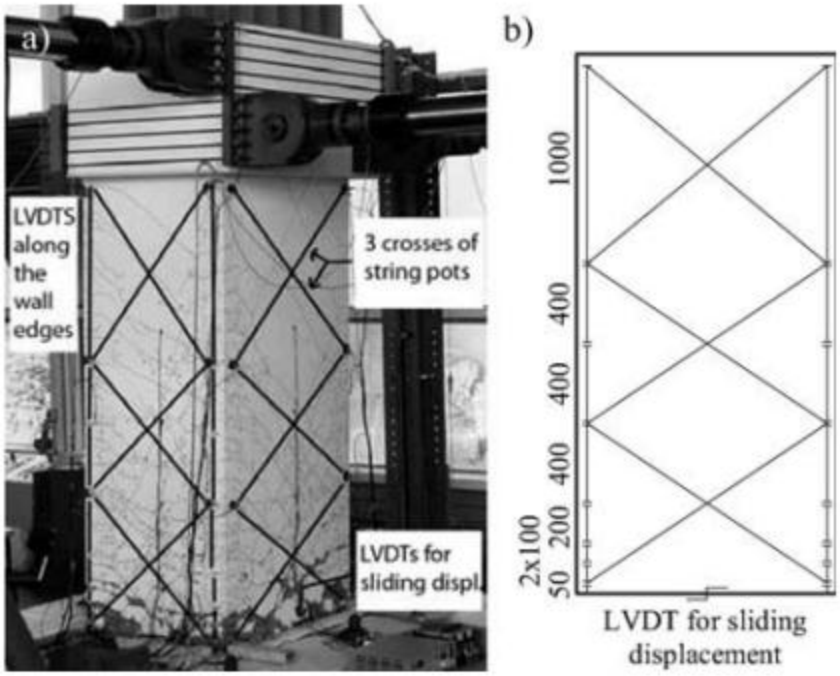


Fig. 2.5 *Instrumentation of U-Shaped wall: (a) instrumentation suitable for determining different displacement components* Δ_f, Δ_ϑ *and* Δ_s *(photo); and (b) sketch of instrumentation of one flange.*

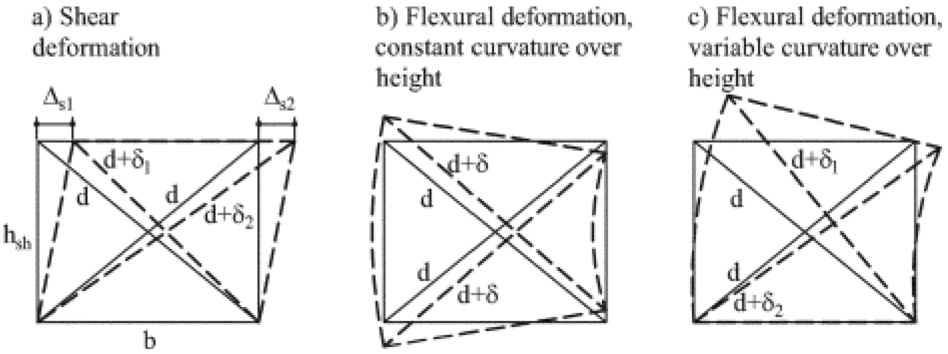


Fig. 2.6 *Variation of length of shear panel diagonals: (a) for shear; (b) for flexural deformation with constant curvature over height; and (c) with variable curvature over height*

For many test series, the shear displacements of a shear panel have been evaluated using one of the following two equations:

$$\Delta_s = \frac{1}{4b}((d+\delta_2)^2 - (d+\delta_1)^2) \text{ …… (a)}$$

$$\Delta_s = \frac{1}{2b}((\delta_2 - \delta_1)^2 \text{ ………… (b)} \qquad (2.2)$$

Where b is the width of the shear panel, d is the original length of the diagonal, and δ_i is the change in length of one of the two diagonals. Equation (2.2(b)) corresponds to the zero and first order terms of the Taylor series of Eq. (2.2(a)). Hiraishi showed that a term needs to be subtracted to account for the variation of curvature over the height of the panel.

$$\Delta_s = \frac{1}{4b}((d+\delta_2)^2 - (d+\delta_1)^2) - (\propto - 0.5)\theta(h_{sh})h_{sh} \qquad (2.3)$$

Where θ (h_{sh}) is the difference of rotations at the top and bottom of the panel of height h_{sh} for which the shear deformations are determined, and α is a measure for the variation of the curvature over the height of the panel.

$$\propto = \frac{\int_0^{h_{sh}} \theta(z)dz}{\theta(h_{sh})h_{sh}} \text{ Where } \alpha \text{ vary between 0.5 and 1} \qquad (2.4)$$

Determining Shear and flexural Deformations from Experimental Measurements

The total top displacement of a cantilever RC wall can be interpreted as the sum of three displacement components

1. The flexural displacement Δ_f , which is the sum of displacement Δ_f' of the wall panel and the displacement Δ_θ caused by the fixed-end-rotation of the wall associated with the strain penetration of the longitudinal reinforcing bars into the foundation;
2. The shear deformations Δ_s of the wall; and
3. The sliding displacement $\Delta_s l$ along the joint between the wall and foundation. For typical wall designs, the sliding displacements are relatively small.

Determining of Displacement Components from Experimental Measurements

Due to the presence of "cracking, plane sections not remaining plane, and the existence of a moment gradient across the element," as well as the fact that the subdivision of deformations of inelastic RC wall members into shear and flexural deformations is—to some extent—artificial, the displacement components determined from experimental measurements are only approximate values. Although they are not exact, however, they provide a useful link between the experiments and numerical models, particularly if beam models are used. Average curvatures can be derived from the chains of LVDTs (Linear variable differential transformers) along the edges of the walls, and the flexural deformations Δ_f' can be computed by integrating the curvatures twice. The total flexural displacement Δ_f' is computed as the sum of Δ_f' plus the wall displacement due to the fixed-end rotation Δ_θ , which is associated with strain penetration into the foundation. Unlike for the experimental flexural deformations, which are mostly determined by the method described previously, and where differences between test series on RC walls chiefly originate from different base lengths of the LVDT measurements rather than the evaluation method, the evaluation of shear deformation is less homogenous between different research groups. For many test series, the shear displacements of a shear panel have been evaluated using one of the following two equations

$$\Delta_s = \frac{1}{4b}\left((d+\delta_2)^2 d - (d+\delta_1)^2\right) \qquad (2.5)$$

$$\Delta_s = \frac{d}{2b}(\delta_2 - \delta_1) \qquad (2.6)$$

Where b is the width of the shear panel, d is the original length of the diagonal, δ_i is the change in length of one of two diagonals.

Leonardo M. Massone, Kutay Orakcal, and John W. Wallace (October 12-17, 2008)

Reinforced concrete squat walls are common in low-rise construction and as wall segments formed by window and door openings in perimeter walls. Existing approaches used to model the lateral force versus deformation responses of walls, typically assume uncoupled axial/flexural and shear responses. A more comprehensive modeling approach, which incorporates flexure-shear interaction, is implemented, validated, and improved upon using test results. The experimental program consisted of reversed cyclic lateral load testing of three-quarter scale, heavily-instrumented, wall segments dominated by shear behavior. Model results indicate that variation in the assumed transverse normal stress or strain distribution produces important response Variations. Use of the average experimentally recorded transverse normal strain data, or a calibrated analytical expression for the horizontal strain, resulted in better predictions of shear strength and lateral load-displacement behavior, as did incorporating a rotational spring at wall ends to model extension of longitudinal rebar within the pedestals. According to experimental evidence, flexural and shear deformation interaction exists even for relatively slender wall with aspect ratio of three to four, with shear deformation contributing approximately 30% and 10% of the first story and roof level lateral displacement, respectively (Massone and Wallace, 2004). There is need for relatively simple modeling approaches which consider interaction between flexure and shear response, and capture important response features. Although a relatively large number of wall tests are reported in the literature, and primary focus for most of these tests is the assessment of wall shear strength and lateral displacement response, as opposed to assessment of relative contribution of flexural, and shear deformation to wall lateral displacements, which is necessary for validating existing and developing new modeling approaches. Therefore, experimental studies that incorporate very detailed instrumentation layouts are needed to allow development and verification of new modeling approaches.

An analytical model that couples wall flexural and shear responses was proposed by Massone (2006) and Massone et al. (2006) based on framework proposed by Petrangeli et al. (1999). The model incorporates RC panel behavior into a two-dimensional macroscopic fiber model (Multiple Vertical Line Element Model, MVLEM (e.g., Orakcal et al., 2004), Fig. 1(a)), in order to capture the experimentally observed shear-flexure interaction in RC walls (Massone and Wallace, 2004).

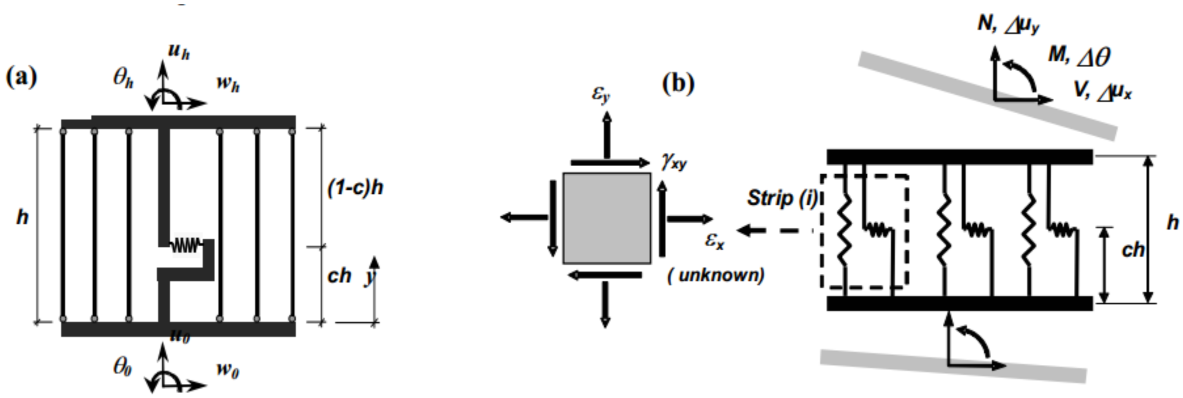


Fig. 2.7 *Element Model: (a) MVLEM element and (b) Coupled Model Element*

As described by massone et al. (2006), the deformation or strains within the components of each panel element are determined from the six prescribed degrees of freedom, (u_x, u_y and θ at both ends of the model element) as show in Fig. 2.7

Transverse normal strains experienced along the length of the wall are significantly reduced for low aspect ratio walls, especially in regions close to the top and bottom of the wall due to the constraining effect of pedestal used at the wall ends required for testing. Thus, using an assumption of zero transverse normal strain ($\varepsilon x = 0$), as an alternative formulation, may be more appropriate than assuming zero resultant transverse normal stress along the entire height of a wall. Comparing predictions of the two alternative model formulations ($\sigma x = 0$, $\varepsilon x = 0$), studies by Massone et al. (2006) revealed that neither model formulation is capable of correctly reproducing the experimental responses observed in walls with low shear span-to-depth ratios (lower than 0.5).

Julian Carrillo, Sergio M. Alcocer, Giovanni GonZalez (June 28th , 2012)

Deformation analysis of structural elements is a valuable tool for researching the relationship of lateral force versus shear sliding and flexural deformations, to assess the strength mechanism of failure mode, to assign suitable values of lateral stiffness, to estimate the contribution of steel reinforcement to strength and displacement capacities, to calibrate analytical models, and to propose appropriate parameters for performance –based seismic design. An experimental and analysis study was conducted to assess the components of deformation of low-rise reinforced concrete wall. The experimental program included shaking table test of 6 low-rise concrete walls. The method and the instrumentation schemes to allow accurate assessment of the three components of deformation for squat walls and walls with openings are proposed. It was found that the proposed method produce consistent results for the test evaluation.

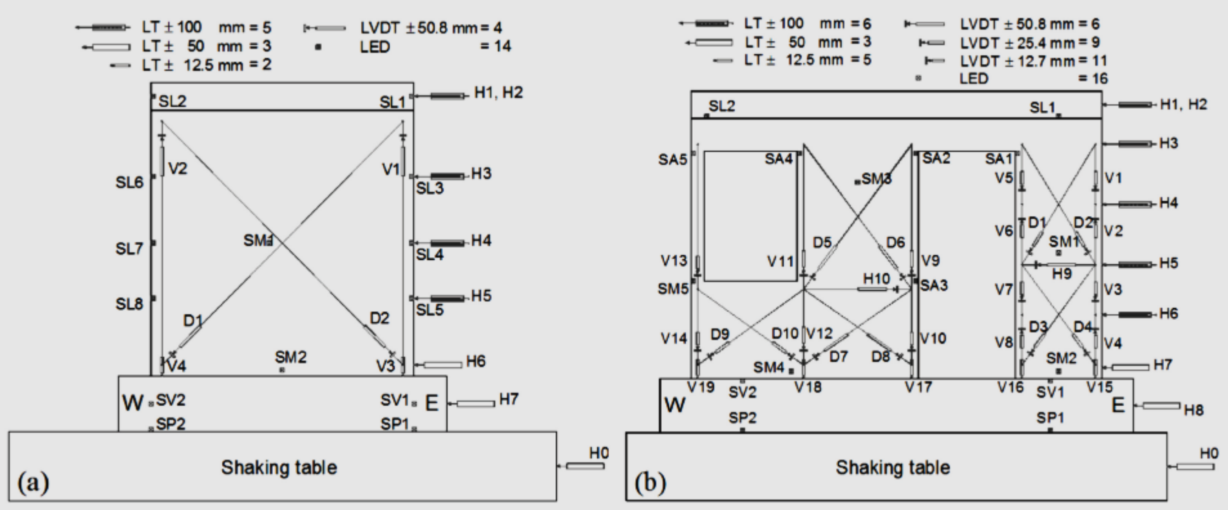


Fig.2.8 *Proposed instrumentation Schemes: (a) Wall without opening (b) Wall with Opening*

This paper aimed at developing a method for estimating web shear, flexural, and sliding components of the deformation of low-rise RC wall under shaking table excitation, an experimental and analytical study was carried out. Instrumentation schemes for estimating the components of deformation of wall with and without opening are proposed. Verification of the proposed method is conducted by means of the analysis of response measured during shaking table test of 6 RC squat walls and walls with door and window openings. Verification includes the discussion of failure modes, the analysis of the contribution of deformation to total story drift, and the evaluation of the dominant deformation model of each wall.

Contribution of flexural deformation:

Flexural deformations on top of a wall should be calculated from area of the rotation diagram of the cantilever wall. The accuracy of calculating flexural deformations depends on the information available on the shape of the rotation diagram (Fig. 2.9). If the area of actual rotation diagram were known, flexural displacement will be accurately calculated. If only the rotation on top of the wall were available, flexural deformations would be overestimated

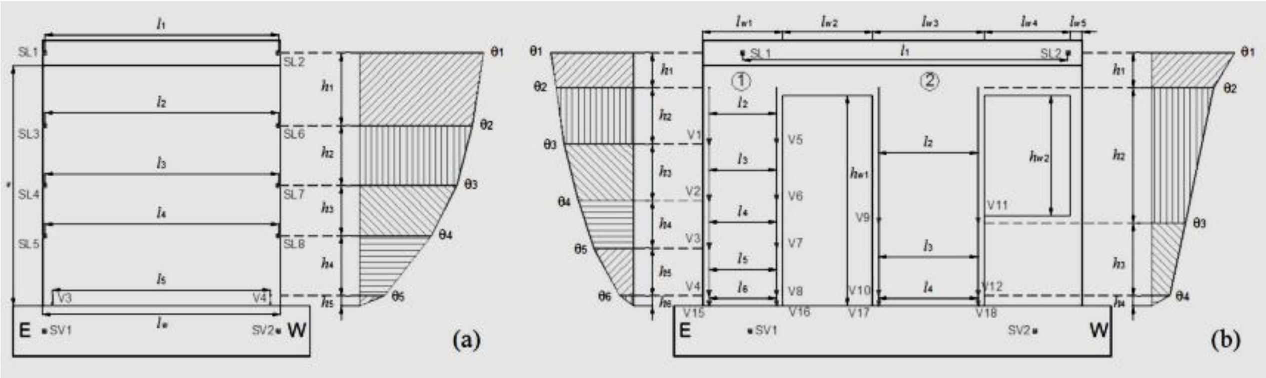


Fig. 2.9 *Calculation of flexural deformation: (a) Wall without opening (b) Wall with opening*

If rotations are measured at least at three heights of the wall, flexural deformation is adequately estimated [2, 4]. Based on a response measured during shaking table tests carried out in this study, it is recommended that one calculate the rotation at three sections of low-rise concrete walls. For squat walls, the rotation of sections should be measured using pairs of Light-Emitting Diode (LEDs) along the wall height and one pair of Linear Displacement Transduction (LTs) placed at the wall base. Therefore, the contribution of the flexural deformations to the total displacement should be calculated using Eqs. (2.7a) to (2.7b) [Fig. 2.15].

$$\Delta_f = \frac{\theta_1}{2}h_1 + \frac{\theta_2}{2}(h_1 + h_2) + \frac{\theta_3}{2}(h_2 + h_3) + \frac{\theta_4}{2}(h_3 + h_4) + \frac{\theta_5}{2}(h_4 + h_5) \qquad (2.7a)$$

$$\theta_i = \frac{(v_{ei} - v_e) - (v_{wi} - v_w)}{l_i} \qquad (2.7b)$$

$$\theta_5 = \frac{v_{e5} - v_{w5}}{l_5} \qquad (2.8)$$

Where v_{ei} and v_{wi} are the vertical displacements recorded by LEDs placed at the east and west side, respectively, at wall height hi, li is the distance between these sensors and ve and vw are the vertical displacements recorded by LEDs placed at east SV1 and west SV2 side, respectively, at the foundation beam. In Eq. (2.9), ve5 and vw5are the lengthening or contraction recorded by Device Diagonal Displacement (DDD) placed vertically at the east (V3) and west (V4) wall sides.

For walls with openings, the rotations of wall sections should be measured using both a pair of LEDs placed on top of the wall and DDDs distributed vertically along the height of the wall segments. Equations 2.9 should be used for segments 1 and 2, respectively [Fig. 2.9]

$$\Delta_f = \frac{\theta_1}{2}h_1 + \frac{\theta_2}{2}(h_1 + h_2) + \frac{\theta_3}{2}(h_2 + h_3) + \frac{\theta_4}{2}(h_3 + h_4) + \frac{\theta_5}{2}(h_4 + h_5) + \frac{\theta_6}{2}(h_5 + h_6)$$

$$\Delta_f = \frac{\theta_1}{2}h_1 + \frac{\theta_2}{2}(h_1 + h_2) + \frac{\theta_3}{2}(h_2 + h_3) + \frac{\theta_4}{2}(h_3 + h_4) \qquad (2.9)$$

Where θ1 is calculated using Eq.2.7b Should be calculated in a way similar to that expressed in Eq. 2.9

Contribution of shear deformations:

The diagonal deformations of each panel can obtained from the principles of materials mechanics, that is, from changes in the length of two diagonals placed between two opposite corners of the wall. The following equation should be used for squat walls ($^{h_w}/_{l_w} = 1$)

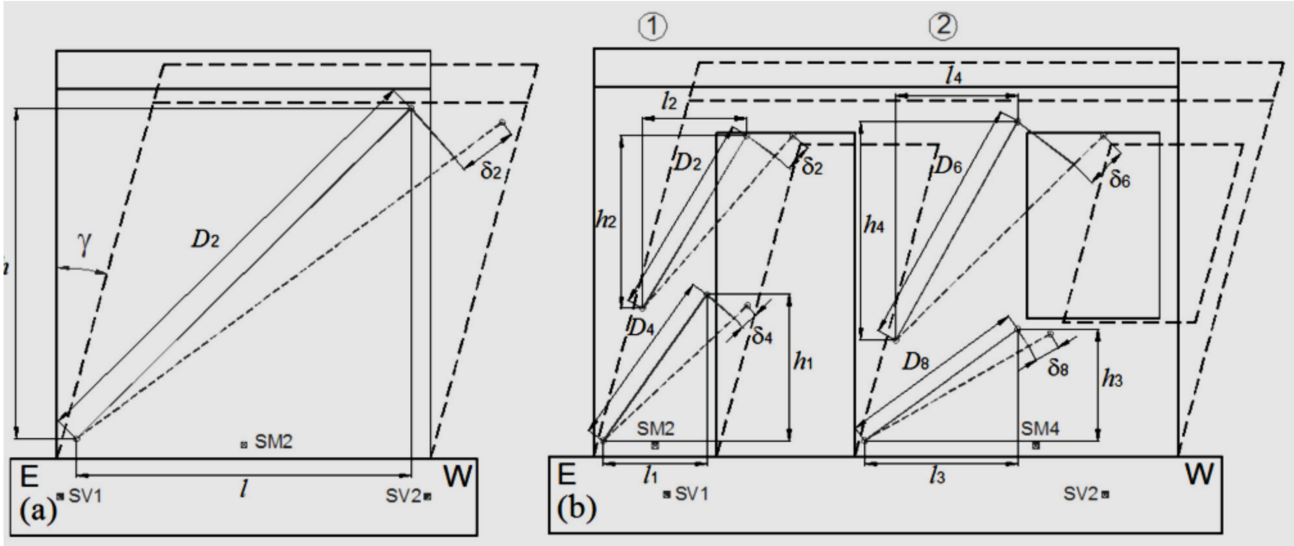


Fig.2.10 *Calculation of shear deformation: (a) Wall without opening (b) Wall with opening*

$$\Delta_c = \Upsilon H = \frac{\delta_2 D_2 - \delta_1 D_1}{2lh} H \qquad (2.11)$$

Where ϒ the web shear deformation, d_1 and d_2 is are the lengthening and construction recorded by the DDD 1and 2, respectively; D_1 and D_2 are the initial length of diagonals (undamaged wall) 1 and 2, respectively; and l and h are the length and height of the undamaged panel, respectively.

DDD records linear displacements between two points located directly on the wall web; therefore, shear deformations are affected by D_{OE}

Finally, this paper concludes that, Negligible measured sliding displacements during the tests demonstrated that a load-displacement curve can be based on a model in which the total displacement is calculated as the sum of contributions related to flexure and shear, and Shear failure mode was observed in all walls and thus, the contribution of flexural deformation was always lower than 36%. This trend allows for one to conclude that a flexural failure mode may be observed in RC walls where the contribution of flexural deformation is higher than 40%. When predicting the governing failure mode, it will be possible to design RC walls in favor of a suitable strength mechanism.

Nayera Mohamed; Ahmed Sabry farghaly; Brahim Benmokrane; and Kenneth W. Neale (2013)

Experimental results of midrise RC shear walls under quasistatic cyclic loading were used to investigate the interaction of flexural and shear deformations. Four large-scale shear walls—one reinforced with steel bars and three totally reinforced with glass fiber–reinforced polymer (GFRP) bars—were tested to failure where the behavior was dominated by flexure. It was found that relying on the diagonal displacement transducers tended to overestimate shear deformations by 30 to 50%. To correct the shear deformations, the center of rotation of the tested shear walls was evaluated. Based on experimental results, the fundamental equation of flexural deformation obtained values of the center of rotation. Using the suggested values of α produced consistent results for the flexure and shear deformations. Using elastic materials (GFRP bars) gave uniform distributions of shear strains along the shear region of the GFRP-reinforced shear walls ranging from 15 to 20% of the total deformation, resulting in less shear deformations than those experienced in the steel-reinforced shear wall; for this yielding of the steel bars intensified the shear strains at the yielding location, causing significant degradation in shear deformation ranging from 2 to 20% of total deformation.

The proper characterization of shear-wall strength and deformation capacities is essential. Strength designs must include assessing the flexural and shear strength of a wall panel. This is especially important for earthquake-resistant design, in which the design load increases as the ductility or deformation capability of a structure decreases. Even though this consideration is implicitly incorporated into building codes and may not be of direct concern to the designer, such information is important for developing or improving code provisions as well as for assessing the seismic safety of a particular design.

The present investigation, therefore, addressed the behavior of shear walls with a medium aspect ratio (defined as wall height to length ratio (h_w:l_w), which is common in midrise buildings and parking garages. A large proportion of shear walls constructed in the United States and Canada are classified as midrise and have wall aspect ratios (h_w:l_w) typically between 2 and 4 (Jiang and Kurama 2010). Therefore, in designing the shear walls presented herein, the aim was to avoid all brittle failures that might occur and that would cause lower deformation capacity (ductility) and thus prevent the shear walls from reaching their strength capacity. The major objective of this study is to propose methods to calculate realistic, rather than conventional, flexural and shear deformation in shear wall controlled by flexure based on experimental result.

The contribution of flexural and shear deformation to the total deformation of the wall showed that, at early loading, flexural deformation dominated the response. At higher level of lateral drift, however, the shear deformation become relatively pronounced, although the factored shear strength is 30% higher than the ultimate lateral capacity of the shear wall.

2.3 Summary of the Previous researches works

So far, in the most literatures reviewed including experimental evidence but some analytical studies also incorporate for solid shear wall (wall without opening) to determine/assess the effect of shear deformation in wall structure. Most papers or research under this idea done using experimental procedure by focused on non-linear behaver shear wall. This experimental method include Quasi-static cyclic test, reversed cyclic lateral test, shaking test etc those are not available in our country. Now, the focus of this thesis work is to use simplified hand procedure (analytical method) for assessment of effect of shear deformation in pierced shear wall with detail parametric study (that is not well done in previous works).

CHAPTER THREE

INVESTIGATION OF THE BEHAVIOUR OF SHEAR WALL DEFORMATION WITH DIFFERENT OPENINGS SIZE

3.1 General

This study investigate the accuracy of simplified hand method recommended in several design guidelines for practicing structural engineers for calculating the lateral deformation of shear wall with and without openings.

3.2 Determination of Shear Wall Deformation

The lateral load capacity of shear wall is mainly dependent on the in-plane resistance rather than out-of-plane stiffness. The distribution of lateral load to shear walls is based on the relative wall rigidities if a rigid diaphragm supports the walls and segment of wall deflects equally. The rigidity of a shear wall (inversely related to wall deformation) is dependent on its dimension, modulus of elasticity (E), modulus of rigidity (G) and support condition.

3.2.1 Pier Analysis

In Wall structure, it is generally assumed that in one-storey building the walls may be considered **cantilevered** and segment of the walls between adjacent openings are called piers and might be considered **fixed at top and bottom**, depending on the relative rigidities of the wall versus those of the floor diaphragms.

Cantilever Pier or wall

If the pier or wall fixed only at the bottom and top is free to translate and rotate, it is considered a cantilevered wall. When a force [P] is applied at top of a pier, it will produce a deflection, Δ_{wall} which is the sum of the deflection due to bending moment $\Delta_{flexural}$ plus that due to shear Δ_{shear}

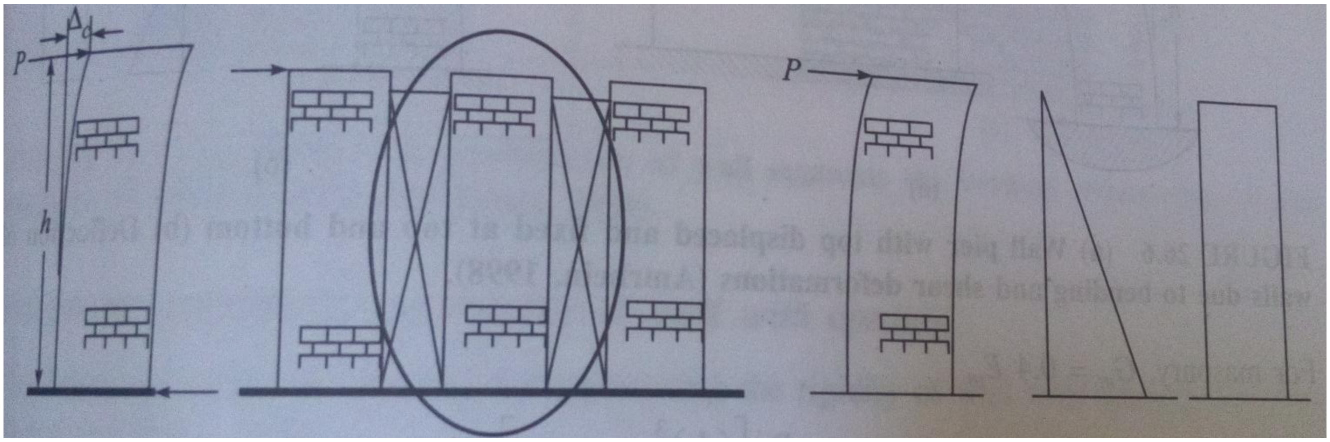


Fig. 3.1 *wall pier displacement at top and cantilevering from fixed bottom and deflection of wall due to bending and shear deformation (Amrhein, 1998)*

$$\Delta_{total} = \frac{PH^3}{3EI} + 1.2\frac{PH}{GA} \qquad (3.1)$$

Where G=0.4*E [For concrete]

$$\Delta_{total}(c) = \frac{p}{Eb} * (\frac{4H^3}{L^3} + 3\frac{H}{L}); \qquad (3.2)$$

Rigidity of cantilever pier:

$$R_c = \frac{1}{\Delta_c} \qquad (3.3)$$

Fixed Pier or wall

For a wall/pier fixed at top and bottom, the deflection from a force p

$$\Delta_{total} = \Delta_{flexural} + \Delta_{shear} \qquad (3.4)$$

$$\Delta_{total} = \frac{PH^3}{12EI} + 1.2\frac{PH}{GA}$$

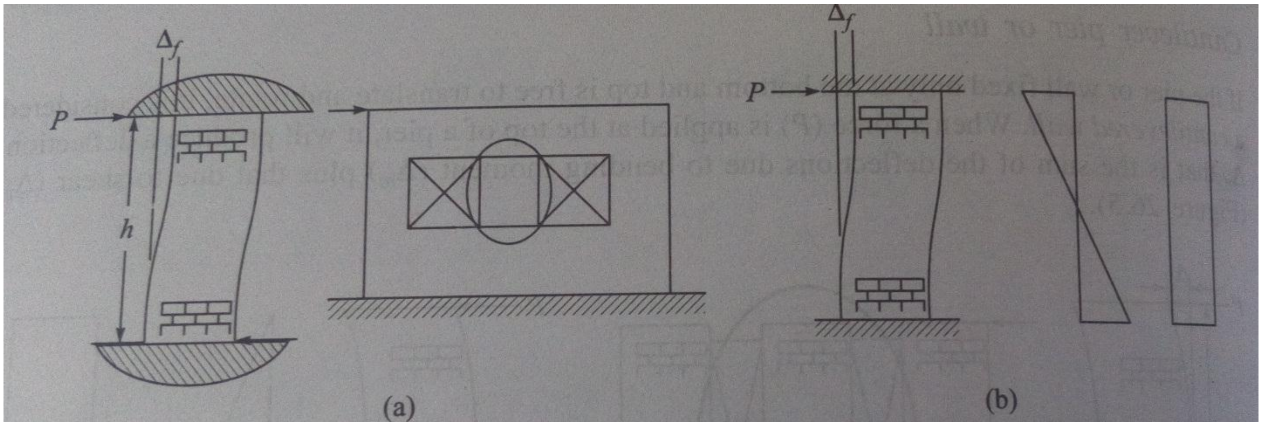


Fig. 3.2 *wall pier displacement at top displacement, fixed at top and bottom of wall due to bending, and shear deformation (Amrhein, 1998)*

$$\Delta_{total}(f) = \frac{p}{Eb} * \left(\frac{H^3}{L^3} + 3\frac{H}{L}\right);$$

Rigidity of fixed pier:

$$R_f = \frac{1}{\Delta_f} \tag{3.5}$$

Horizontal and Vertical Combination

If the shear wall segment are combined horizontal, the combined rigidity $R = R_{c1} + R_{c2} + R_{c3}$, if the segments are combined vertically, the combined rigidity $1/R = 1/R_{c1} + 1/R_{c2} + 1/R_{c3}$

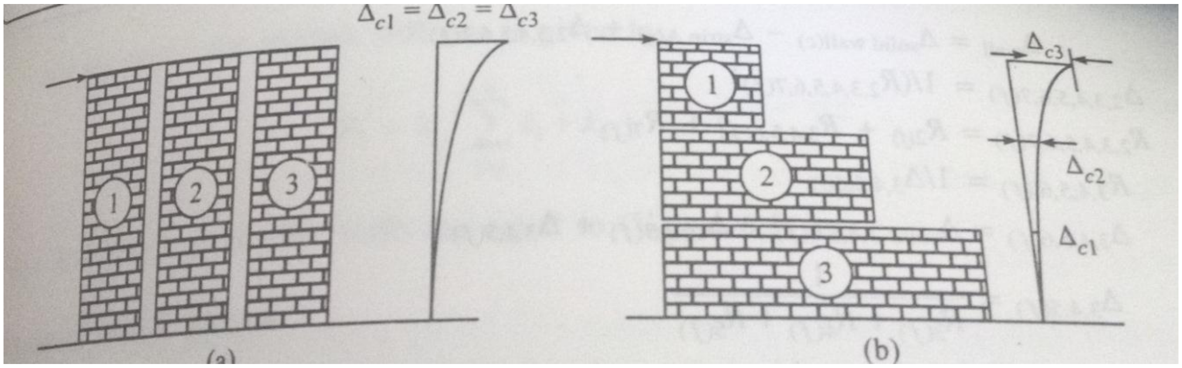


Fig. 3.3 *(a) Horizontal combination of wall segment (b) vertical combination of wall segment (Drydale,Hamid and Baker, 1994)*

3.2.2 Method for calculating the deformation of wall (one over rigidity of wall) with opening

The following steps are required for calculating the rigidity of the wall with opening (Drydale, Hamid and Baker, 1994)

[1] Calculate the deflection of the solid wall as a cantilever, $\Delta_{solid(c)}$(for one-or two-storey building)

[2] Calculate the cantilever deflection of an interior strip, having a height equal to that of the highest opening, is calculated and subtracted from the solid wall deflection. This step removes the entire portion of the wall containing all the openings ($\Delta_{strip\ of\ highst\ opening}$)

[3] Calculate the deflection of all the piers as fixed within that interior strip being determined by their own individual rigidity. ($\Delta_{peirs(f)}$)

[4] Add deflections of piers to the modified wall deflection to arrive at the total deflection of the actual wall with opening (Δ_{total})

3.3. Introduction for Simplified Hand Method

3.3.1. Solid Rectangular Shear Wall

As per Brandow et al. 1997; Lindeburg and Baradr 2001 simplified procedure to determine deformation of shear wall with and without opening is as follows.

For solid rectangular shear wall the thickness (t) much lesser than width of wall (L) [t<<<L]

$$\Delta_x = P * \left(\frac{H^3}{3EI_y} + 3\frac{H}{A_y E}\right);$$

$$I_y = \frac{L^3 t}{12}$$

$$I_x = \frac{t^3 L}{12} \approx o$$

$$\Delta_{solid\ wall} = \frac{P}{Et}\left(\frac{4H^3}{L^3} + \frac{3H}{L}\right) \qquad (3.6)$$

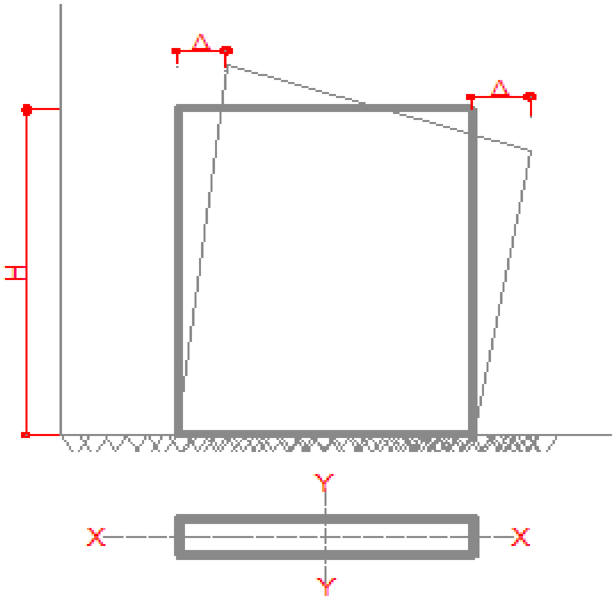


Fig. 3.4 *Deflection of Cantilever shear Wall*

3.3.2 Shear Wall With opening

For the case of shear wall with opening first calculates the deflection of solid cantilever wall ($\Delta_{solid\ wall}$) by ignoring all opening. Next, a strip is considered whose height is that of the tallest opening. The strip displacement ($\Delta_{solid\ strip}$) is calculated and subtracted from that of the solid wall. As far as the support conditions for the strip are concerned, we find conflicting information in the literature. While Brandow et al. 1997 suggest considering the strip fixed-fixed, Lindeburg and Baradr 2001 recommend cantilever action. Thus, the displacement of solid strip was calculated using the relation:

$$\Delta_{Solid\ strip} = \frac{P{y_o}^3}{12EI} + \alpha\frac{PH}{GA} = \frac{P}{Eb}\left(\frac{{y_o}^3}{L^3} + \frac{3y_0}{L}\right) \qquad (3.7)$$

Finally, the deformation of all piers contained in the opening are summed up assuming fixed-fixed condition as shown in Fig3.5. The displacement of piers (Δ_{piers}) is then the reciprocal of combined pier stiffness and is added as a correction to the difference of the gross and strip deflection. The final displacement of the wall having openings is in Eq. (3.10). For fixed-fixed conditions, the shear deformation is identical to that Eq. (3.6) and the flexure deformation term ${y_o}^3/3EI$ will reduced to ${y_o}^3/12EI$ (four times smaller than that for cantilever) such that:

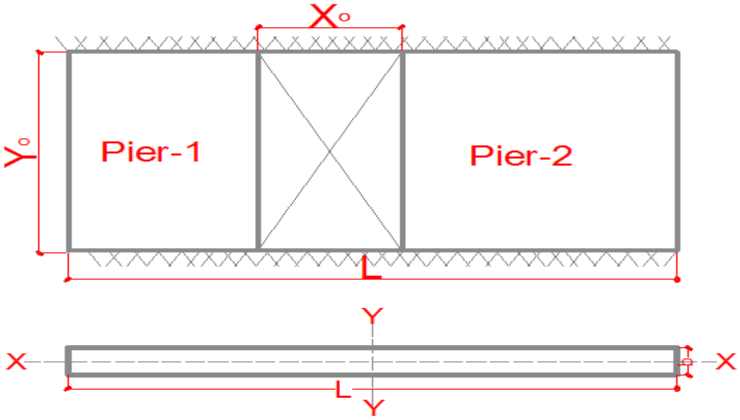


Fig. 3.5 *Wall Element Fixed at Both End*

$$\Delta_{Piers} = \frac{P{y_o}^3}{12EI} + \alpha\frac{PH}{GA}$$

$$= \frac{P}{Eb}\left(\frac{{y_o}^3}{{x_0}^3} + \frac{3y_0}{x_0}\right) \qquad (3.8)$$

Displacement of pier-1 and pier-2, as shown in fig. 3.5 were calculate using the above equation, and the combined displacement of piers was obtained using the following relation:

$$\Delta_{piers} = \frac{1}{\frac{1}{\Delta_{pier1}} + \frac{1}{\Delta_{pier2}}} \qquad (3.9)$$

$$\Delta_{wall} = \Delta_{solid\ wall} - \Delta_{Solid\ strip} + \Delta_{piers} \qquad (3.10)$$

3.3.3 Deep Beam Concept

For validation purpose, the shear wall is analyzed as a Deep Beam where the design lateral force is applied only at the top wall as shown in figure below.

Deep beams are structural elements loaded as simple beams in which a significant amount of the load is carried to the supports by a compression force combining the load and the reaction.

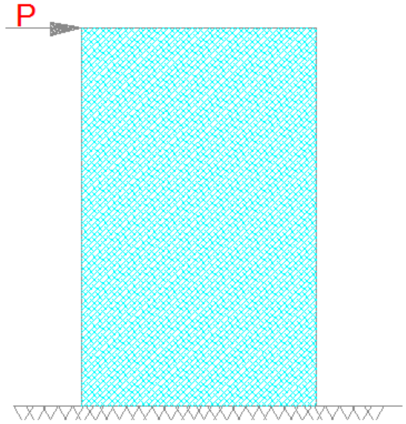


Fig. 3.6 *Cantilever Shear Wall*

The flexure term considers the wall as a vertical cantilever with moment of inertia I. The shear term contains the shape factor α which accounts for the distribution of shear stresses across the section and the shear area A. The material properties E and G = modulus of elasticity and shear modulus, respectively, which are related by

$$G = \frac{E}{2(1+\nu)} = \frac{E}{2.4} \qquad (3.11)$$

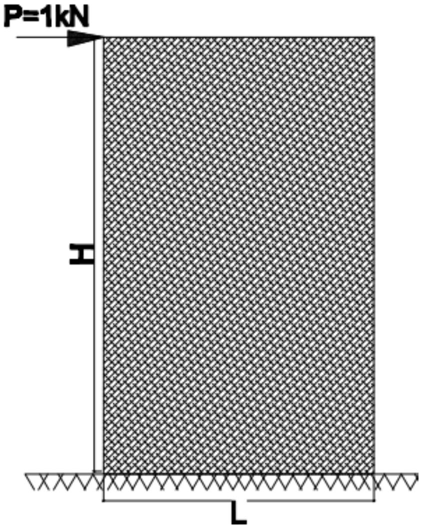
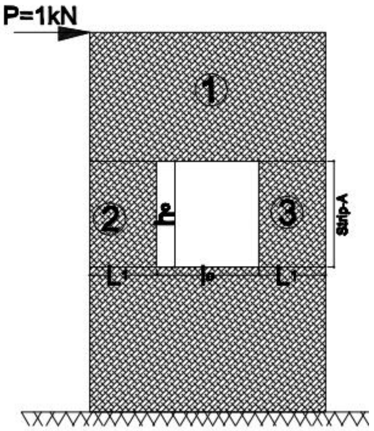
Where ν=poisson's ratio. Using α=1.2 and I=$b\,L^3/12$ for rectangular wall and selected $\nu = 0.25$ for un-cracked section.

To study the effects of shear deformation on different size and shape of openings in shear wall with different wall dimension using simplified hand method and verification is done using linear elastic analysis ANSYS 10 software.

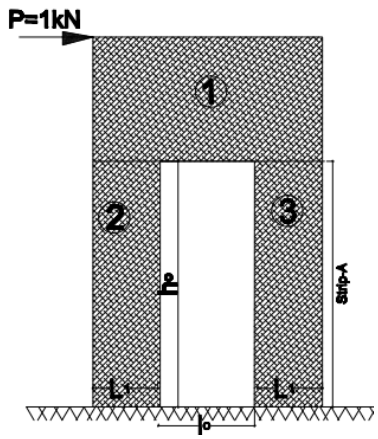
3.4 Description of Sample shear wall Model

The shear walls selected in this study used to determine the effect of shear deformation on lateral load (action) on behavior of concrete shear wall without and with openings by changing dimension and location of opening and by changing dimension of shear wall. Majorly, those shear wall samples categorized in to five depend on location of opening and based on simplified hand procedure, formula derivation for deformation presented on Table 3.1.

Table 3.1 *Description of Five Parameters*

Cases			Description	Formula Derivation
I			*Solid Shear wall*	$\Delta_{total}= \Delta_{Flex} + \Delta_{Shear}$ $= \frac{PH^3}{3EI} + \alpha\frac{PH}{GA},$ $\Delta_{Flex}= \frac{1}{Et}[4(\frac{H}{L})^3$ $\Delta_{Shear}= \frac{1}{Et}[3\left(\frac{H}{L}\right)]$
II	*a*		*Shear Wall with Center Window and Door Type of Opening*	$\Delta_{total} = \Delta_{Flex} + \Delta_{Shear}$ $\Delta_{wall}= \Delta_{\substack{solid\\wall(c)}} - \Delta_{strip\ A(c)} + \Delta_{2,3,(f)}$ $\Delta_{\substack{solid\\wall}}(c) = \frac{p}{Eb} * (\frac{4H^3}{L^3} + 3\frac{H}{L});$ $\Delta_{Strip\ A}(f) = \frac{p}{Eb} * [(\frac{h_o}{L})^3 + 3(\frac{h_o}{L})];$ $\Delta_{2,3}(f) = \frac{1}{R_{2f} + R_{3f}} = \frac{1}{\frac{1}{\Delta_{2f}} + \frac{1}{\Delta_{3f}}} = \frac{1}{2 * \frac{1}{\Delta_{2f}}}$ *Where* $\Delta_{2,3f}= \Delta_{2f}= \Delta_{3f}$ $\Delta_{2f}= \frac{p}{Eb} * \left(\frac{{h_o}^3}{{L_1}^3} + 3\frac{h_0}{L_1}\right), L_1 = {(L - l_o)}/{2}$ $\Delta_{Shear}= \frac{1}{Et}[3\left(\frac{H}{L}\right) - 3\left(\frac{h_o}{L}\right) + \frac{3}{2}(\frac{h_o}{((L - l_o)/2)})]$

<table>
<tr><th>Cases</th><th colspan="2"></th><th>Description</th><th>Formula Derivation</th></tr>
<tr><td></td><td><i>b</i></td><td>



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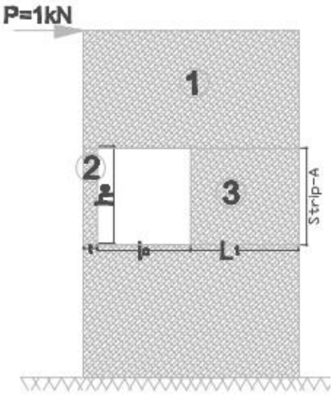
$$\Delta_{total} = \Delta_{Flex} + \Delta_{Shear}$$
$$\Delta_{wall} = \Delta_{\substack{solid\\wall(c)}} - \Delta_{strip\ A(c)} + \Delta_{2,3,(f)}$$
$$\Delta_{\substack{solid\\wall}}(c) = \frac{p}{Eb} * \left(\frac{4H^3}{L^3} + 3\frac{H}{L}\right);$$
$$\Delta_{Strip\ A}(c) = \frac{p}{Eb} * \left[4\left(\frac{h_o}{L}\right)^3 + 3\left(\frac{h_o}{L}\right)\right];$$
$$\Delta_{2,3}(f) = \frac{1}{R_{2f} + R_{3f}} = \frac{1}{\frac{1}{\Delta_{2f}} + \frac{1}{\Delta_{3f}}} = \frac{1}{2 * \frac{1}{\Delta_{2f}}}$$
Where $\Delta_{2,3f} = \Delta_{2f} = \Delta_{3f}$
$$\Delta_{2f} = \frac{p}{Eb} * \left(\frac{{h_o}^3}{{L_1}^3} + 3\frac{h_0}{L_1}\right), L_1 = {(L - l_o)}/{2}$$
$$\Delta_{Shear} = \frac{1}{Et}\left[3\left(\frac{H}{L}\right) - 3\left(\frac{h_o}{L}\right) + \frac{3}{2}\left(\frac{h_o}{{((L - l_o)}/{2})}\right)\right]$$

</td></tr>
<tr><td>III</td><td><i>a</i></td><td>



</td><td><i>Shear Wall with Window and Door Type of Asymmetric Opening[Eccentric to Left]</i></td><td>

$$\Delta_{total} = \Delta_{Flex} + \Delta_{Shear}$$
$$\Delta_{wall} = \Delta_{\substack{solid\\wall(c)}} - \Delta_{strip\ A(c)} + \Delta_{2,3,(f)}$$
$$\Delta_{\substack{solid\\wall}}(c) = \frac{p}{Eb} * \left(\frac{4H^3}{L^3} + 3\frac{H}{L}\right);$$
$$\Delta_{Strip\ A}(f) = \frac{p}{Eb} * \left[\left(\frac{h_o}{L}\right)^3 + 3\left(\frac{h_o}{L}\right)\right];$$
$$R_{2,3(f)} = R_{2(f)} + R_{3(f)}$$
$$\Delta_{2,3}(f) = \frac{1}{R_{2f} + R_{3f}}$$
$$R_{2f} = \frac{Et}{\left[\left(\frac{h_o}{t}\right)^3 + 3\left(\frac{h_o}{t}\right)\right]}$$
$$R_{3f} = \frac{Et}{\left[\left(\frac{h_0}{L_1}\right)^3 + 3\left(\frac{h_p}{L_1}\right)\right]}$$
Where $L_1 = L - l_o - t$

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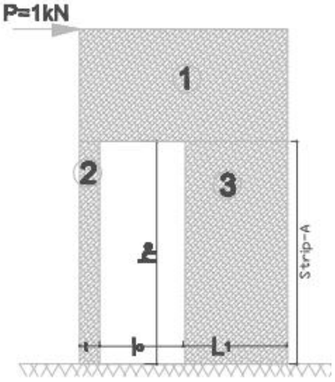
<tr><td></td><td><i>b</i></td><td>



</td><td></td><td>

$$\Delta_{total} = \Delta_{Flex} + \Delta_{Shear}$$
$$\Delta_{wall} = \Delta_{\substack{solid\\wall(c)}} - \Delta_{strip\ A(c)} + \Delta_{2,3,(f)}$$
$$\Delta_{\substack{solid\\wall}}(c) = \frac{p}{Eb} * \left(\frac{4H^3}{L^3} + 3\frac{H}{L}\right);$$
$$\Delta_{Strip\ A}(c) = \frac{p}{Eb} * \left[4\left(\frac{h_o}{L}\right)^3 + 3\left(\frac{h_o}{L}\right)\right];$$
$$R_{2,3(f)} = R_{2(f)} + R_{3(f)}$$
$$\Delta_{2,3}(f) = \frac{1}{R_{2f} + R_{3f}}$$
$$R_{2f} = \frac{Et}{\left[\left(\frac{h_o}{t}\right)^3 + 3\left(\frac{h_o}{t}\right)\right]}$$
$$R_{3f} = \frac{Et}{\left[\left(\frac{h_0}{L_1}\right)^3 + 3\left(\frac{h_p}{L_1}\right)\right]}$$
Where $L_1 = L - l_o - t$

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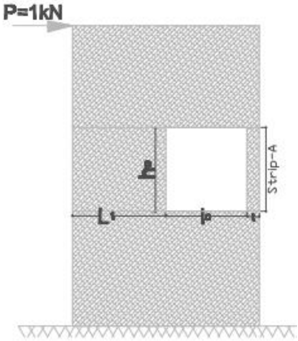
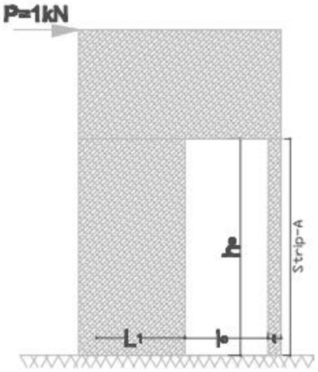
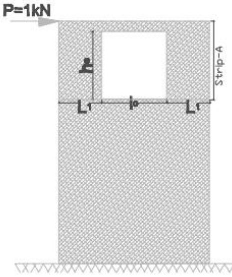
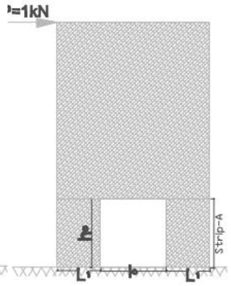
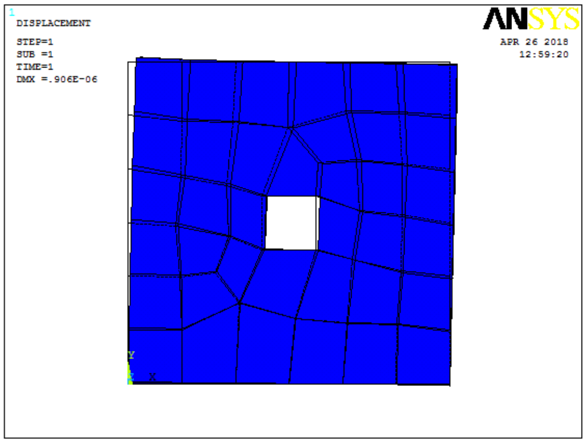
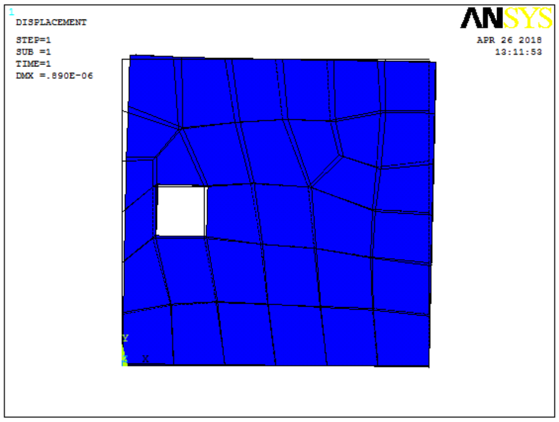
</table>

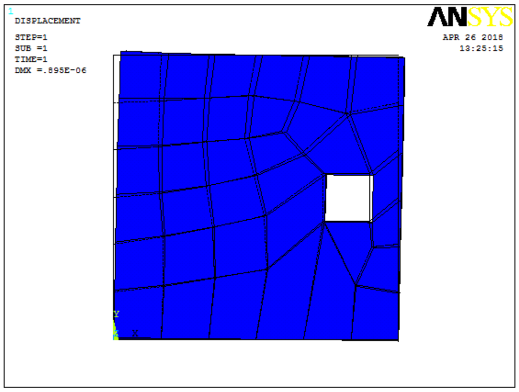
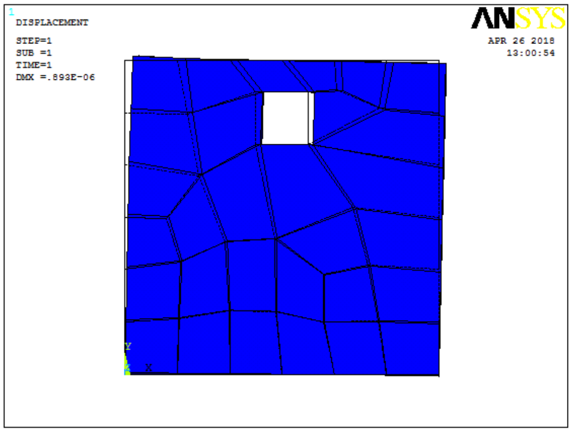
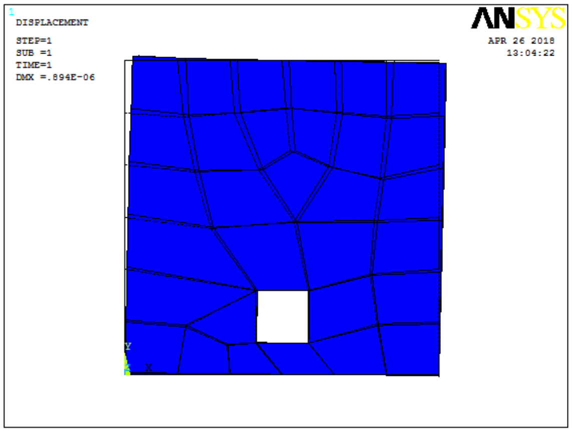
Cases		Description	Formula Derivation
IV		*Shear Wall with Window and Door Type of Asymmetric Opening[Eccentric to Right]*	*Same as Typology IIIa*
			*Same as Typology IIIa*
IV	 	*Shear Wall with Window Type of Opening[Top and bottom opening]*	*Same as Typology IIa*

3.4.1 Analysis of Effect of Location of Opening in Shear Wall

Window and Door type in typology from II to VI has the same total wall deformation according to simplified hand method. In this section, validation are carry out for the significance of location of opening in shear wall using ANSYS 10 SHELL181 element type.

Table 3.2 *Verification Analysis using ANSYS*

Typology	ANSYS Result	Total Deformation(m)	Error
IIa	 DISPLACEMENT STEP=1 SUB =1 TIME=1 DMX =.906E-06 APR 26 2018 12:59:20	0.906e-6	
IIIa	 DISPLACEMENT STEP=1 SUB =1 TIME=1 DMX =.890E-06 APR 26 2018 13:11:53	0.89e-6	1.8%

Typology	ANSYS Result	Total Deformation(m)	Error
IVa		0.895e-6	1.2%
V		0.893e-6	1.4%
		0.894e-6	1.3%

Based on the above verification, deformation for center type of opening and other type the location of opening not significantly defer. As result, probabilistic assessment of shear deformation for typology I –solid shear wall and typology from II-VI as centered window and door type of opening is undertake by generating systematic random sampling using LHS method.

3.5 Sampling Method

The combinations are generated using Latin Hypercube Sampling (LHS) Method. LHS is a sampling method designed to accurately recreate the input distribution through sampling in fewer trails when compared with the Monte Carlo method in which the distribution of each random variable is assumed normal. In the LHS sampling method, the cumulative distribution function of each factor is divided into intervals with equal probability, and then sampling is done by only once from each interval. [11] LHS is sampling method designed to accurately recreate the input distribution through sampling in fewer trial when compared with the Monte Carol Method, which is need thousands trial.

LHS, a sampling technique used, forces the samples drawn to correspond more closely with the input distribution and thus converges faster on the true statistics of the input distribution [2].

Typology-I: Shear wall Without Opening

In this case, the 32 combinations of random variables of LHS table are found to be sufficient and considered in the determination of deformation. The statistical variations and the 32x3 layers of random variables are shown in Table 3.6

Table 3.3 *Statistical Variations of Random Variables for SW without Opening*

Input variables	Unit	Min. Value	Max. Value	Mean Values	Standard deviation
Height of Shear Wall (H)	m	2.4	5	3.7	0.787
Width of Shear wall (L)	m	3	7.5	5.25	1.362
Shear wall thickness (t)	m	0.15	0.6	0.375	0.136

Typology-II-V: Shear wall With Center Opening

In this typology, also 32 combinations of random variables of LHS table are found to be sufficient and considered in the determination of deformation. The statistical variations and the 32x5 layers of random variables are categorized in to two (window and door type of opening) shown in Table 3.6.

Table 3.4 *Statistical Variations of Random Variables for SW with Window Type of Opening*

Input variables	Unit	Min. Value	Max. Value	Mean Values	Standard deviation
Height of Shear Wall (H)	m	2.4	5	3.7	0.787
Width of Shear wall (L)	m	3	7.5	5.25	1.362
Vertical Dimension of Opening (ho)	m	0.7	3.8	2.25	0.938
Horizontal Dimension of Opening(lo)	m	0.7	6.3	3.5	1.695
Shear wall thickness (t)	m	0.15	0.6	0.375	0.136

Table 3.5. *Statistical Variations of Random Variables for SW with Door Type of Opening*

Input variables	Unit	Min. Value	Max. Value	Mean Values	Standard deviation
Height of Shear Wall (H)	m	2.4	5	3.7	0.787
Width of Shear wall (L)	m	3	7.5	5.25	1.362
Vertical Dimension of Opening (ho)	m	2	4.4	2.9	0.545
Horizontal Dimension of Opening(lo)	m	0.7	6.3	4.1	1.695
Shear wall thickness (t)	m	0.15	0.6	0.375	0.136

Table 3.6 *32X5 LHS Combination of random variable for shear wall with and without opening*

	Window Type of Opening					Door Type of Opening					Without Opening		
Cases	H	L	ho	lo	t	H	L	ho	lo	t	H	L	t
Case-1	4.40	4.30	1.20	1.40	0.30	4.40	4.30	2.40	1.40	0.30	4.40	4.30	0.20
Case-2	3.00	6.10	0.90	3.80	0.50	3.00	6.10	2.20	3.80	0.50	3.00	6.10	0.20
Case-3	3.00	6.50	0.70	5.90	0.50	3.00	6.50	2.00	5.90	0.50	3.00	6.50	0.10
Case-4	3.90	6.90	3.10	2.10	0.40	3.90	6.90	3.90	2.10	0.45	3.90	6.90	0.50
Case-5	2.90	4.00	2.00	2.30	0.20	2.90	4.00	3.00	2.30	0.20	2.90	4.00	0.30
Case-6	4.20	5.20	1.60	3.70	0.20	4.20	5.20	2.70	3.70	0.20	4.20	5.20	0.30
Case-7	3.80	3.80	2.80	5.10	0.30	3.80	3.80	3.60	5.10	0.30	3.80	3.80	0.40
Case-8	2.70	5.00	2.60	4.60	0.30	2.70	5.00	3.50	4.60	0.30	2.70	5.00	0.40
Case-9	3.20	5.50	2.30	4.70	0.30	3.20	5.50	3.20	4.70	0.30	3.20	5.50	0.40
Case-10	4.30	8.20	2.10	2.70	0.10	4.30	8.20	3.10	2.70	0.10	4.30	8.20	0.40
Case-11	3.40	4.10	0.20	1.10	0.40	3.40	4.10	1.60	1.10	0.40	3.40	4.10	0.10
Case-12	3.60	4.90	2.10	2.40	0.30	3.60	4.90	3.10	2.40	0.30	3.60	4.90	0.30
Case-13	3.70	7.50	3.80	5.60	0.70	3.70	7.50	4.40	5.60	0.70	3.70	7.50	0.60
Case-14	5.40	5.10	3.60	0.70	0.60	5.40	5.10	4.20	0.70	0.60	5.40	5.10	0.60
Case-15	2.00	6.70	1.80	3.30	0.60	2.00	6.70	2.90	3.30	0.60	2.00	6.70	0.30
Case-16	4.00	4.50	2.40	1.70	0.40	4.00	4.50	3.30	1.70	0.40	4.00	4.50	0.40
Case-17	4.50	5.60	1.10	3.40	0.40	4.50	5.60	2.30	3.40	0.40	4.50	5.60	0.20
Case-18	3.10	5.30	1.70	3.60	0.30	3.10	5.30	2.80	3.60	0.30	3.10	5.30	0.30
Case-19	2.40	3.30	1.50	2.30	0.40	2.40	3.30	2.60	4.30	0.40	2.40	3.30	0.30
Case-20	3.30	6.20	2.70	7.20	0.50	3.30	6.20	3.50	7.20	0.50	3.30	6.20	0.40
Case-21	3.90	5.70	2.90	-0.15	0.40	3.90	5.70	3.70	-0.20	0.40	3.90	5.70	0.50
Case-22	4.10	4.40	1.40	4.40	0.40	4.10	4.40	2.50	4.40	0.40	4.10	4.40	0.20
Case-23	3.48	5.41	3.03	4.10	0.40	3.50	5.40	3.80	4.10	0.40	3.50	5.40	0.50
Case-24	3.70	5.90	2.40	2.60	0.30	3.70	5.90	3.30	2.60	0.30	3.70	5.90	0.40
Case-25	2.60	3.00	3.40	2.90	0.50	2.60	3.00	4.10	2.90	0.50	2.60	3.00	0.50
Case-26	3.50	4.80	3.30	1.90	0.40	3.50	4.80	4.00	1.90	0.40	4.40	6.00	0.30
Case-27	4.40	6.00	1.90	5.30	0.30	4.40	6.00	2.90	5.30	0.30	4.70	6.40	0.50
Case-28	4.70	6.40	2.80	4.00	0.20	4.70	6.40	3.70	4.00	0.20	4.80	3.60	0.40
Case-29	4.80	3.60	2.20	4.90	0.10	4.80	3.60	3.20	4.90	0.10	5.00	7.20	0.70
Case-30	5.00	7.20	4.30	3.00	0.50	5.00	7.20	4.80	3.00	0.50	4.10	4.60	0.30
Case-31	4.10	4.60	1.70	6.30	0.20	4.10	4.60	2.70	6.30	0.20	3.30	2.30	0.40
Case-32	3.30	2.30	2.50	3.20	0.50	3.30	2.30	3.40	3.20	0.50	3.50	4.80	0.50

For the different combinations considered, the shear deformation of the wall is computed using simplified hand method. The corresponding 32 cases outputs are also given in Table 3.7.

Scaling Factor of the Output Parameter Deformation of Shear wall

The range of input wall deformation parameters for the model varied by taking in to consideration some essential points which will be helpful on the parametric study on shear deformation of a concrete shear wall.

Maximum size Openings are allowed beyond the ends of the perforated shear wall, but should not be included in the width of perforated shear wall, for the minimum opening size sates from practical point of view (minimum window and door size). For the case of wall height, minimum and maximum values are set from the building having mezzanine floor. Thickness of wall varied from minimum (code provision) to maximum value depend on height of the building. To investigate the effect of wall length, it ranges from minimum value that satisfies code provision intended for minimum length of wall for resistance lateral action to maximum span length of ordinary building.

In general, the above minimum and maximum values are stuffs from practical point of view and minimum and maximum requirement on deferent codes.

3.6 Deformation Analysis

Here the deformation of shear wall with and without opening using simplified hand method is presented. Thirty-two isolated shear wall are analyzed with three category having five variables. Results for each three category are presented below in tabular and graphical forms according to their category. Detail analysis results are annexed.

Table 3.7 *Simplified Hand Method results for 32x5 LHS Combination of random variables for three type of shear wall.*

	Window Type of Opening					Door Type of Opening					SW Without Opening			
Cases	ΔShear	ΔFlxural	% opening	AR	Status	ΔShear	ΔFlxural	% opening	AR	Status	ΔShear	ΔFlxural	AR	Status
Case-1	0.000346	0.000549	9.45	1.02	C	0.000387	0.000602	18.44	1.02	C	0.000462	0.000643	1.02	C
Case-2	0.000144	0.000109	18.98	0.50	C	0.000210	0.000203	44.77	0.50	C	0.000283	0.000094	0.50	C
Case-3	0.000300	0.000252	20.71	0.45	C	0.000692	0.000678	60.59	0.45	C	0.000318	0.000087	0.45	C
Case-4	0.000179	0.000201	24.59	0.56	C	0.000190	0.000190	30.47	0.56	C	0.000114	0.000047	0.56	C
Case-5	0.000632	0.000740	40.02	0.72	C	0.000789	0.000769	60.31	0.72	C	0.000221	0.000153	0.72	C
Case-6	0.000774	0.000867	26.67	0.81	C	0.001038	0.001151	45.40	0.81	C	0.000302	0.000262	0.81	C
Case-7	-0.000594	-0.000284	97.87	1.00	NC	-0.000875	-0.000825	127.65	1.00	NC	0.000232	0.000311	1.00	C
Case-8	0.001963	0.002009	86.73	0.55	C	0.002568	0.002542	116.01	0.55	NC	0.000134	0.000054	0.55	C
Case-9	0.000939	0.000961	61.09	0.58	C	0.001252	0.001252	86.24	0.58	C	0.000158	0.000071	0.58	C
Case-10	0.000460	0.000406	16.81	0.52	C	0.000505	0.000487	24.47	0.52	C	0.000150	0.000055	0.52	C
Case-11	0.000245	0.000241	1.79	0.83	C	0.000281	0.000351	12.75	0.83	C	0.001046	0.000959	0.83	C
Case-12	0.000436	0.000511	28.66	0.74	C	0.000513	0.000550	42.42	0.74	C	0.000220	0.000161	0.74	C
Case-13	0.000301	0.000321	77.23	0.49	C	0.000335	0.000333	89.24	0.49	C	0.000084	0.000026	0.49	C
Case-14	0.000212	0.000415	8.60	1.06	C	0.000215	0.000323	10.15	1.06	C	0.000193	0.000289	1.06	C
Case-15	0.000096	0.000097	44.91	0.30	C	0.000122	0.000132	70.50	0.30	C	0.000098	0.000012	0.30	C
Case-16	0.000314	0.000447	21.92	0.88	C	0.000346	0.000411	30.52	0.88	C	0.000233	0.000241	0.88	C
Case-17	0.000272	0.000293	14.71	0.81	C	0.000354	0.000406	30.95	0.81	C	0.000402	0.000350	0.81	C
Case-18	0.000452	0.000453	37.59	0.59	C	0.000600	0.000605	60.44	0.59	C	0.000202	0.000094	0.59	C
Case-19	-0.000300	-0.000256	79.19	0.72	NC	-0.000656	-0.000675	139.82	0.72	NC	0.000283	0.000194	0.72	C
Case-20	-0.000632	-0.000616	91.30	0.54	NC	-0.000872	-0.000874	120.59	0.54	NC	0.000128	0.000049	0.54	C
Case-21	0.000187	0.000245	-1.96	0.68	NC	0.000186	0.000194	-2.50	0.68	C	0.000149	0.000093	0.68	C
Case-22	-0.050833	-0.050725	33.68	0.92	NC	-0.093962	-0.093848	62.13	0.92	NC	0.000387	0.000438	0.92	C
Case-23	0.000605	0.000658	66.10	0.64	C	0.000718	0.000706	82.99	0.64	C	0.000136	0.000075	0.64	C
Case-24	0.000382	0.000421	28.93	0.64	C	0.000432	0.000444	39.72	0.64	C	0.000164	0.000089	0.64	C
Case-25	0.008624	0.008754	128.26	0.87	NC	0.010325	0.009907	154.23	0.87	NC	0.000166	0.000168	0.87	C
Case-26	0.000326	0.000430	36.63	0.74	C	0.000353	0.000316	44.73	0.74	C	0.000148	0.000109	0.74	C
Case-27	0.001151	0.001190	38.34	0.74	C	0.001634	0.001681	58.92	0.74	C	0.000236	0.000174	0.74	C
Case-28	0.000831	0.000948	37.82	0.73	C	0.000955	0.001019	48.72	0.73	C	0.000164	0.000117	0.73	C
Case-29	-0.001176	0.001916	63.09	1.35	NC	-0.002450	-0.000065	90.41	1.35	NC	0.000377	0.000912	1.35	C
Case-30	0.000233	0.000290	35.89	0.70	C	0.000243	0.000249	40.04	0.70	C	0.000108	0.000071	0.70	C
Case-31	-0.000189	-0.000027	55.11	0.89	NC	-0.000556	-0.000405	90.99	0.89	NC	0.000317	0.000332	0.89	C
Case-32	-0.000573	0.000089	104.60	1.42	NC	-0.000886	-0.000969	141.73	1.42	NC	0.000355	0.000949	1.42	C

C- Calculated
NC-Not calculated/ Not applicable

The probabilistic distribution and the influence of random variables on the statistical variation of the estimated shear deformation of shear wall is investigated. To consider the probabilistic distribution of random variables on the deformation of shear wall with and without opening, the concept of normal distribution is used.

The probability function, f(x), using normal distribution [12] is given in Eq. (3.12). The probabilistic distribution of the deformation of the wall and its cumulative percentage are shown in Fig. 3.7, 3.8 & 3.9. Those Figures describes that for a given range of interval 95% data falls within two standard deviation of mean.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \qquad (3.12)$$

Where, x: random variable

μ: Mean value

σ: Standard deviation

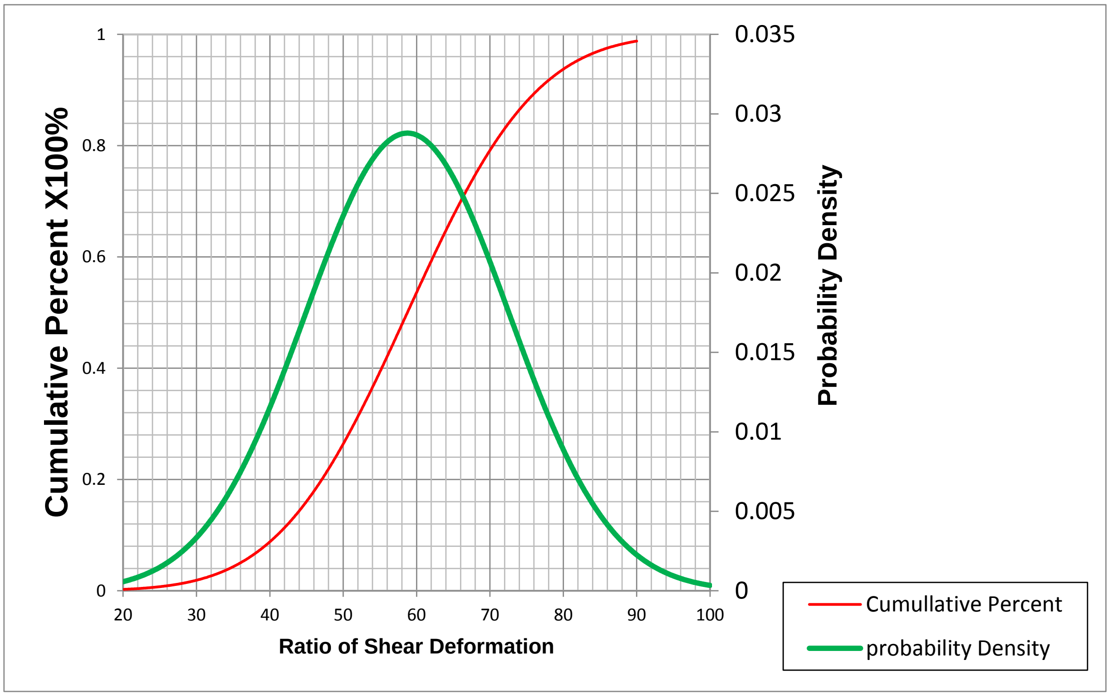


Fig. 3.7 *Probability Distribution of Ratio of shear Deformation for Shear wall without Opening*

Table 3.8 *Confidence Interval for shear wall with without opening*

Random Variables	Mean value	Standard deviation	Coefficient of Variation
Ratio of Shear Deformation	58.747	14.079	23.96%

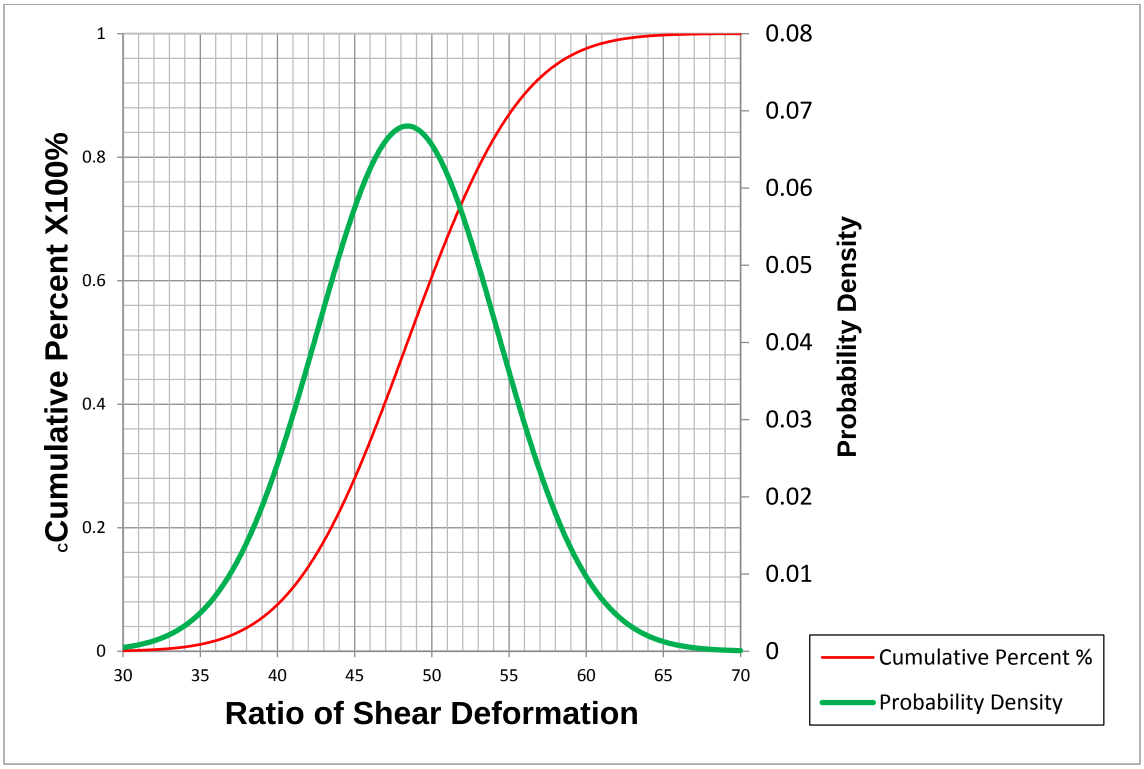


Fig. 3.8 *Probability Distribution of Ratio of shear Deformation for Shear wall with Window type Opening*

Table 3.9 *Confidence Interval for shear wall with window type of opening*

Random Variables	Mean value	Standard deviation	Coefficient of Variation
Ratio of Shear Deformation	48.416	5.968	12.33%

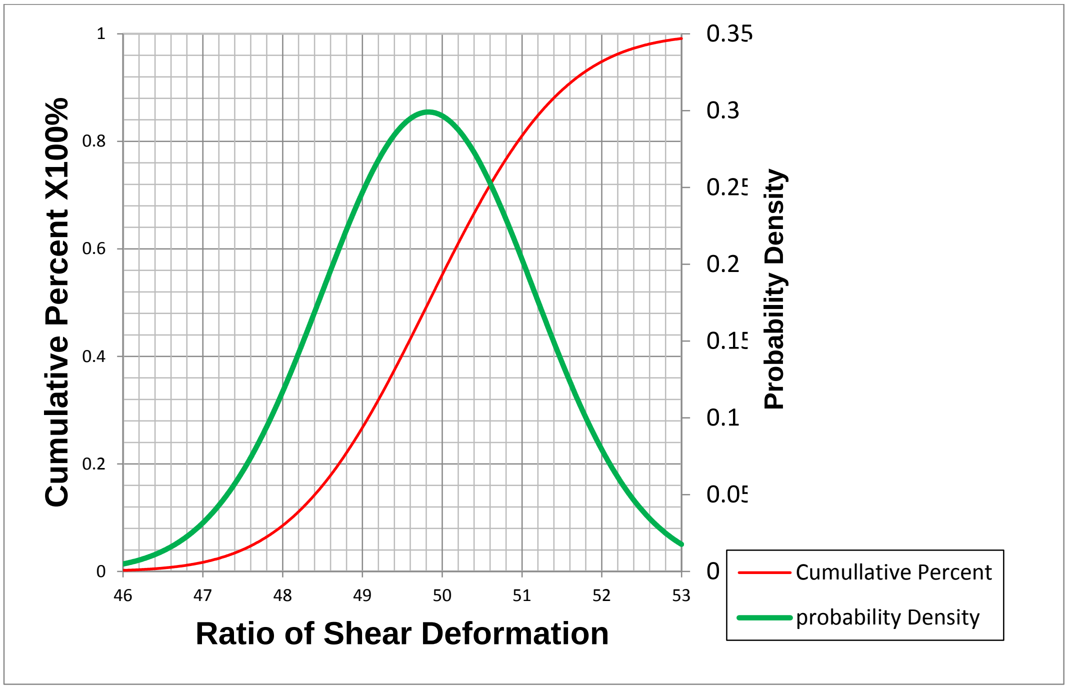


Fig. 3.9 *Probability Distribution of Ratio of shear Deformation for Shear wall with Door type Opening*

Table 3.10 *Confidence Interval for shear wall with door type of opening*

Random Variables	Mean value	Standard deviation	Coefficient of Variation
Ratio of Shear Deformation	49.827	1.366	2.8%

Detail graphical presentation on simplified hand procedure analysis for those systematically selected shear wall with and without opening are annexed.

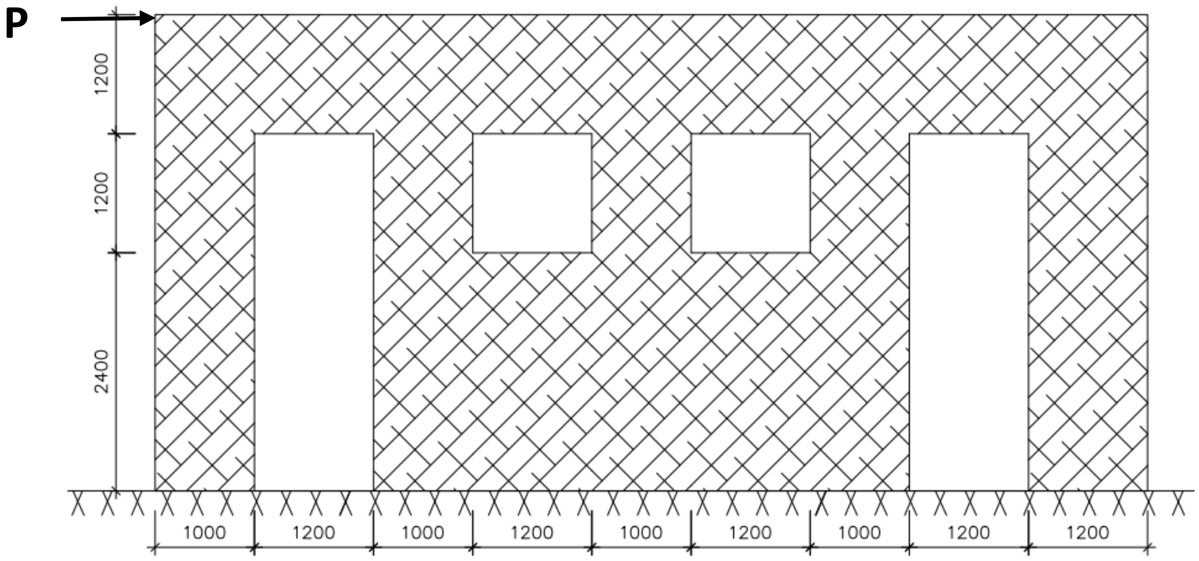
3.7 Validation of Simplified Hand Method on Shear Wall Deformation

In this section, first sample shear wall with combination of window and door type opening problem is solved both in numerically and Analysis System (ANSYS) software (Using shell element SHELL 181). The main verification parameter for this comparison is shear deformation.

3.7.1 Illustrative Example [Earthquake Resistant Design of Structures by Pankaj Agarwal and Manish shrikhande]

Example:

Determine the deformation [Shear and Flexural deformation] of the shear wall?

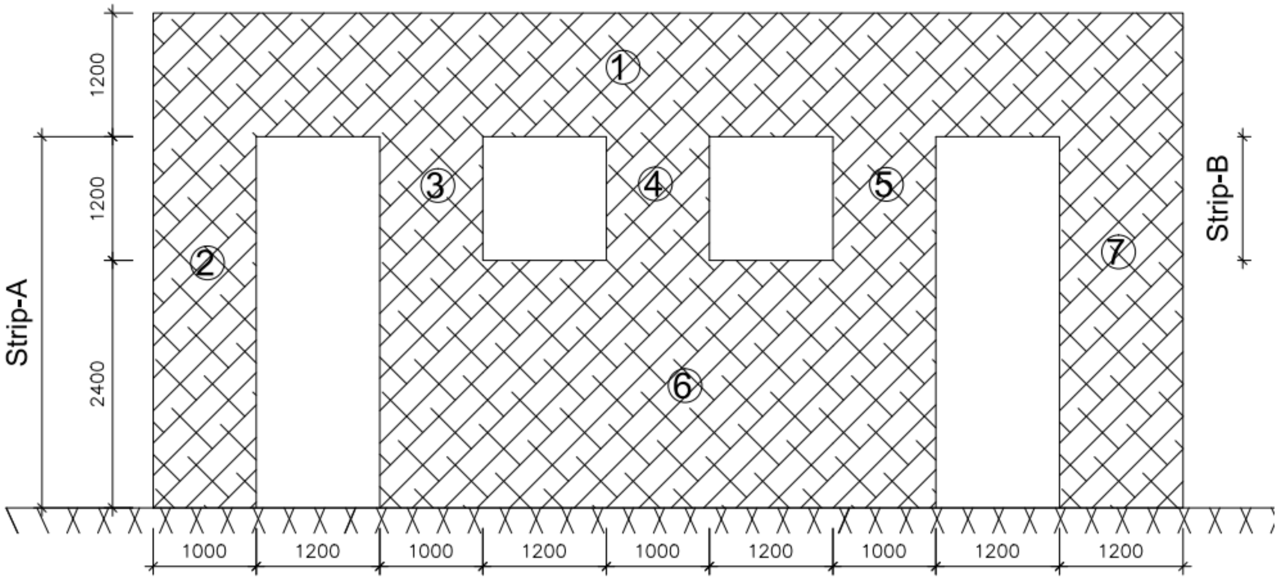


Given: P=1kN, L=10m, H=4.8m, B=30cm

Material Data: Concrete C25 E=29GPa,

Required: Shear wall Deformation

Solution I: Using Simplified Hand Method



$\Delta_{wall}= \Delta_{solid\ wall(c)} - \Delta_{strip\ A(c)} + \Delta_{2,3,4,5,6,7(f)}$

$\Delta_{solid(c)}= \frac{1}{Et}[4\left(\frac{h}{l}\right)^3 + 3\left(\frac{h}{l}\right)]=1.882/Et$______________where: h=4.8 & l=10

$\Delta_{solid\ A(c)}= \frac{1}{Et}[4\left(\frac{h}{l}\right)^3 + 3\left(\frac{h}{l}\right)]= 1.266/Et$______________where: h=3.6 & l=10

$$\Delta_{2,3,4,5,6,7}= \frac{1}{R_{2,3,4,5,6,7}}$$

$$R_{2,3,4,5,6,7} = R_{2(f)} + R_{3,4,5,6(f)} + R_{7(f)}$$

$$R_{3,4,5,6} = \frac{1}{\Delta_{3,4,5,6(f)}}$$

$$\Delta_{3,4,5,6(f)}= \Delta_{solid\ 3,4,5,6(f)} - \Delta_{strip\ B(f)} + \Delta_{3,4,5(f)}$$

$$\Delta_{3,4,5(f)}= \frac{1}{R_{3(f)} + R_{4(f)} + R_{5(f)}}$$

$R_{3(f)} = R_{4(f)} = R_{5(f)} = \frac{Et}{[\left(\frac{h}{l}\right)^3+3*\left(\frac{h}{l}\right)]}$=0.187Et________________where: h=1.2 & l=1

$$\Delta_{3,4,5(f)}= \frac{1}{3*0.187Et} = {}^{1.782}/_{Et}$$

$\Delta_{solid\ 3,4,5,6(f)}= \frac{1}{Et}[\left(\frac{h}{l}\right)^3 + 3*\left(\frac{h}{l}\right)] = {}^{2.3}/_{Et}$ _______________ where: h=3.6 & l=5.4

$$\Delta_{strip\ B(f)}= \frac{1}{Et}\left[\left(\frac{h}{l}\right)^3 + 3*\left(\frac{h}{l}\right)\right] = {}^{0.67}/_{Et}$$

$\Delta_{3,4,5,6(f)}= (2.3 - 0.677 + 1.782)/Et$=3.422/Et

$$R_{3,4,5,6} = \frac{1}{3.422/Et} = 0.292Et$$

$R_{2(f)} = \frac{Et}{[\left(\frac{h}{l}\right)^3 + 3*\left(\frac{h}{l}\right)]} = 0.017Et$________________ where: h=3.6 & l=1

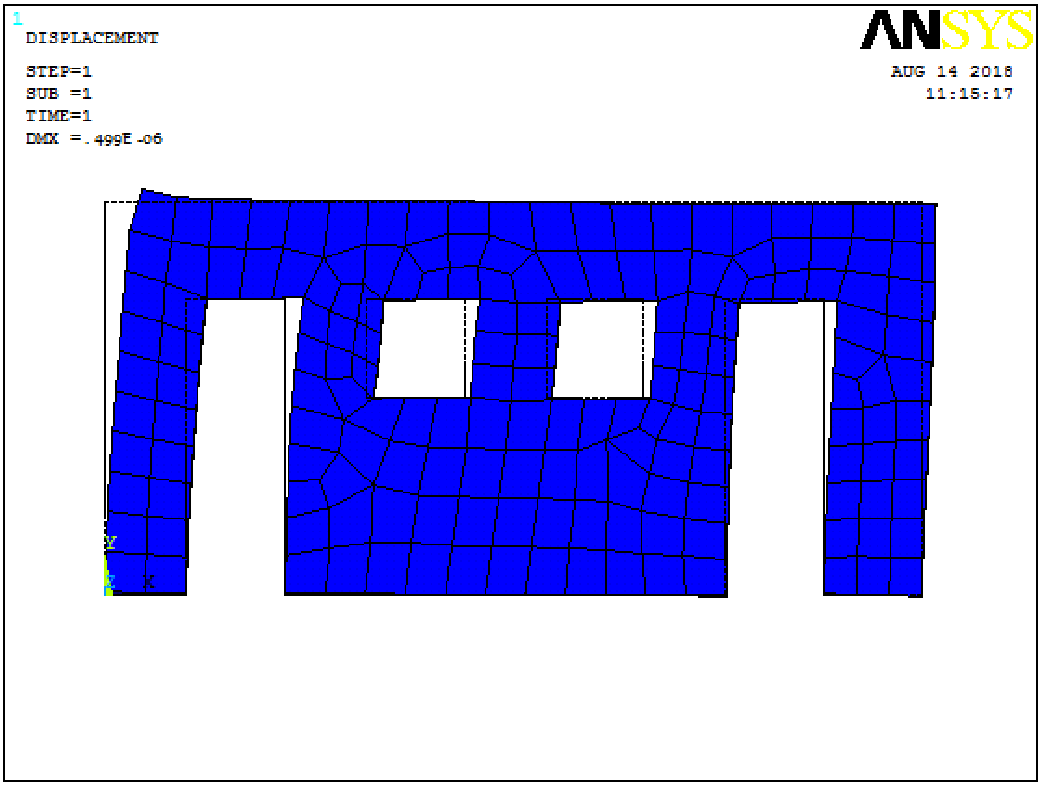
$R_{7(f)} = \frac{Et}{[\left(\frac{h}{l}\right)^3 + 3*\left(\frac{h}{l}\right)]} = 0.028Et$________________ where: h=3.6 & l=1.2

$$R_{2,3,4,5,6,7} = 0.017Et + 0.292Et + 0.028Et = 0.337Et$$

$$\Delta_{2,3,4,5,6,7}= \frac{1}{0.337Et} = {}^{2.967}\!/_{Et}$$

$$\Delta_{wall}= {}^{1.882}\!/_{Et} - {}^{1.266}\!/_{Et} + {}^{2.967}\!/_{Et} = {}^{3.583}\!/_{Et} = 0.412 * 10^{-6}m$$

Solution II: Using ANSYS 10 using SHELL181 element type



$\Delta_{Ansys}= 0.499e - 6m$

With wide mesh	$\Delta_{Ansys}(X10^{-6}m)$	$\Delta_{Hand\ method}$ $(X10^{-6}m)$	**Error (%)**
	0.499	0.412	21

Under the above section, the result obtained from analysis of the shear wall with different type of opening on ANSYS and Simplified hand method were numerically computed. As a result, shear deformation analysis for shear with and without opening using simplified hand method would approximate with satisfactory precision as compare to ANSYS result with wide meshing. In spite of the fact that, for fine mesh ANSYS result simplified hand method underestimate shear deformation of wall.

CHAPTER FOUR

PARAMETRIC STUDY

4.1 Introduction

A Parametric study allows to investigate the effect of different random variables and their combinations of selected processing parameter values on part quality. The range of variables will depend on the modelling process being used. In this study, to identify the effect of parameters affecting the deformation of shear wall, thirty-two different combinations are considered and sensitivity analysis of random variables has been investigated.

One of the advantage of regression analysis model is that parametric study can be carried out to evaluate the effect of all the influencing input parameters on the shear deformation of a Shear wall. The parametric study can easily be done by systematic randomly varying input parameters and analyzing the input parameters using simplified hand method to get an output of shear deformation. The error metric can also be easily evaluated using the statistical data analysis. [9]

4.2 Statistical Data Analysis

4.2.1 The XLSTAT Approach

The XLSTAT interface totally depend on Microsoft Excel, either for inputting the data or for displaying the results. The computations are completely independent of excel and the corresponding program relies to Visual Basic application for the interface and have been developed with the C++ programming language for the mathematical and statistical computations.

4.2.2 Sensitivity Analysis

Sensitivity Analysis (SA) is defined as “a method to determine the robustness of an assessment by examining the extent to which results are affected by changes in methods, models, values of unmeasured variables, or assumptions” with the aim of identifying “results that are most dependent on questionable or unsupported assumptions” [4]. The sensitivity factor α_i is a kind of an index to estimate the contribution of the uncertainty of x_i to the uncertainty of the function [4.5]. Since the objective function f is given, the effects of random variables can be determined as follows:

$$\alpha_i = \frac{\partial y}{\partial x} * \frac{\bar{x}_i}{\bar{f}} \qquad (i=1, 2,3.. \ldots n) \qquad (4.1)$$

$$U_i = \alpha_i (COV)_i \qquad (i = 1, 2,3.. \ldots n) \qquad (4.2)$$

Where, α_i: sensitivity factor of random variable i

U_i: uncertainty of random variable i

f: function with statistical variations

$\bar{f}$: mean of f

x_i : random variable i

$\bar{x_i}$: mean of xi

COVi: Coefficient of variation of random variable i

The general model for the shear deformation of shear wall, f (Δ_{shear}), given Eq.5.1 is derived using simplified hand analysis. Based on this, the uncertainty of random variables for the shear deformation of shear walls are calculated and plotted in figure 4.1, 4.2 and 4.3.

4.2.2.1 Uncertainty of Input Variable on Wall Deformation

4.2.2.1.1 Window Type Opening

The statistical data analysis using sensitivity analysis gives the most significant variable from the entire uncertain input variable. The evaluation showed that height of wall (H), height of opening (h_o) and length of opening (l_o) are most significant parameter from all the uncertain input data analyzed with uncertainty coefficient ratio of -0.156,0.254 and -0.141 respectively. The remaining uncertain input parameters have an uncertainty coefficient ratio of 0.101 for length of shear wall (L) and -0.012 for thickness of wall (t).For such type of opening, height of wall, length of opening and thickness of wall has inverse relationship with shear deformation of shear wall.

As the height of opening and length of wall increases, shear deformation increases linearly. However, the increasing rate for shear deformation due to height of opening is high. On the hand, as the height of wall and length of opening increase, shear deformation decreases linearly. Thickness of wall less significant parameter for determination of shear deformation.

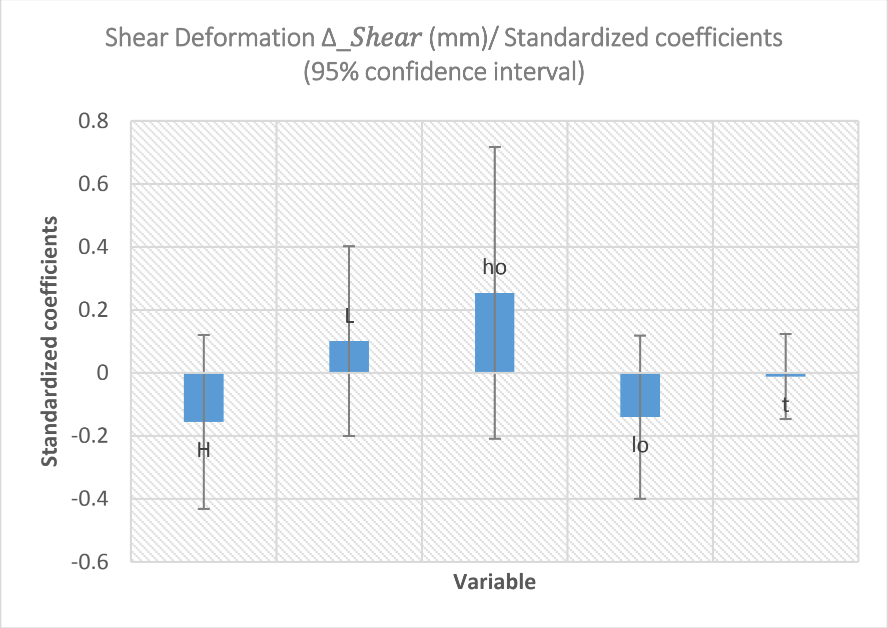


Fig. 4.1 *Uncertainty of random Variable for window type of opening*

4.2.2.1.2 Door Type Opening

For shear wall with door type of opening, evaluation showed that height of wall (H) is most significant parameter from all the uncertain input data analyzed with uncertainty coefficient ratio of -0.140. The remaining uncertain input parameters have an uncertainty coefficient ration of 0.242 for height of opening (h_o), 0.110 for length of shear wall (L), -0.132 for length of opening (l_o) and -0.028 for thickness of wall (t). For such type of shear wall height of wall, length of wall and length of opening has inverse relationship with shear deformation of shear wall.

As the height of opening and length of wall increases, shear deformation increases linearly. However, the increasing rate for shear deformation due to height of opening is high. On the hand, as the height of wall and length of opening increase, shear deformation decreases linearly. Thickness of wall less significant parameter for determination of shear deformation.

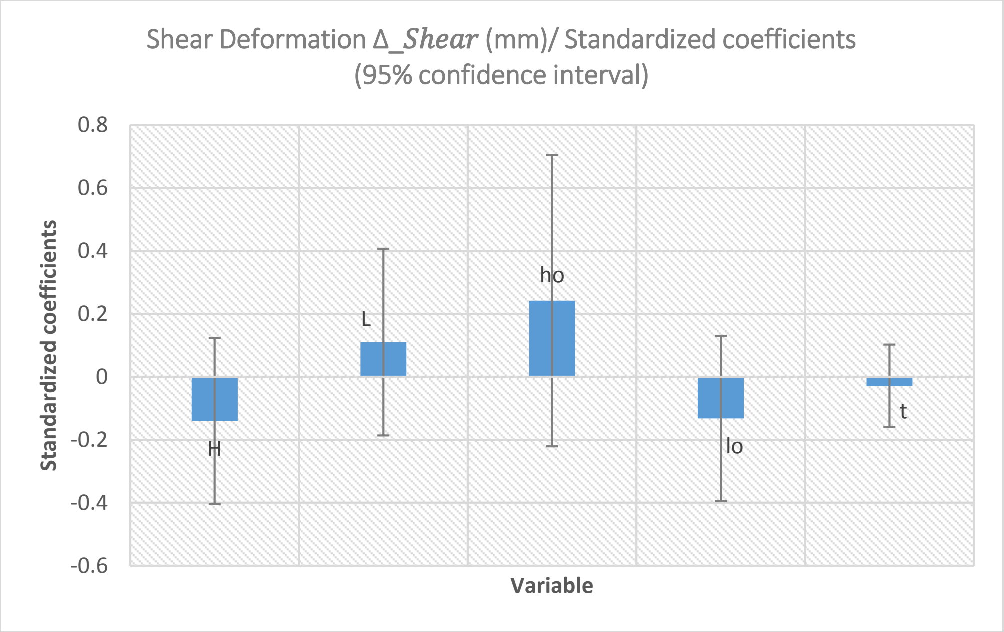


Fig. 4.2 *Uncertainty of random Variable for door type of opening*

4.2.2.1.3 Solid Shear Wall (without opening)

For such type of wall, evaluation showed that thickness wall (t) is most significant parameter from all the uncertain input data analyzed with uncertainty coefficient ratio of -0.620. The remaining uncertain input parameters have an uncertainty coefficient ratio of -0.062 for height of wall (H) and -0.375 for length wall (L).For solid shear wall, height of wall, length wall has inverse relationship with shear deformation of shear wall.

As the height wall increases, shear deformation increases linearly. On the hand, as the length and thickness of wall increase, shear deformation decreases linearly. However, the decreasing rate for shear deformation due to thickness of wall is high.

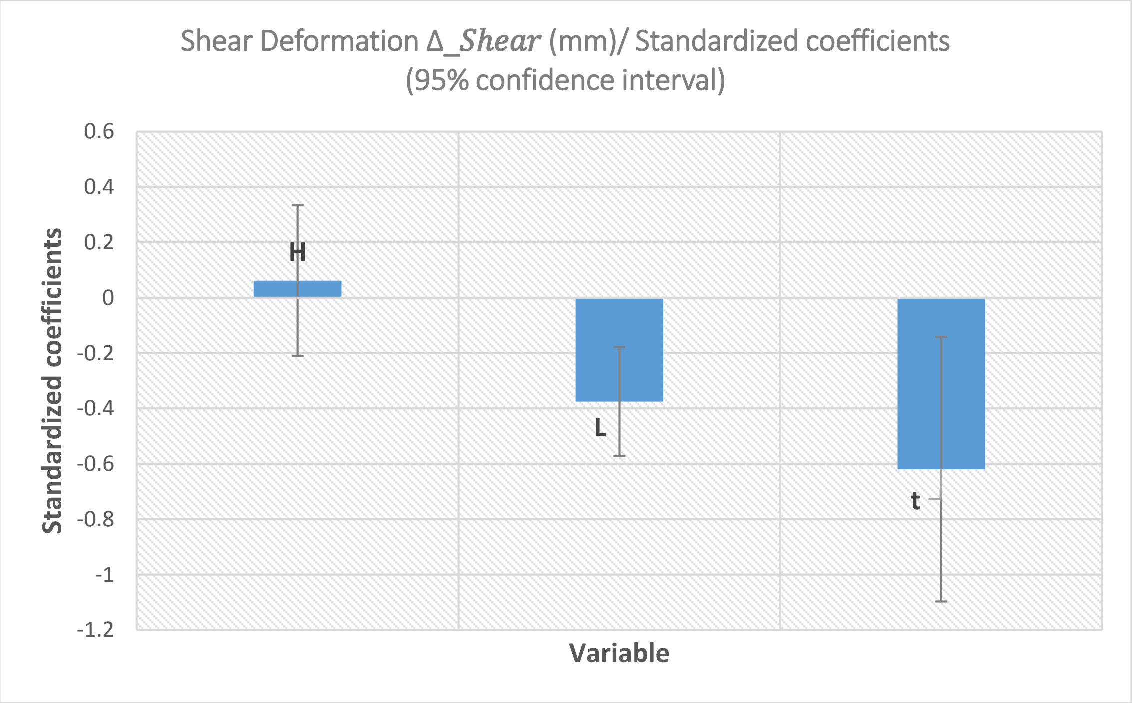


Fig. 4.3 *Uncertainty of random Variable for solid wall type (without opening)*

4.2.3 Variable Importance in The Project VIP

The variable importance in the project (VIP) was modeled using partial least square analysis XLSTAT, 2017 program and the results shown in the Table 4.4, 4.5 and 4.5. Variable who lied inside the border line between $0.8 \leq VIP \leq 1$ indicated the variable are moderately influential while who lied above one ($VIP \geq 1$) indicated the variable are highly influential.

4.2.3.1 Window type of opening

For window type of opening, the measure important parameter that affect the shear deformation of shear wall are height of shear wall (H) with an importance of 1.011, length of shear wall (L) with an importance of 0.653, height of opening (h_o) with 1.648, length of opening (l_o) with importance of 0.911, and thickness of wall (t) with importance of 0.077.

Table 4.1: *Relative Importance of Input Parameter for the Model: for window type of opening*

Variable	VIP	Standard deviation
ho	1.648	0.496
H	1.011	0.559
lo	0.911	0.345
L	0.653	0.595
t	0.077	0.726

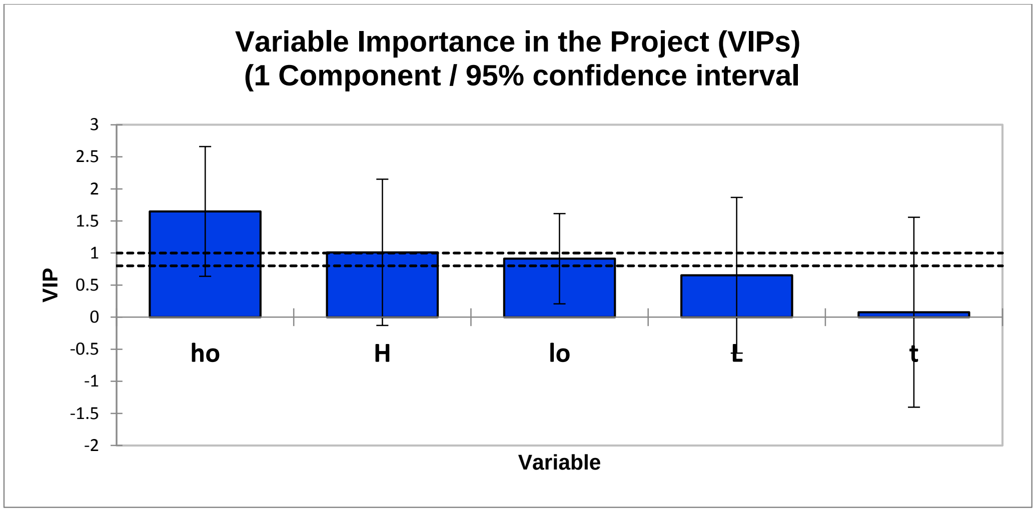


Fig. 4.4 *Variable Importance of Window Type of Opening*

Figure 4.7 explains height of opening (h_o) and height of wall (H) are highly influential parameters on shear deformation of shear wall. The remaining input parameters length of wall, length of opening and thickness of wall are moderately influential on shear deformation of shear wall.

4.2.3.2 Door type of opening

For door type of opening the measure important parameter that affect the shear deformation of shear wall are height of shear wall (H) with an importance of 0.949, length of shear wall (L) with an importance of 0.748, height of opening (h_o) with 1.641, length of opening (l_o) with importance of 0.899, and thickness of wall (t) with importance of 0.193.

Table 4.2: *Relative Importance of Input Parameter for the Model: for door type of opening*

Variable	VIP	Standard deviation
ho	1.641	0.545
H	0.949	0.605
lo	0.899	0.442
L	0.748	0.529
t	0.193	0.478

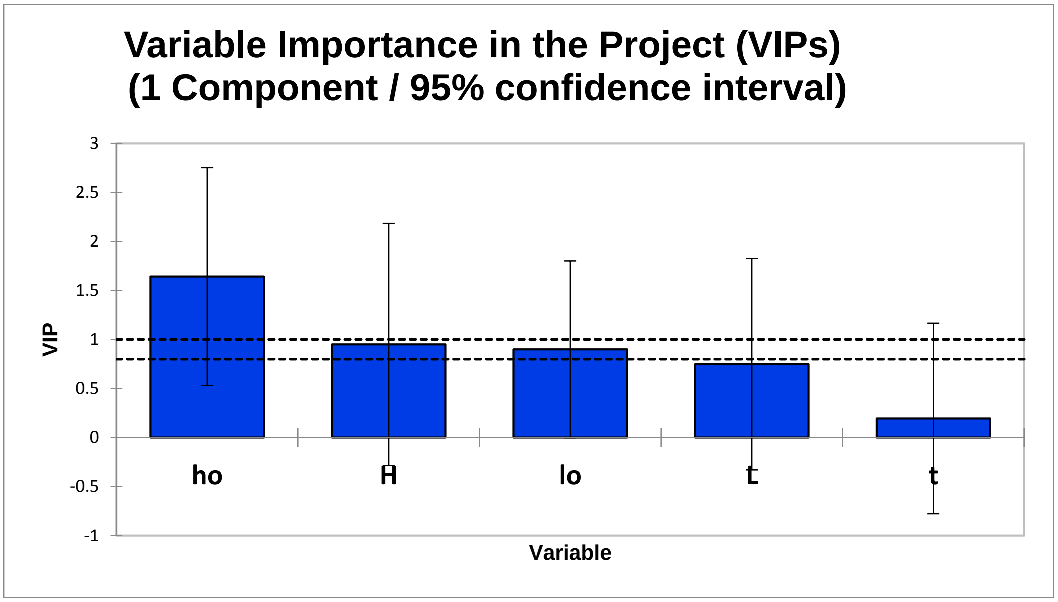


Fig. 4.5 *Variable Importance of Door Type of Opening*

The above type of opening explains, height of opening (h_o) and height of wall (H) are highly influential parameters on shear deformation of shear wall. The remaining input parameters length of wall, length of opening and thickness of wall are moderately influential on shear deformation of shear wall.

4.2.3.3 Solid Shear Wall (without opening)

Such type of shear walls the measure important parameter that affect the shear deformation of shear wall are height of shear wall (H) with an importance of 0.147, length of shear wall (L) with an importance of 0.894 and thickness of wall (t) with importance of 1.476.

Table 4.3: *Relative Importance of Input Parameter for Solid Shear Wall* without opening

Variable	VIP	Standard deviation
t	1.476	0.185
L	0.894	0.218
H	0.147	0.364

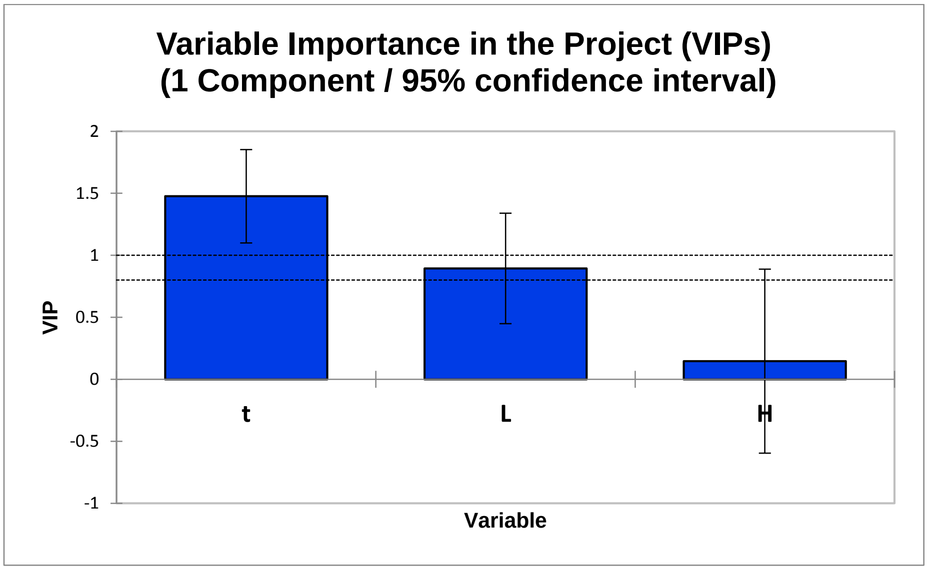


Fig. 4.6 *Variable Importance of Solid Shear Wall Type (without opening)*

The above type of shear wall, thickness of the wall (t) are highly influential parameters on shear deformation of shear wall. The remaining input parameters height and length of wall are moderately influential on shear deformation of shear wall.

CHAPTER FIVE

SUMMARY OF RESULTS AND DISCUSSION

In this chapter the findings are summarized and discussion on those results are made in simplified hand procedure

a) The equation is formulates in terms of modules of elasticity, height of wall, opening, length of wall, and opening, and thickness of wall using simplified hand procedure for shear wall with window and door type of opening.

$$\Delta_{Shear}=\frac{1}{Et}\left[3\left(\frac{H}{L}\right)-3\left(\frac{h_o}{L}\right)+\frac{3}{2}\left(\frac{h_o}{((L-l_o)/2)}\right)\right] \quad (5.1)$$

Where, H and L: Height and Length of wall in m

H_o and l_o : Height and Length of Opening in m

t: thickness of wall in m

E: Modules of elasticity in GPa

Δ_{Shear}: Shear deformation in m.

- As rate of change of percentage of opening increasing by 60% and with increasing aspect ratio, ratio of shear deformation will decrease by 5% for shear wall with window type of opening. However, for shear wall with door type of opening, rate of change of opening increases by 51% when ratio of shear deformation decrease by 0.2%.
- On other hand, as rate of change of percentage of opening decreased by 58% with increase aspect ratio, ratio of shear deformation increased by 9% for shear wall with window type of opening. However, for shear wall with door type of opening rate of change of opening decreased by 33% with increased aspect ratio, ratio of shear deformation increase by 1% .
- If thickness of wall decreases by 40% with same rate change of aspect ratio, ratio of shear deformation will decrease by 4% for window type of opening. However, for shear wall with door type of opening thickness of wall decreased by 27%, as ratio of shear deformation increases by 1%

- If thickness of wall increases by 18% with same increasing rate of aspect ratio, ratio of shear deformation decreases by 3.5% for window type of opening. However, for shear wall with door type of opening thickness of wall increase by 10%, the ratio of shear deformation decreases by 0.5%.

- In general, change in percentage of opening more affects ratio of shear deformation for shear wall with window type of opening than shear wall with door type of opening. On the other hand, effect of change wall thickness affects by other parameters. See Fig. 5.1, 5.2.

b) Result and discussions on parametric analysis of shear deformation

- Variable important in project (VIP) and Sensitivity analysis for deferent parameter in shear deformation summarized as follow :

Table 5.1: *Relative importance of input parameter for different type of shear wall*

VIP	***Opening Type***		
Variable	**Window type**	**Door type**	**Without Opening**
H	1.011	0.949	0.147
L	0.653	0.748	0.894
h_o	1.648	1.641	-
l_o	0.911	0.899	-
t	0.077	0.193	1.476

Table 5.2: *Uncertainty of random variables for different type wall type*

Sensitivity	**Opening Type**		
Variable	**Window type**	**Door type**	**Without Opening**
H	-0.168	-0.140	0.063
L	0.049	0.110	-0.375
h_o	0.266	0.242	-
l_o	-0.133	-0.132	-
t	0.026	-0.029	-0.620

- With respect to percentage of opening and aspect ratio VIP and Sensitivity analysis of shear deformation summarized graphical as follow:

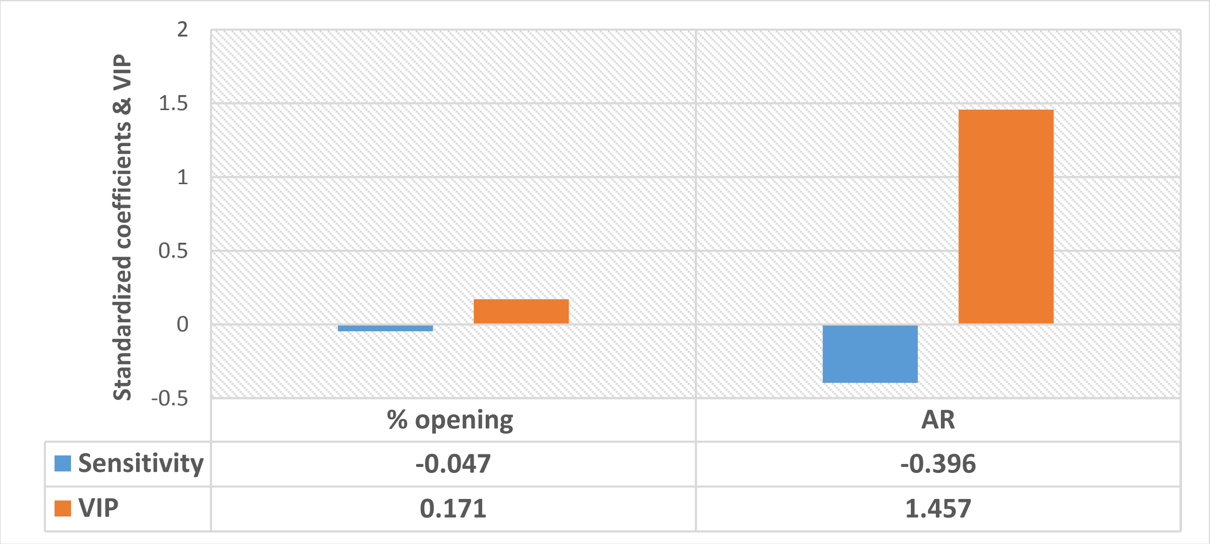


Fig. 5.1 *Uncertainty of random variable and VIP for Window type of opening*

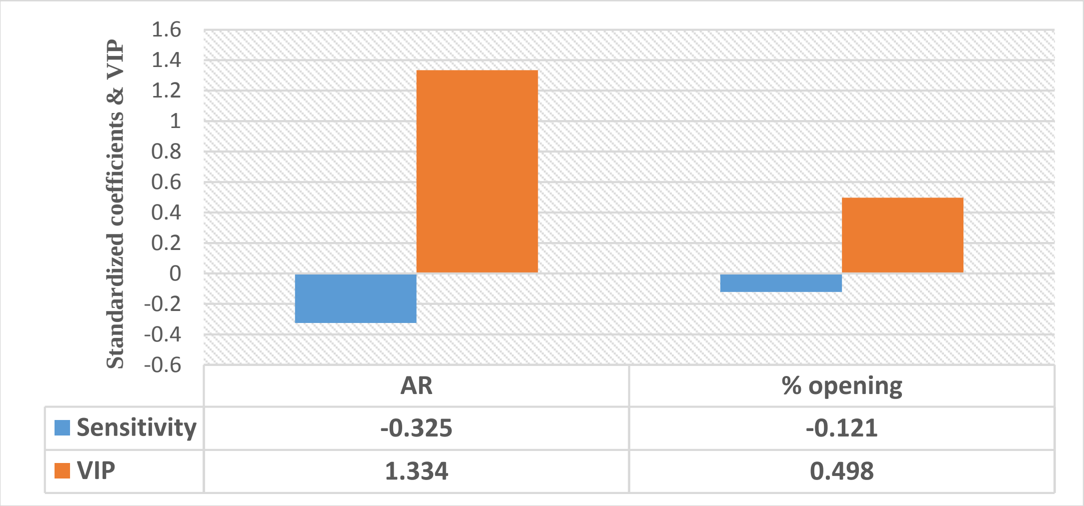
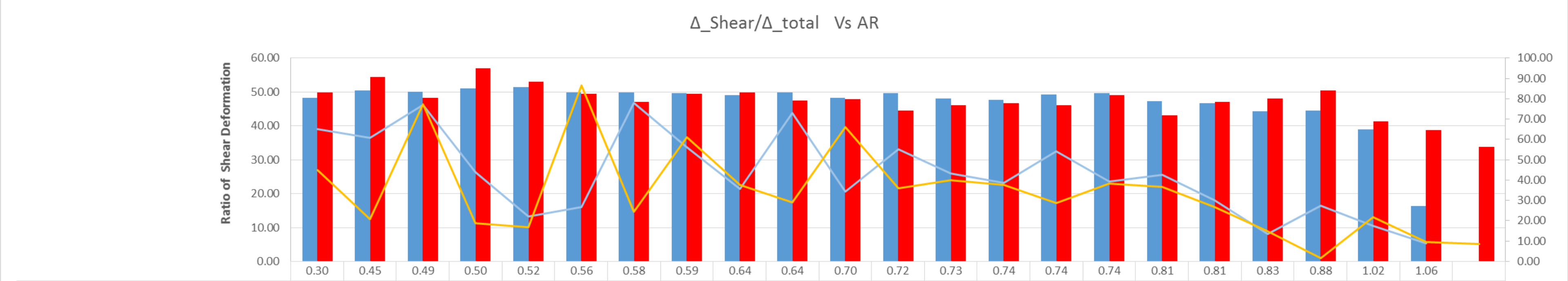
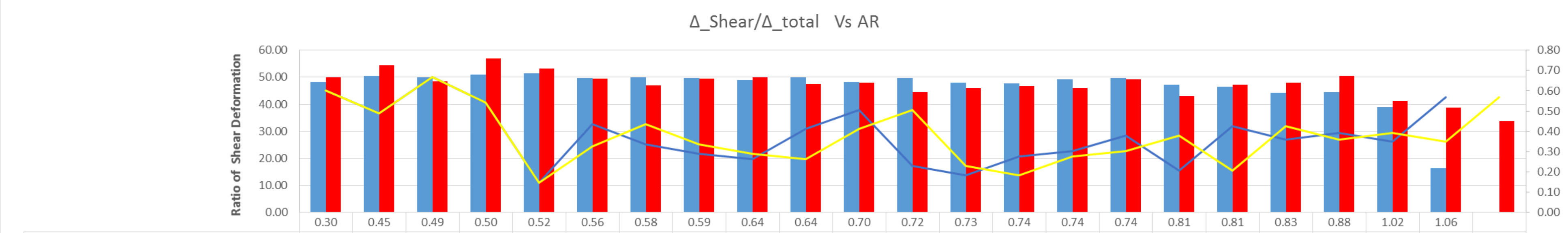


Fig. 5.2 *Uncertainty of random variable and VIP for Door type of opening*



	0.30	0.45	0.49	0.50	0.52	0.56	0.58	0.59	0.64	0.64	0.70	0.72	0.73	0.74	0.74	0.74	0.81	0.81	0.83	0.88	1.02	1.06	
🟦 Δ_Shear/Δ_total -for door type of opening	48.23	50.48	50.00	50.97	51.53	49.79	49.92	49.73	49.05	49.86	48.26	49.61	48.10	47.77	49.26	49.71	47.32	46.59	44.30	44.54	39.00	16.42	
🟥 Δ_Shear/Δ_total - for window type of opening	49.87	54.33	48.37	56.94	53.12	49.42	47.02	49.42	49.96	47.56	47.89	44.49	46.07	46.72	46.06	49.17	43.09	47.17	48.10	50.38	41.24	38.69	33.81
— % opening - for door type of opening	65.12	60.69	77.05	43.87	22.28	26.77	78.04	56.06	35.73	73.16	34.24	55.29	43.21	38.75	54.21	39.17	42.54	29.91	13.45	27.53	17.64	8.82	
— % opening-for window type of opening	44.906	20.711	77.228	18.975	16.810	86.727	24.594	61.087	37.594	28.929	66.099	35.893	40.018	37.822	28.658	38.339	36.627	26.665	14.707	1.790	21.924	9.451	8.595

Fig. 5.3 *Effect of Aspect ratio and percentage of opening in ratio of shear deformation to total deformation of shear wall*



	0.30	0.45	0.49	0.50	0.52	0.56	0.58	0.59	0.64	0.64	0.70	0.72	0.73	0.74	0.74	0.74	0.81	0.81	0.83	0.88	1.02	1.06	
🟦 Δ_Shear/Δ_total -for door type of opening	48.23	50.48	50.00	50.97	51.53	49.79	49.92	49.73	49.05	49.86	48.26	49.61	48.10	47.77	49.26	49.71	47.32	46.59	44.30	44.54	39.00	16.42	
🟥 Δ_Shear/Δ_total - for window type of opening	49.87	54.33	48.37	56.94	53.12	49.42	47.02	49.42	49.96	47.56	47.89	44.49	46.07	46.72	46.06	49.17	43.09	47.17	48.10	50.38	41.24	38.69	33.81
— Thickness of wall-door type (t)	0.60	0.49	0.67	0.54	0.15	0.44	0.34	0.29	0.26	0.41	0.50	0.23	0.18	0.28	0.30	0.38	0.21	0.42	0.36	0.39	0.35	0.57	
— "Thickness of wall-window type (t)"	0.60	0.49	0.67	0.54	0.15	0.33	0.44	0.34	0.29	0.26	0.41	0.50	0.23	0.18	0.28	0.30	0.38	0.21	0.42	0.36	0.39	0.35	0.57

Fig. 5.4 *Effect of Aspect ratio and wall thickness in ratio of shear deformation to total deformation of shear wall*

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

Parametric study was carried out on shear deformation of shear wall with and without opening after computation with simplified hand method to determine shear deformation on thirty-two cantilever shear wall subjected to point load at the top of wall. Based on the statistical data analysis, the following conclusions can be drawn.

a) Parametric study has showed the influence of five systematically selected variables on shear deformation of shear wall with and without opening. Height of opening (h_o) is highly influential for shear wall with door type of opening. Thickness of wall (t) is influential for shear wall without opening. Height of wall (H) and length of opening (l_o) have moderate influence on shear deformation of shear wall with window and door type of opening. Length of wall has moderate influences shear deformation of solid shear wall.

b) During the sensitivity analysis, it is further verified that height of wall has inverse relationship with shear deformation for wall with window and door type of opening, whereas direct relationship for shear wall without opening. Length of wall has inverse relationship with shear deformation for shear wall without and with door type of opening, whereas direct relationship for shear wall with window type of opening. Height of opening and length of opening have direct and inverse relationship respectively for both shear wall with window and door type of opening. Finally, thickness of wall has direct relationship for shear wall with window and door type of opening, whereas inverse relationship with shear wall without opening.

c) Aspect ratio is highly influential parameter than wall opening in shear wall with door and window type of opening. Increasing aspect ratio shear deformation decrease linearly. As opening size increases, shear deformation decreases in both shear wall with window and door type of opening. However, decreasing rate for shear deformation is high in door type of opening than window type of opening Fig. 5.1 and Fig. 5.2.

6.2 Recommendation

Assessment of the effect of shear deformation in shear wall with and without opening prepared in this thesis work is only using simplified hand procedure and parametric study by assessing the effect of different parameter. The author recommends for future to extend study on the effect of shear deformation on following listed below ideas:

- ✓ Assess experimentally and analytically effects of different input variables on shear deformation determination specially; size effect, influence of shear span to depth ratio, effects of shear wall material (concrete, steel, and wood) with a large data set collection.
- ✓ Assessment of effect of shear and flexural deformation in shear wall having opening using macro modeling (beam-column model, multiple spring model, truss model, three vertical line element model (TVLEMs) and Multiple vertical line element model (MVLEMs) and micro modeling (finite element method or fiber analysis.

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APPENDIX A

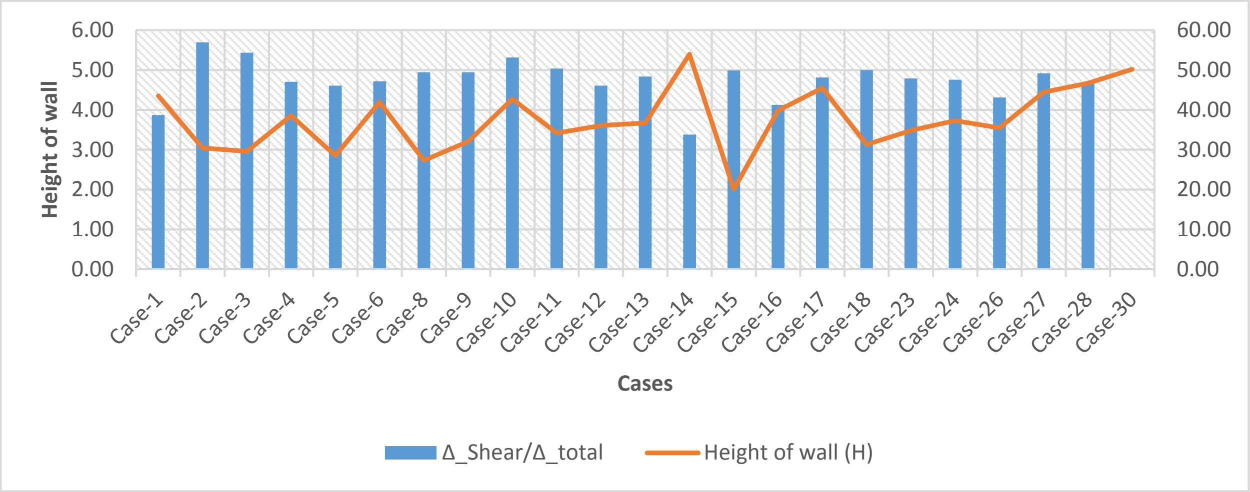
SIMPLIFIED HAND PROCEDURES RESULTS

This section illustrate detail results of deformation analysis (shear deformation) in shear wall with opening and also describes the effects deferent input parameters in shear deformation and presented below in tabular and graphical form.

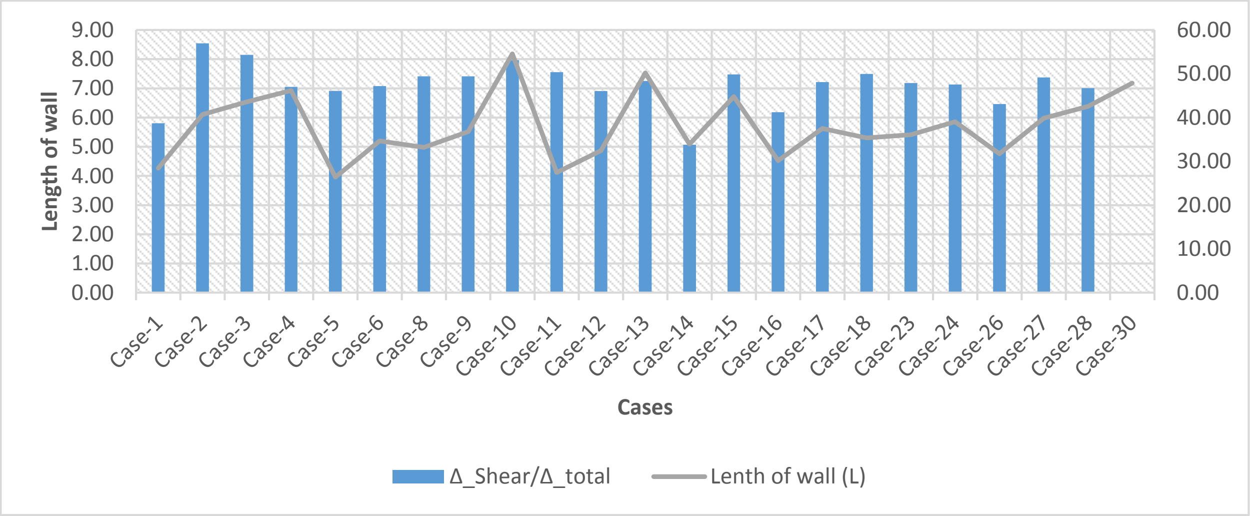
[A1] Shear wall with Window Type of opening

Table A.1 *Simplified Hand Method results for LHS combination of random variables for shear wall with Window type of opening*

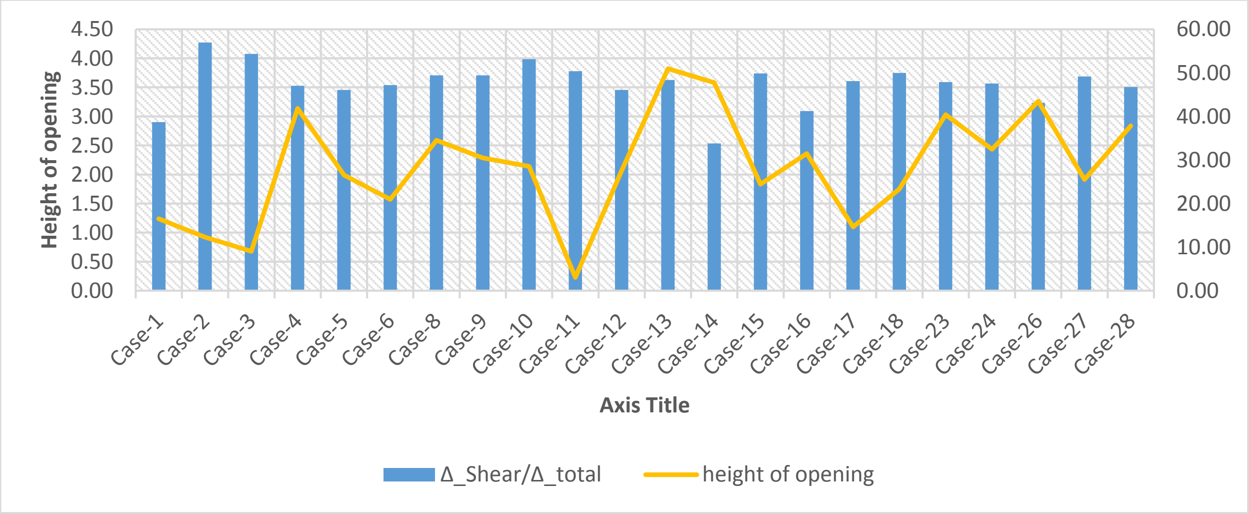
	P=	1								
	E=	29000000								
Cases	**H**	**L**	**ho**	**lo**	**t**	**ΔShear**	**ΔFlxural**	**Δ_Shear/Δ _total**	**% opening**	**AR**
Case-1	4.35	4.26	1.24	1.42	0.35	0.000346	0.000549	38.69	9.451	1.02
Case-2	3.05	6.10	0.92	3.83	0.54	0.000144	0.000109	56.94	18.975	0.50
Case-3	2.95	6.54	0.68	5.90	0.49	0.000300	0.000252	54.33	20.711	0.45
Case-4	3.86	6.93	3.14	2.09	0.44	0.000179	0.000201	47.02	24.594	0.56
Case-5	2.85	3.96	1.99	2.27	0.23	0.000632	0.000740	46.07	40.018	0.72
Case-6	4.19	5.20	1.57	3.70	0.21	0.000774	0.000867	47.17	26.665	0.81
Case-8	2.73	4.98	2.59	4.56	0.33	0.001963	0.002009	49.42	86.727	0.55
Case-9	3.21	5.52	2.29	4.73	0.34	0.000939	0.000961	49.42	61.087	0.58
Case-10	4.27	8.18	2.14	2.75	0.15	0.000460	0.000406	53.12	16.810	0.52
Case-11	3.42	4.12	0.23	1.10	0.36	0.000245	0.000241	50.38	1.790	0.83
Case-12	3.61	4.87	2.07	2.44	0.28	0.000436	0.000511	46.06	28.658	0.74
Case-13	3.67	7.53	3.82	5.58	0.67	0.000301	0.000321	48.37	77.228	0.49
Case-14	5.40	5.09	3.58	0.66	0.57	0.000212	0.000415	33.81	8.595	1.06
Case-15	2.00	6.72	1.83	3.30	0.60	0.000096	0.000097	49.87	44.906	0.30
Case-16	3.98	4.52	2.36	1.67	0.39	0.000314	0.000447	41.24	21.924	0.88
Case-17	4.55	5.63	1.10	3.43	0.42	0.000272	0.000293	48.10	14.707	0.81
Case-18	3.13	5.30	1.75	3.57	0.29	0.000452	0.000453	49.96	37.594	0.59
Case-23	3.48	5.41	3.03	4.11	0.41	0.000605	0.000658	47.89	66.099	0.64
Case-24	3.73	5.86	2.43	2.60	0.26	0.000382	0.000421	47.56	28.929	0.64
Case-26	3.54	4.76	3.26	1.90	0.38	0.000326	0.000430	43.09	36.627	0.74
Case-27	4.45	5.98	1.91	5.33	0.30	0.001151	0.001190	49.17	38.339	0.74
Case-28	4.67	6.38	2.84	3.97	0.18	0.000831	0.000948	46.72	37.822	0.73
Case-30	5.02	7.18	4.27	3.03	0.50	0.000233	0.000290	44.49	35.893	0.70



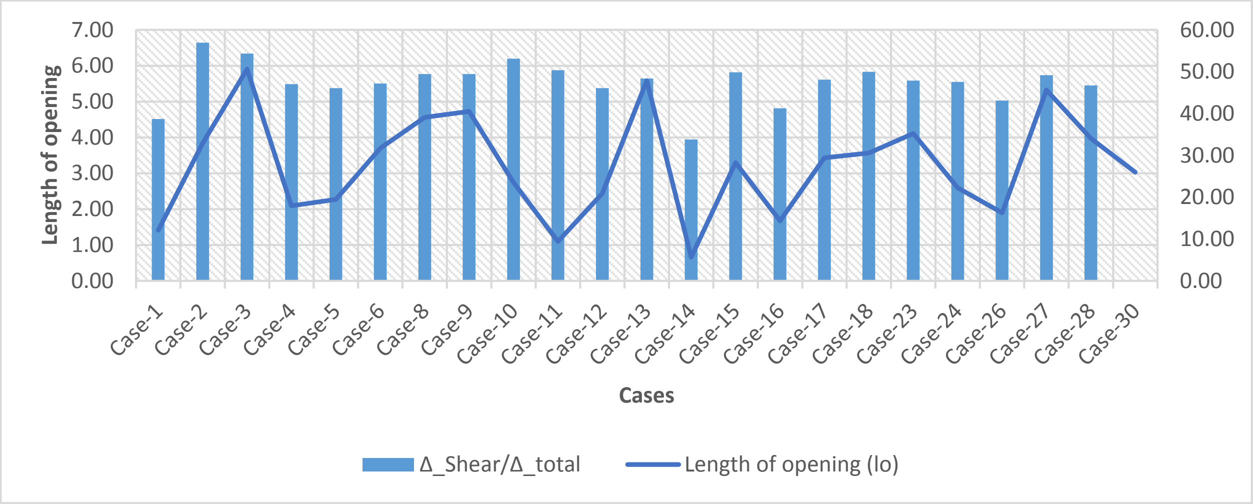
(a) *Effect of wall height on ratio of shear deformation*



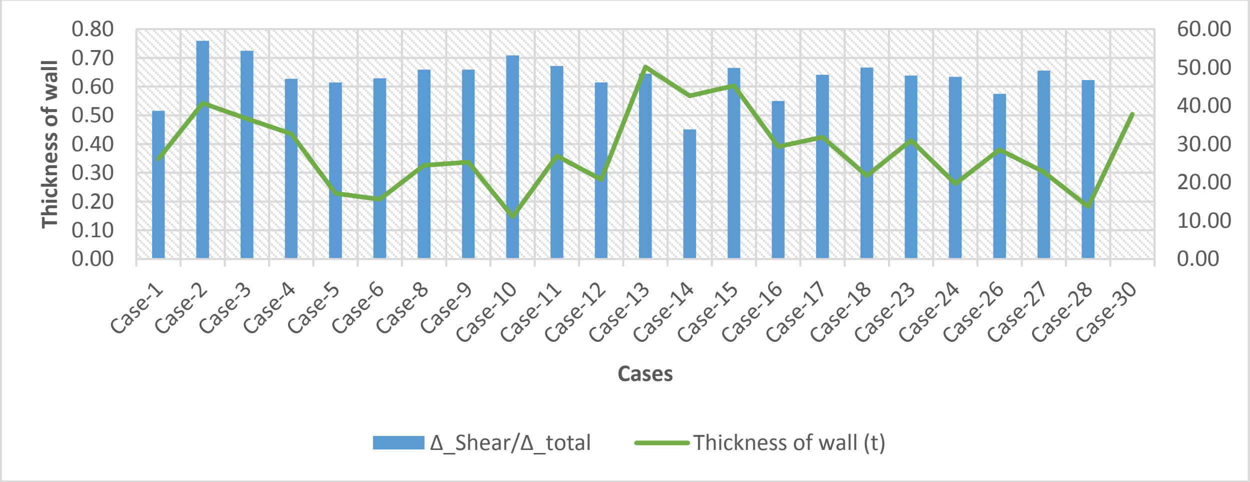
(b) *effect of wall length on ratio of shear deformation*



(c) *effect of opening height on ratio of shear deformation*



(d) *effect of opening length on ratio of shear deformation*



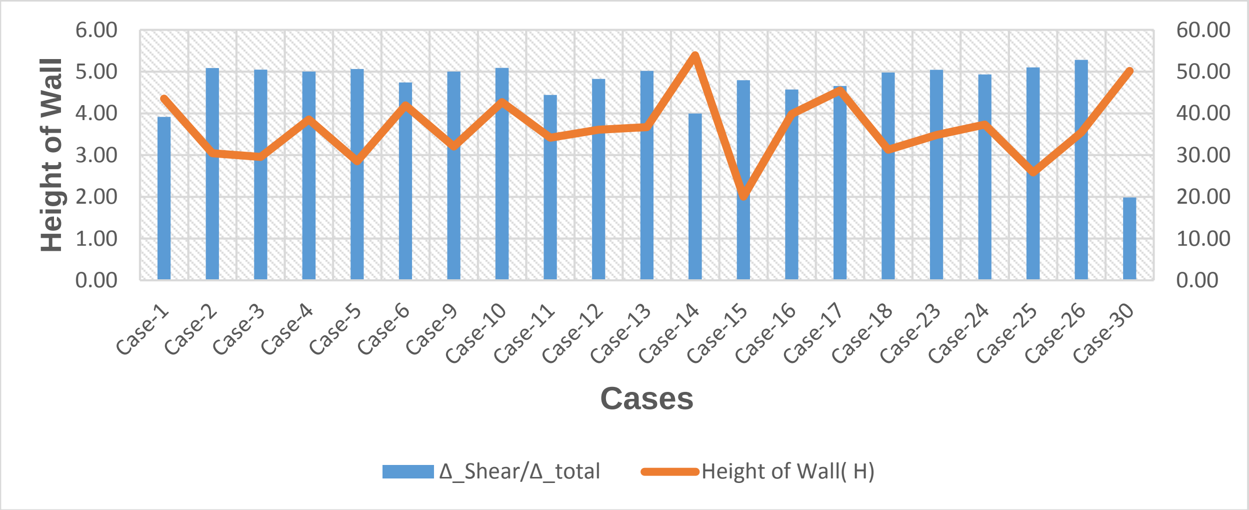
(e) *effect of wall thickness on ratio of shear deformation*

Fig. A.1 *Effect of different parameters in shear wall with Window type of opening (from a to e)*

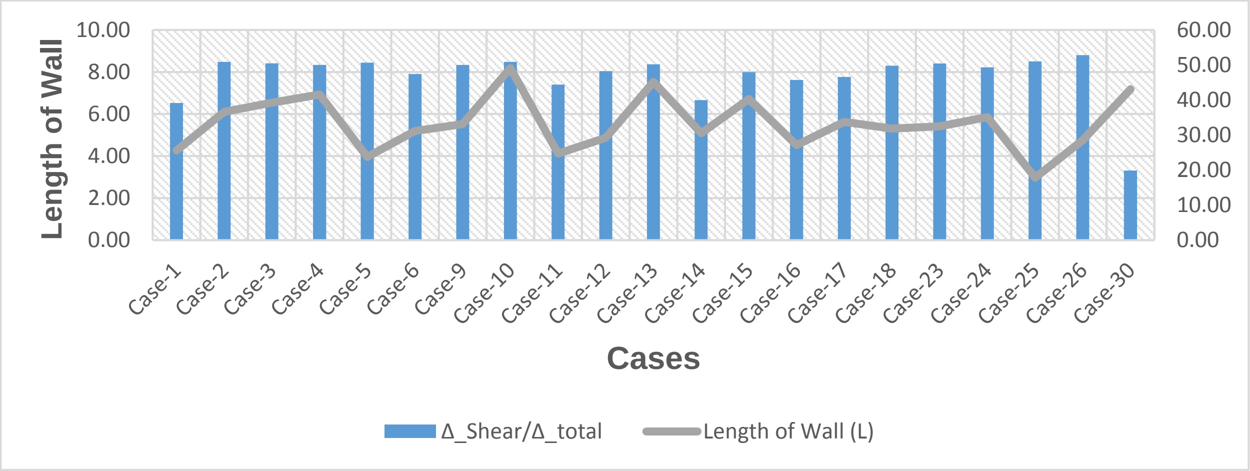
[A2] Shear wall with Door Type of opening

Table A.2 *Simplified Hand Method results for LHS combination of random variables for shear wall with Door type of opening*

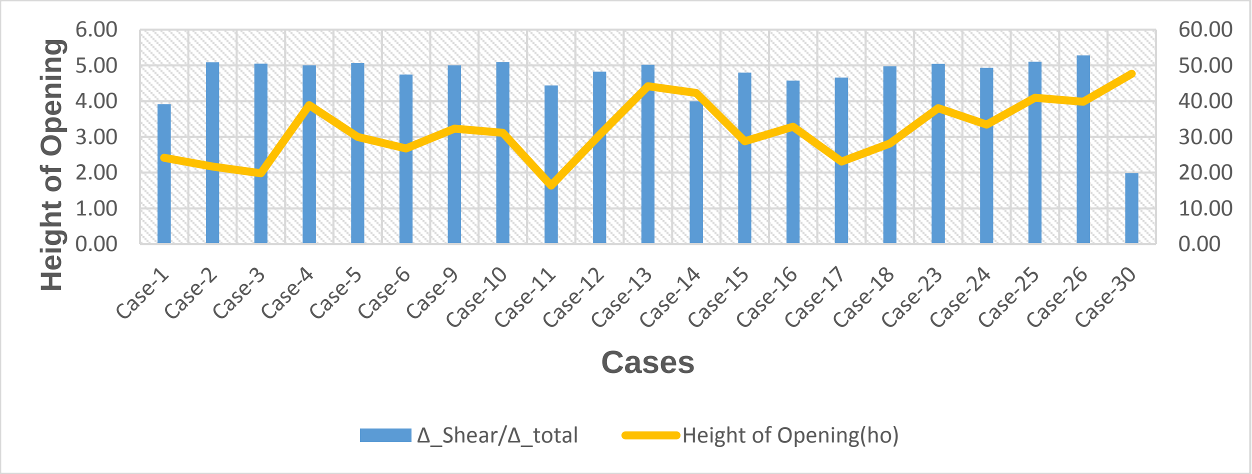
	P=	1								
	E=	29000000								
Cases	H	L	ho	lo	t	ΔShear	ΔFlxural	Δ_Shear/Δ_total	AR	% opening
Case-1	4.35	4.26	2.42	1.42	0.35	0.000387	0.000602	39.145054	1.02	18.44
Case-2	3.05	6.10	2.17	3.83	0.54	0.000210	0.000203	50.870169	0.50	44.77
Case-3	2.95	6.54	1.98	5.90	0.49	0.000692	0.000678	50.485206	0.45	60.59
Case-4	3.86	6.93	3.89	2.09	0.44	0.000190	0.000190	50.036420	0.56	30.47
Case-5	2.85	3.96	3.00	2.27	0.23	0.000789	0.000769	50.636512	0.72	60.31
Case-6	4.19	5.20	2.67	3.70	0.21	0.001038	0.001151	47.417972	0.81	45.40
Case-9	3.21	5.52	3.23	4.73	0.34	0.001252	0.001252	50.008468	0.58	86.24
Case-10	4.27	8.18	3.11	2.75	0.15	0.000505	0.000487	50.901454	0.52	24.47
Case-11	3.42	4.12	1.64	1.10	0.36	0.000281	0.000351	44.408889	0.83	12.75
Case-12	3.61	4.87	3.06	2.44	0.28	0.000513	0.000550	48.257242	0.74	42.42
Case-13	3.67	7.53	4.42	5.58	0.67	0.000335	0.000333	50.178677	0.49	89.24
Case-14	5.40	5.09	4.23	0.66	0.57	0.000215	0.000323	39.970637	1.06	10.15
Case-15	2.00	6.72	2.88	3.30	0.60	0.000122	0.000132	47.961739	0.30	70.50
Case-16	3.98	4.52	3.29	1.67	0.39	0.000346	0.000411	45.710268	0.88	30.52
Case-17	4.55	5.63	2.31	3.43	0.42	0.000354	0.000406	46.569372	0.81	30.95
Case-18	3.13	5.30	2.81	3.57	0.29	0.000600	0.000605	49.772484	0.59	60.44
Case-23	3.48	5.41	3.80	4.11	0.41	0.000718	0.000706	50.425459	0.64	82.99
Case-24	3.73	5.86	3.34	2.60	0.26	0.000432	0.000444	49.311241	0.64	39.72
Case-26	3.54	4.76	3.98	1.90	0.38	0.000353	0.000316	52.810773	0.74	44.73
Case-27	4.45	5.98	2.94	5.33	0.30	0.001634	0.001681	49.287260	0.74	58.92
Case-28	4.67	6.38	3.65	3.97	0.18	0.000031	0.001019	2.994622	0.73	48.72
Case-30	5.02	7.18	4.76	3.03	0.50	0.000062	0.000249	19.862048	0.70	40.04



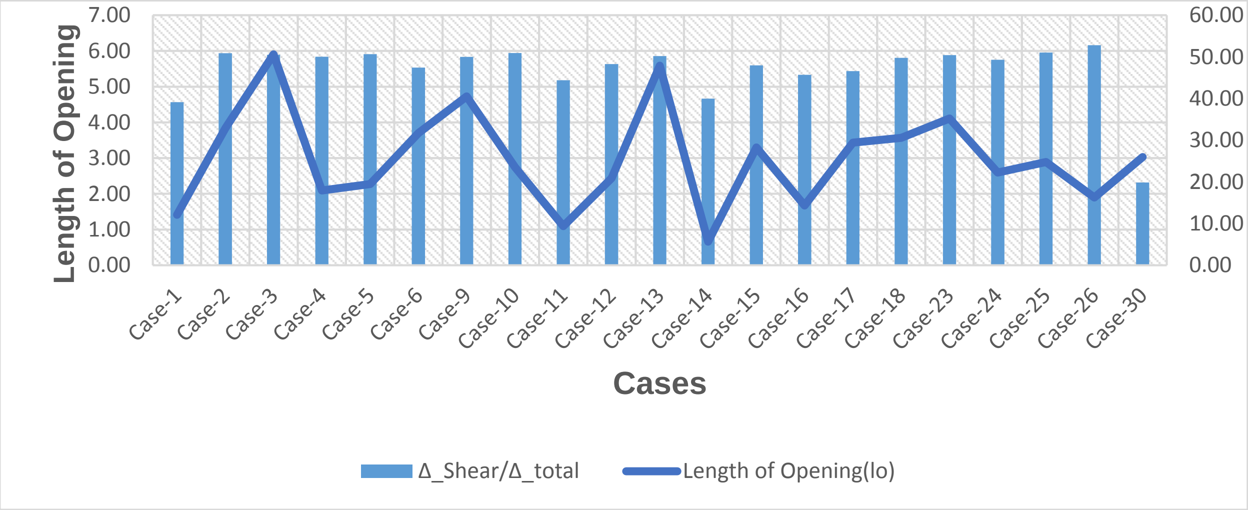
***(a)** Effect of wall height on ratio of shear deformation*



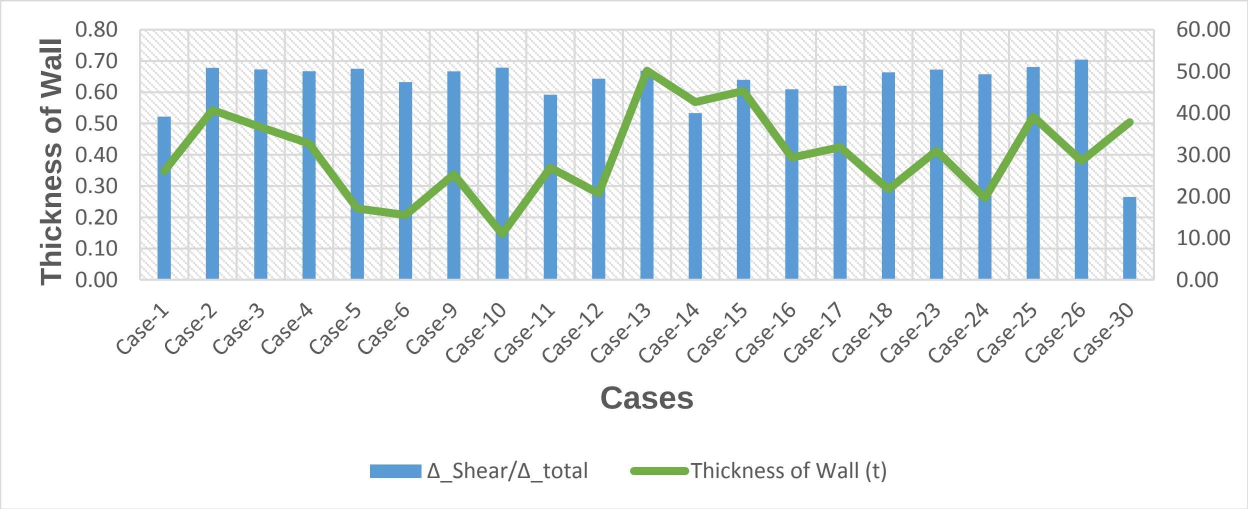
***(b)** effect of wall length on ratio of shear deformation*



***(c)** effect of opening height on ratio of shear deformation*

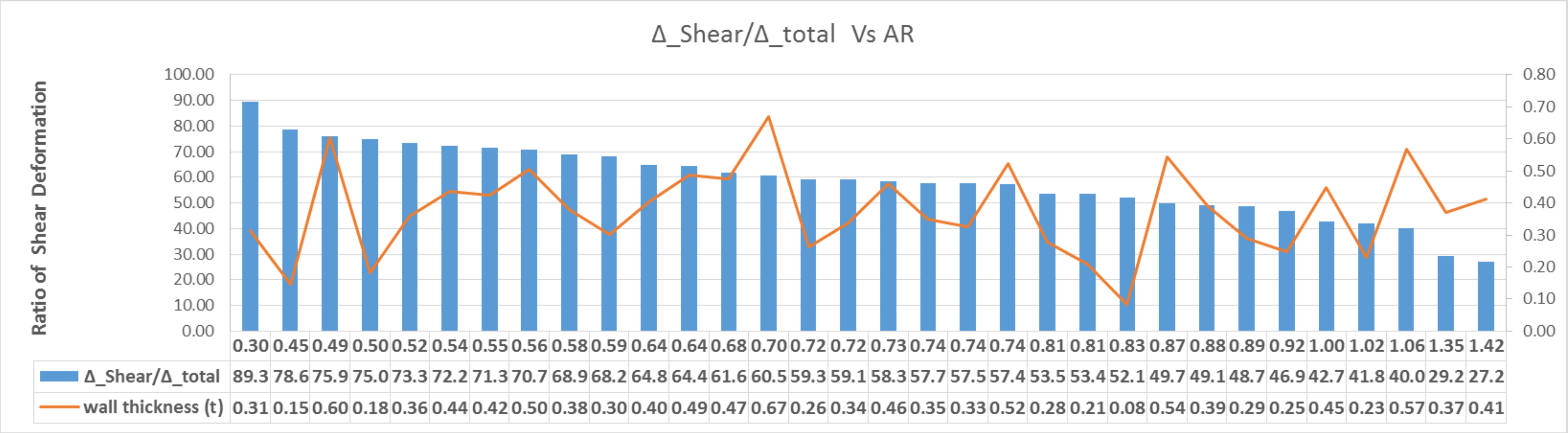


(d) *effect of opening length on ratio of shear deformation*



(e) *effect of wall thickness on ratio of shear deformation*

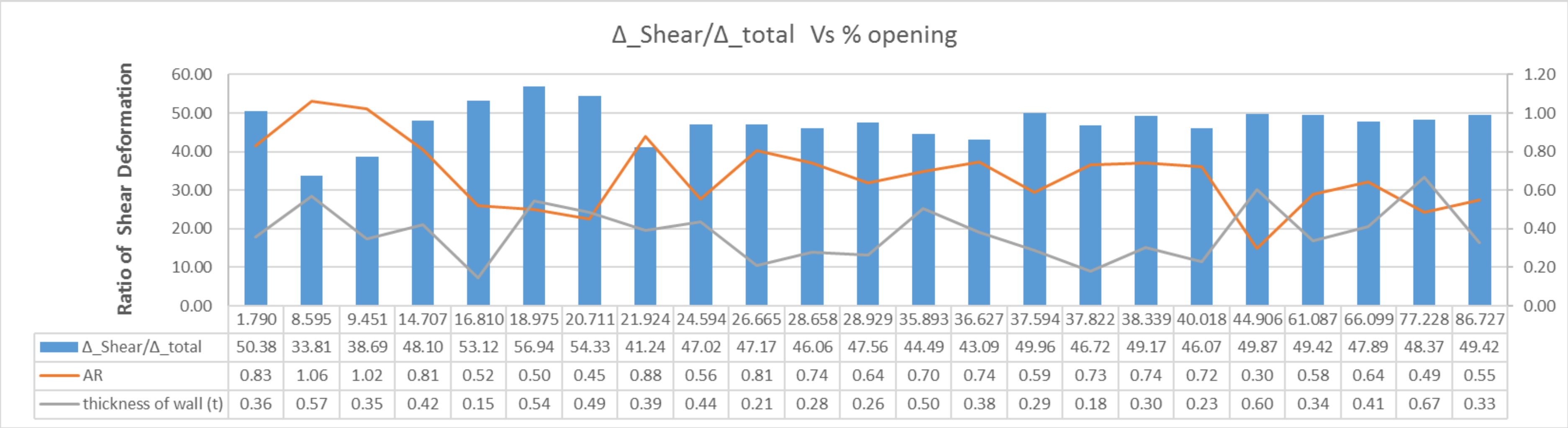
Fig. A.2 *Effect of different parameters in shear wall with Door type of opening (from a to e)*



	0.30	0.45	0.49	0.50	0.52	0.54	0.55	0.56	0.58	0.59	0.64	0.64	0.68	0.70	0.72	0.72	0.73	0.74	0.74	0.74	0.81	0.81	0.83	0.87	0.88	0.89	0.92	1.00	1.02	1.06	1.35	1.42
▬ Δ_Shear/Δ_total	89.3	78.6	75.9	75.0	73.3	72.2	71.3	70.7	68.9	68.2	64.8	64.4	61.6	60.5	59.3	59.1	58.3	57.7	57.5	57.4	53.5	53.4	52.1	49.7	49.1	48.7	46.9	42.7	41.8	40.0	29.2	27.2
— wall thickness (t)	0.31	0.15	0.60	0.18	0.36	0.44	0.42	0.50	0.38	0.30	0.40	0.49	0.47	0.67	0.26	0.34	0.46	0.35	0.33	0.52	0.28	0.21	0.08	0.54	0.39	0.29	0.25	0.45	0.23	0.57	0.37	0.41

Fig. A.3 *Ratio of shear deformation vs Aspect ratio for shear wall without opening*

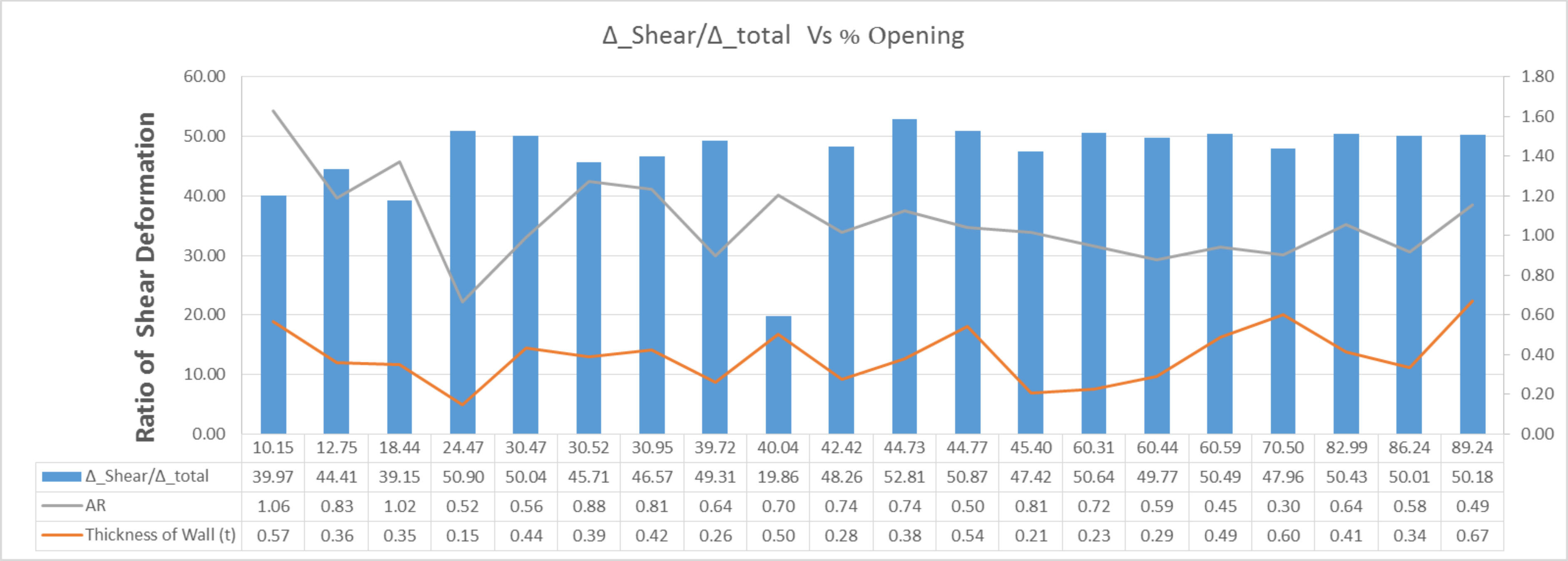
- ✓ As can be seen, shear deformation increase by decreasing aspect ratio.



	1.790	8.595	9.451	14.707	16.810	18.975	20.711	21.924	24.594	26.665	28.658	28.929	35.893	36.627	37.594	37.822	38.339	40.018	44.906	61.087	66.099	77.228	86.727
Δ_Shear/Δ_total	50.38	33.81	38.69	48.10	53.12	56.94	54.33	41.24	47.02	47.17	46.06	47.56	44.49	43.09	49.96	46.72	49.17	46.07	49.87	49.42	47.89	48.37	49.42
AR	0.83	1.06	1.02	0.81	0.52	0.50	0.45	0.88	0.56	0.81	0.74	0.64	0.70	0.74	0.59	0.73	0.74	0.72	0.30	0.58	0.64	0.49	0.55
thickness of wall (t)	0.36	0.57	0.35	0.42	0.15	0.54	0.49	0.39	0.44	0.21	0.28	0.26	0.50	0.38	0.29	0.18	0.30	0.23	0.60	0.34	0.41	0.67	0.33

Fig. A.4 *Ratio of shear deformation vs percentage of opening for shear wall with window type opening*

- ✓ The above graph show that ratio of shear deformation decreases for increasing aspect ratio(AR)



	10.15	12.75	18.44	24.47	30.47	30.52	30.95	39.72	40.04	42.42	44.73	44.77	45.40	60.31	60.44	60.59	70.50	82.99	86.24	89.24
Δ_Shear/Δ_total	39.97	44.41	39.15	50.90	50.04	45.71	46.57	49.31	19.86	48.26	52.81	50.87	47.42	50.64	49.77	50.49	47.96	50.43	50.01	50.18
AR	1.06	0.83	1.02	0.52	0.56	0.88	0.81	0.64	0.70	0.74	0.74	0.50	0.81	0.72	0.59	0.45	0.30	0.64	0.58	0.49
Thickness of Wall (t)	0.57	0.36	0.35	0.15	0.44	0.39	0.42	0.26	0.50	0.28	0.38	0.54	0.21	0.23	0.29	0.49	0.60	0.41	0.34	0.67

Fig. A.5 *Ratio of shear deformation vs percentage of opening for shear wall with door type opening*

- ✓ Similar to the above two cases, ratio shear deformation in shear wall with door type of shear wall decreases by increasing aspect ratio(AR)

Generally, the effect of wall thickness on shear deformation need additional parametric study because its effect on shear deformation influenced by other parameters.

APPENDIX B

ELEMENT USED FOR MODELING IN ANSYS

[B] Beam and Shell Element used in the FEM

BEAM189 is an element suitable for analyzing slender to moderately stubby/thick beam structures. This element is based on Timoshenko beam theory. Shear deformation effects are included. This element is well-suited for linear, large rotation, and/or large strain nonlinear applications. BEAM189 includes stress stiffness terms, by default, in any analysis with NLGEOM, ON. The provided stress stiffness terms enable the elements to analyze flexural, lateral, and torsional stability problems (using eigenvalue buckling or collapse studies with arc length methods).

The beam elements are based on Timoshenko beam theory, which is a first order shear deformation theory: transverse shear strain is constant through the cross section; that is, cross sections remain plane and undistorted after deformation. BEAM188/BEAM189 elements can be used for slender or stout beams. Due to the limitations of first order shear deformation theory, only moderately "thick" beams may be analyzed.

In Euler – Bernoulli beam theory, shear deformations are neglected, and plane sections remain plane and normal to the longitudinal axis. In the Timoshenko beam theory, plane sections still remain plane but are no longer normal to the longitudinal axis. The difference between the normal to the longitudinal axis and the plane section rotation is the shear deformation. These relations are shown in figure.

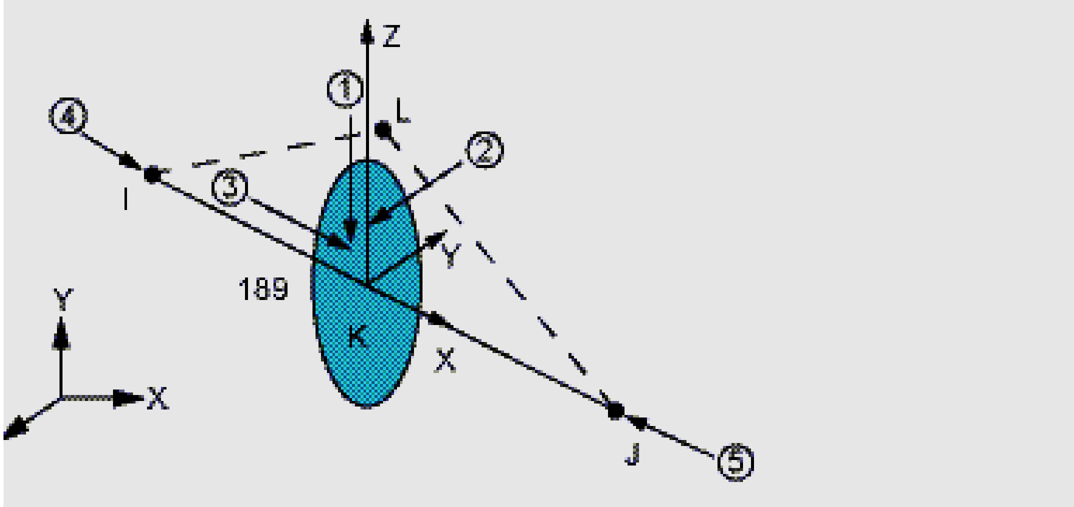


Fig. B.1 *BAME189 Geometry*

Shell 181:

SHELL181 is suitable for analyzing thin to moderately-thick shell structures. It is a 4 node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. (If the membrane option is used, the element has translational degrees of freedom only). The degenerate triangular option should only be used as filler elements in mesh generation.

SHELL181 is well-suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. In the element domain, both full and reduced integration schemes are supported.

SHELL181 accounts for follower (load stiffness) effects of distributed pressures.

SHELL181 may be used for layered applications for modeling laminated composite shells or sandwich construction. The accuracy in modeling composite shells is governed by the first order shear deformation theory (usually referred to as Mindlin-Reissner shell theory).

Shell181 includes the effects of transverse shear deformation. An assumed shear strain formulation of Bathe-Dvorkin is used to alleviate shear locking. The transverse shear stiffness of the element is a 2X2 matrix as shown below.

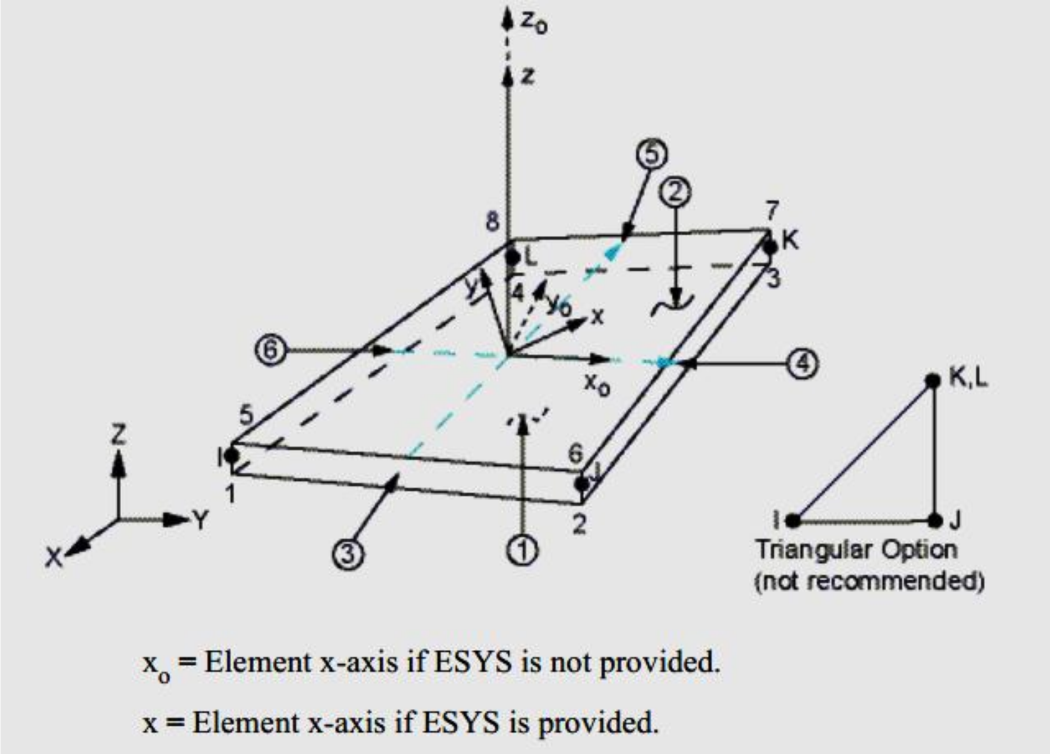
$$E = \begin{bmatrix} E_{11} & E_{12} \\ sym & E_{22} \end{bmatrix} = \begin{bmatrix} R7 & R9 \\ sym & R8 \end{bmatrix}$$

In the above matrix, R7, R8, and R9 are real constants 7, 8, and 9. By override the default transverse shear stiffness value by assigning different values to those real constant. This option is effective for analyzing sandwich shell.

For a single-layer shell with isotropic material, default transverse shear stiffnesses are:

$$E = \begin{bmatrix} kFh & 0 \\ 0 & kGh \end{bmatrix}$$

In the above matrix, k=5/6, G= shear modulus, and h= thickness of the shell



x_o = Element x-axis if ESYS is not provided.

x = Element x-axis if ESYS is provided.

Fig. B.2 *shell181 Geometry*

APPENDIX C

OUTLIERS ANALYSIS

Outliers Analysis

In statistic, an outlier is a value recorded for a given variable that seems unusual and suspiciously lower or great than other observed values. An outlier can be reading error or due to typical events. When there are outliers in the data, depending on the stage of the study, we must identify them, possibility with the aid of test, flag them in the report, delete or use method able to tread them as such. XLSTAT gives an approximation of critical values above which one should reject null for a given significant level. XLSTAT gives approximation based on Monte Carlo simulation. XLSTAT gives the p-value that corresponds to the computed statistic as well as the conclusion of typical between -1.96 to 1.96 for critical independent variable and between -1.454 to 1.454 for the dependent variable for 95% confidence of interval.

Distance from each observation to the model in the space X variable (DModX) allow identifying outlier for the explanatory variable and distance from each observation to the model in the space of Y(DModY) allow identify outlier for the dependent variables. [9]

Value of the DModX for the ith observation writes:

$$\mathrm{DModX}_{\boldsymbol{i}} = \sqrt{\frac{\boldsymbol{n}}{\boldsymbol{n-h-1}}\,\frac{\sum_{\boldsymbol{j-1}}^{\boldsymbol{p}} \boldsymbol{e(x,t)_{ij}^{2}}}{\boldsymbol{P-h}}} \qquad (\boldsymbol{C1})$$

Where the $e(X,t)_{ij}$ (i=1…n) are residuals of the regression of X on the jth component.

The value of the DModY for the ith observation writes:

$$\mathrm{DModY}_{\boldsymbol{i}} = \sqrt{\frac{\sum_{\boldsymbol{j-1}}^{\boldsymbol{q}} \boldsymbol{e(y,t)_{ij}^{2}}}{\boldsymbol{q-h}}} \qquad (\boldsymbol{C2})$$

Where q is the number of dependent variable and $e(Y,t)_{ij}$ (i=1…n) are residuals of the regression of Y on the jth component.

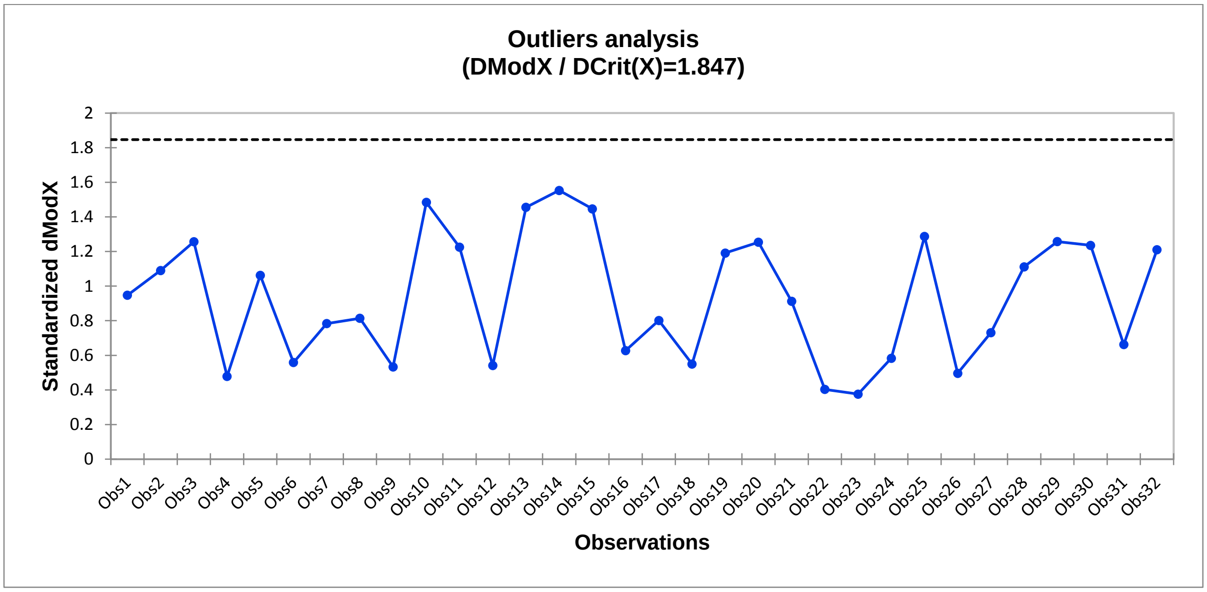


Fig. C.1 *Outlier Analysis with respect to input Variable for Shear wall with window type of opening*

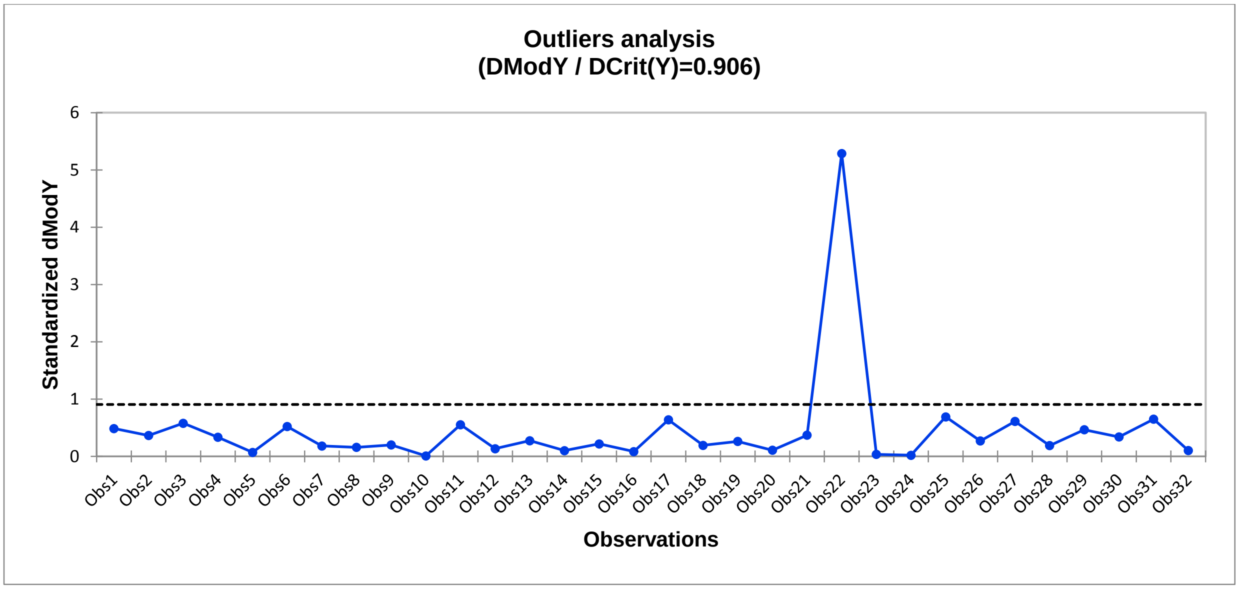


Fig. C.2 *Outlier Analysis with respect to Dependent Variable for Shear wall with window type of opening*

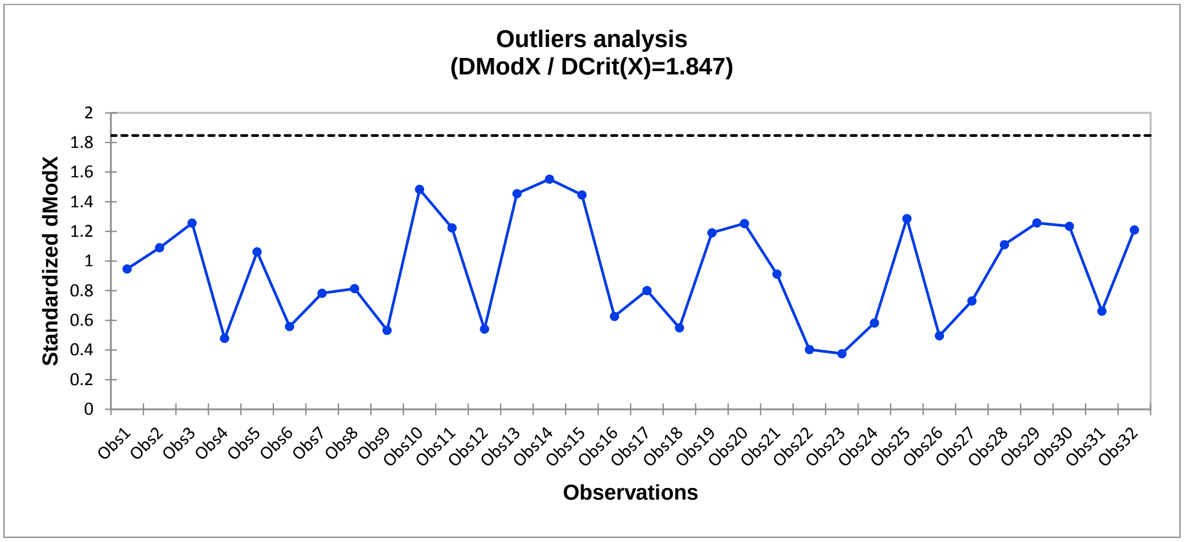


Fig. C.3 *Outlier Analysis with respect to input Variable for Shear wall with Door type of opening*

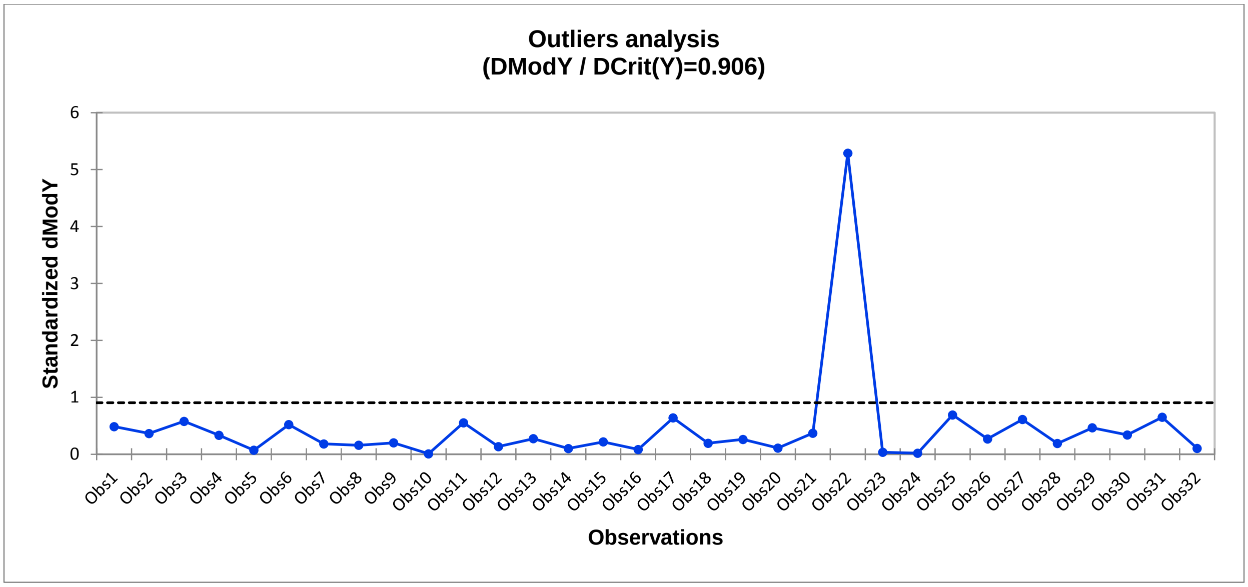


Fig.C.4 *Outlier Analysis with respect to Dependent Variable for Shear wall with Door type of opening*

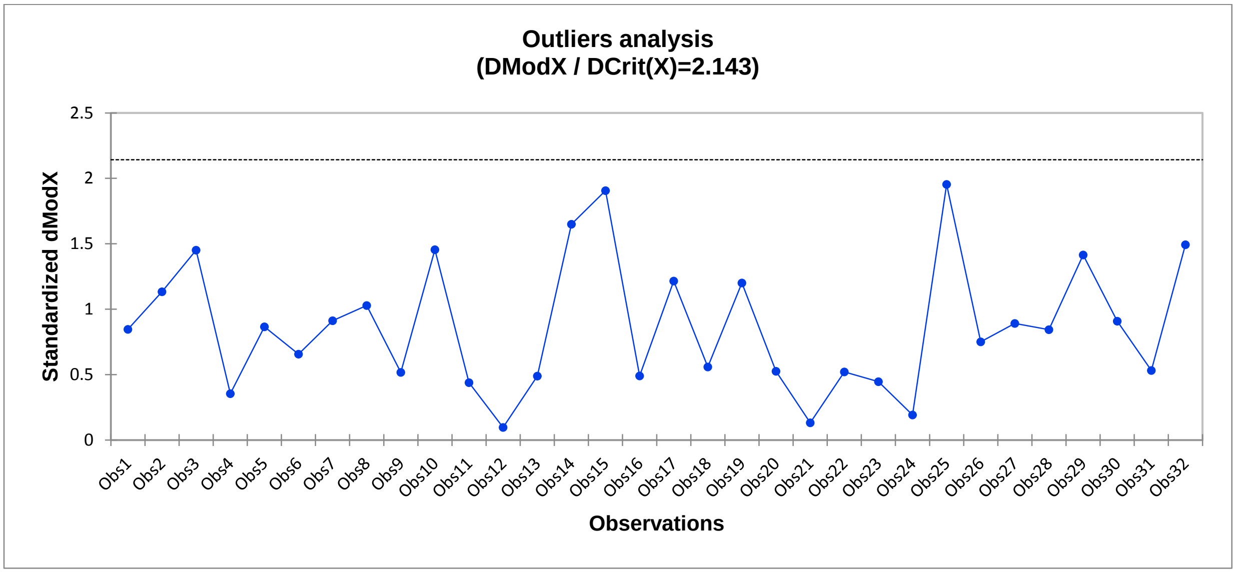


Fig. C.5 *Outlier Analysis with respect to input Variable for Shear wall without opening*

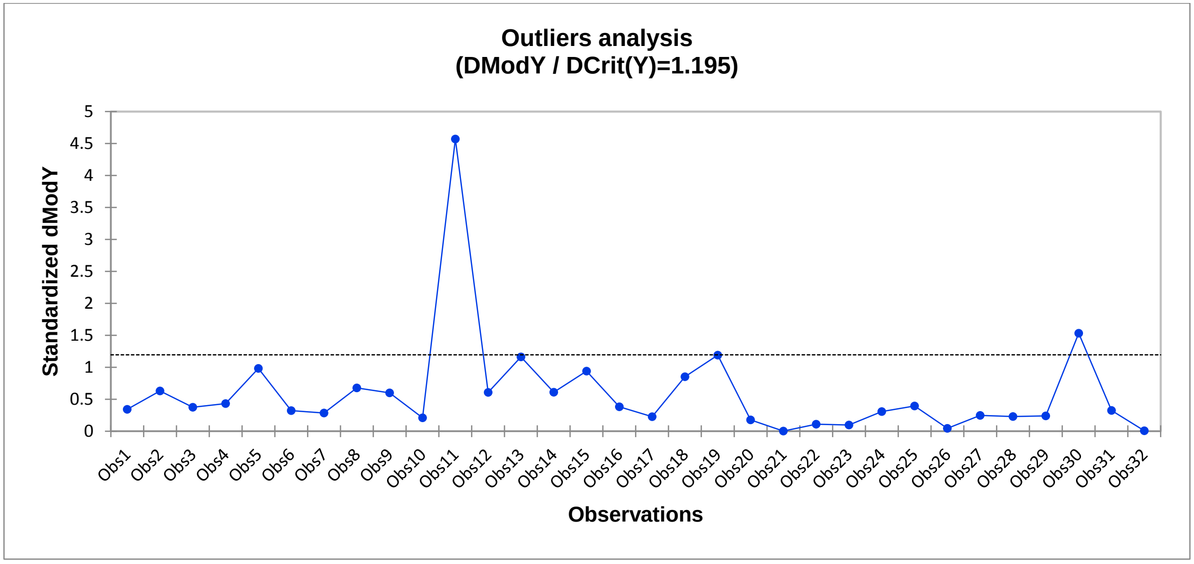


Fig. C.6 *Outlier Analysis with respect to Dependent Variable for Shear wall without opening*