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The Behaviour of Concrete Wall Panel with Opening

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The Behaviour of Reinforced Concrete Wall Panel with Opening

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DECLARATION

I, Chong Fung Yun (12060118) from Faculty of Engineering UNIMAS hereby declare that the work entitled “The Behaviour of Reinforced Concrete Wall Panel with Opening” is my original work. I have not copied from any other students’ work or from any other sources, except where due reference or acknowledgement is made explicitly in the text, nor has any part been written for me by another person. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Date:

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Last but not least, I would like to extend my appreciation to all who ever involved directly or indirectly to help me complete this research.

ABSTRACT

Reinforced concrete wall panels with cut-out opening are the common structural component which are utilised in the construction industry. This research study carries out is aimed at evaluating and determining the structural behaviour of the reinforced concrete wall panels with various cut-out opening sizes, shapes and location. The maximum principal strain and stress, deformation and failure load were used to explain the behaviour of the reinforced concrete wall panels. A parametric study was performed with layered finite element method (LFEM) wall modelling by using the ANSYS software (Version 19.1). In order to evaluate the behaviour of the one-way reinforced concrete wall panels on its opening size, seven different wall types have been modelled, one solid wall and six walls with square opening size ratios, A_o/A between 1% to 20%. The failure loads decrease by around 90% when the opening size ratio increases to 20%. The results shown is in accordance to the hypothesis tested of which the increase in opening size tends to decrease the strength of the reinforced concrete wall panels. In addition, as the 10% of square opening size was taken as the controlled results, the parametric study showed that the investigated shapes of opening gave a reduction in failure load. The effect of the opening shapes which influenced the behaviour of the reinforced concrete wall panels was due to the top or bottom spandrel to the opening and also the areas remained between the left or right piers to the opening sides. To fully understand the behaviour of the reinforced concrete wall panels with opening, the hypothesis design criteria was carried out by manipulating the locations of the opening by shifting it towards the vertical, horizontal and diagonal directions. When the location of the opening is shifted vertically downwards, the failure load has increased. It was mainly due to the increase in the spandrel areas and distance between the top of the opening to the axial loads. Likewise,

when the location of the opening was shifted away from the centre towards the incline directions, it exhibited the same trend of result outcomes with the increase in failure load because the eccentricity has moved away from the centre towards the concentrated areas of which the load acts on the wall panel. For the horizontal allocations of opening, it shows that the further the opening located from the centre, the smaller the failure loads since the eccentricity of the axial loads applied to the opening has been altered and therefore it caused the unbalance distributions of stresses and strains around the areas of the opening and caused the wall panel to deform and decrease in strength. In summary, the variety of the opening sizes, shapes and locations influenced the behaviour of the reinforced concrete wall panels. If the size of opening on the reinforced concrete wall panel is greater, then the strength of the wall panel will be decreased. When the reinforced concrete wall panels are loaded under one-way axial loads, the distributions of the maximum stresses and strains always concentrated around the areas of the opening. The degree of deformations illustrated by the wall panels corresponding to its failure loads of which the wall can be sustained before failure. As this research study is aims to reveal the utilisation of the reinforced concrete wall panel in the construction industry especially the on-site cut off opening due to uncertainty situations on site, therefore, this research contributes valuable knowledge on the effect of opening to the behavior of reinforced concrete wall panels.

Keywords: Reinforced concrete wall panel, opening, maximum principal stress, maximum principal strains, deformations

Sifat bagi Panel Dinding Konkrit Bertetulang dengan Pembukaan Potong di Tapak Pembinaan

ABSTRAK

Panel dinding konkrit bertetulang dengan pembukaan potong di tapak pembinaan adalah komponen struktur biasa yang digunakan dalam industri pembinaan. Kajian penyelidikan yang dijalankan ini bertujuan untuk menilai dan menentukan tingkah laku struktur panel dinding konkrit bertetulang dengan pelbagai pembukaan yang beza dalam ukuran, bentuk dan lokasi. Tegasan maksimum, ubah bentuk dan beban kegagalan digunakan untuk menjelaskan kelakuan panel dinding konkrit bertetulang dengan pembukaan potong di tapak pembinaan. Kajian parametrik dilakukan dengan pemodelan dinding kaedah linear (LFEM) dengan menggunakan perisian ANSYS (Versi 19.1). Untuk menilai tingkah laku panel dinding konkrit bertetulang sehalu pada ukuran pembukaannya, tujuh jenis dinding yang berbeza telah dimodelkan, satu dinding padat dan enam dinding dengan nisbah ukuran pembukaan persegi, A_o / A antara 1% hingga 20%. Beban kegagalan menurun sekitar 90% apabila nisbah ukuran bukaan meningkat sehingga 20%. Hasil yang ditunjukkan adalah sesuai dengan hipotesis yang diuji dimana peningkatan ukuran pembukaan cenderung menurunkan kekuatan panel dinding konkrit bertetulang. Di samping itu, saiz 10% pembukaan persegi diambil sebagai hasil yang dikawal, kajian diteruskan dengan mengkaji kesan pembukaan dengan bentuk yang berlainan. Kajian parametrik menunjukkan bahawa bentuk pembukaan yang disiasat memberikan pengurangan beban kegagalan. Kesan bentuk pembukaan yang mempengaruhi kelancaran panel dinding konkrit bertetulang adalah disebabkan oleh luas permukaan dinding di keliling pembukaan. Untuk memahami sepenuhnya tingkah laku panel dinding konkrit bertetulang dengan bukaan, kriteria reka bentuk hipotesis dilakukan dengan memanipulasi lokasi bukaan dengan mengalihkannya ke

arah menegak, mendatar dan pepenjuru. Apabila lokasi pembukaan dialihkan secara menegak ke bawah, beban kegagalan meningkat. Ini terutama disebabkan oleh peningkatan kawasan spandel dan jarak antara bahagian atas pembukaan ke paksi beban. Begitu juga, ketika lokasi pembukaan dipindahkan dari pusat ke arah lereng, ia menunjukkan arah aliran hasil yang sama dengan peningkatan beban kegagalan kerana eksentrisitas telah bergerak jauh dari pusat ke arah kawasan pekat yang bebannya bertindak pada panel dinding. Untuk peruntukan bukaan mendatar, ini menunjukkan bahawa semakin jauh pembukaan yang terletak dari tengah, semakin kecil beban kegagalan kerana eksentrisitas beban paksi yang dikenakan pada pembukaan telah diubah. Oleh itu ia menyebabkan pembahagian tekanan dan ketegangan yang tidak seimbang kawasan pembukaan dan menyebabkan ketidak sempurnaan panel dinding dan penurunan kekuatan. Ringkasnya, pelbagai ukuran, bentuk dan lokasi pembukaan mempengaruhi tingkah laku panel dinding konkrit bertetulang. Sekiranya ukuran bukaan pada panel dinding konkrit bertetulang lebih besar, maka kekuatan panel dinding akan berkurang. Apabila panel dinding konkrit bertetulang dimuat di bawah beban paksi sehalu, pengedaran tegasan dan regangan maksimum selalu tertumpu di sekitar kawasan bukaan. Tahap ubah bentuk yang digambarkan oleh panel dinding sesuai dengan beban kegagalannya yang mana dinding dapat ditahan sebelum kegagalan. Oleh kerana kajian penyelidikan ini bertujuan untuk mendedahkan penggunaan panel dinding konkrit bertetulang dalam industri pembinaan terutamanya pembukaan terputus di lokasi kerana keadaan tidak menentu di lokasi, oleh itu, penyelidikan ini menyumbang pengetahuan berharga mengenai kesan pembukaan terhadap tingkah laku panel dinding konkrit bertetulang.

Kata kunci: Panel dinding konkrit bertetulang, pembukaan, tegasan pokok maksimum, regangan utama maksimum, ubah bentuk

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LIST OF ABBREVIATIONS

ACI	American Concrete Institute
A_g	Gross cross-sectional area of wall in plane
A_0	Area of opening
A_{sv}	Area of vertical steel in wall
AS	Australian Standard
BS	British Standard
f_v	Yield strength of steel
H	Height of wall panel
H_0	Height of opening
IBS	Industrialised Building System
L	Length of wall panel
LFEM	Linear Finite Element Analysis
L_0	Length of opening
N_u	Ultimate load for solid wall
N_{uo}	Ultimate load for wall with openings
s_x	Opening spacing parameter for walls with two openings located side by side
t_w	Thickness of concrete wall panel
x	Opening geometry parameter
x_x	Opening parameter with respect to the influence of opening size and location in the horizontal direction
x_y	Opening parameter with respect to the influence of opening size and location in the vertical direction

x_{xy}	Opening parameter defined by the opening size and location in both horizontal and vertical directions and the spacing between opening
α	Dimensionless parameter accounting for the opening width
α_{xy}	Dimensionless parameter accounting for the opening width and opening height
β	Effective height factor
η_x	Distance between centre of gravity of solid wall and the centre of gravity of wall with opening in x direction
$\tilde{\eta}_x$	Distance from the left vertical edge to the center of gravity of the cross-section of the panel with openings
η_y	Distance between centre of gravity of solid wall and the centre of gravity
$\tilde{\eta}_y$	Distance from the top vertical edge to the center of gravity of the cross-section of the panel with openings

CHAPTER 1

INTRODUCTION

1.1 General

Industrialised building system (IBS) is a term used in Malaysia for a technique of construction where-by components are produced in a controlled environment, either at site or off site, placed and assembled during construction works. Over the years, precast reinforced concrete wall panels are widely use in the construction industry. The demand for precast product particularly on precast concrete wall panels is continuously increasing in IBS. Precast reinforced concrete wall panels are usually used as load-bearing structural elements because these concrete products are able to resist high compressive stresses. Therefore, a precast reinforced concrete wall panel is acceptable as an important structural element apart from slabs, beams and columns. This acceptance is due to the increase in research undertaken by the researchers on the behaviour of concrete wall panels to improve and uplift their performance in construction industry.

Eurocode 2 (2014) defines a wall as reinforced concrete wall panel with a length to-thickness ratio of 4 or more, in which the reinforcement is taken into account in the strength analysis. IBS has categorised the reinforced concrete wall panel as in the form of precast concrete wall panel. Reinforced concrete wall panels have several advantages when they are used in IBS. By using this type of walls, some structural components such as beams and columns can be eliminated. Consequently, it may help to reduce the dead loads on the building which in turn reduce the cost of footings and foundations. Reinforced concrete wall panels are easy to design and use in fast track project. The reduction in time of construction will save the cost of construction at the same time.

In order to satisfy the demand in construction, functional modifications need to be made on the reinforced concrete wall panels. These modifications refer to the door and window openings, and also openings for ventilation system, electricity and water pipe. Figure 1.1 shows a cut-out opening for a window on the reinforced concrete wall. Therefore, modification on reinforced concrete wall panels is a necessity. It is more beneficial both environmental and economic to make these modifications of existing building than demolishing them and build up a new building. Therefore, the reinforced concrete wall panels with opening have become important structural elements in construction works. The opening in the reinforced concrete wall causes local cracking around the opening which leads to decrease in load carrying capacity (Mohammed et al., 2012).

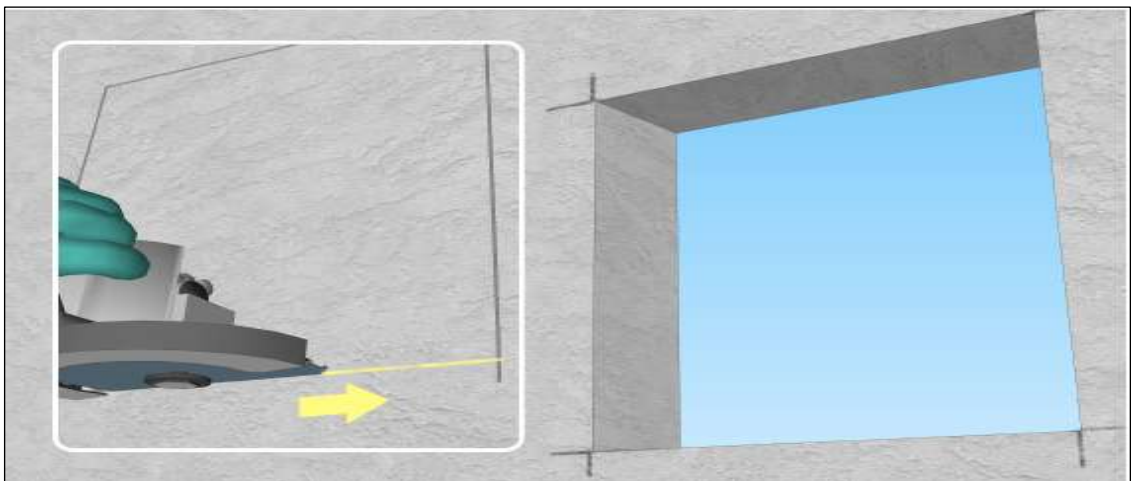


Figure 1.1: Cut out opening for a window opening, WikiHow (2018)

Generally, there are three types of openings in walls, which are, existing openings, enlarged existing openings and newly created openings (Popescu et al., 2015b). Existing opening is an opening that has been deliberately created in the factory. Once the location of the opening has been identified, the reinforcement can be placed around the opening according to the design method. An enlarged existing opening is the opening that cut the

surrounding wall to enlarge the opening. Newly created opening is an opening that is modified or created in an existing reinforced concrete wall. A cut-out opening has no design method. The opening is cut-out from an existing reinforced concrete wall panel. Previous researchers have studied on the behaviour of reinforced concrete wall panel with openings with different boundary condition, aspect ratio, size and position of opening and loading conditions (Saheb & Desayi, 1990a; Lee, 2008; Doh et al., 2010; Guan et al., 2010; & Fragomeni et al., 2015). However, the study on cut-out opening on reinforced concrete wall is less explored and the research on the subject is very limited. The cut-out opening on the concrete wall affects the structural capacity and stress distribution of the concrete wall panel due to the cut-off and reduction of reinforcement. Popescu et al. (2015a) studied the behaviour of cut-out opening on concrete wall panel and found that fibre-reinforced polymer can increase the strength of the wall panel as externally bonded reinforcement. The change in behaviour of the reinforced concrete wall panel with opening influenced the load carrying capacity of wall panels, but none came to conclude regarding the ideal behaviour and the optimal size of existing opening of reinforced concrete wall panels. Recently, Jaseela and Pillai (2017) found the optimum shape of cut-out opening on concrete structural wall panel. Majority of the previous researchers studied the effect of boundary conditions in one-way and two-way wall but the study on the effect of load eccentricity and reinforcement ratio are less pronounced.

1.2 Problem Statement

The modification of opening on reinforced concrete wall panels is a necessity for door and window openings, and also openings for ventilation system, electricity and water pipe. Moreover, most Malaysians prefer to improve their house by doing renovation and

extension (star online, 2015). However, Malaysians have limited knowledge about reinforced concrete wall panel with opening. The opening created on the wall panel will reduce the load bearing capacity and lead to crack.

In the precast construction project, precast reinforced concrete wall panel is not the preferred material chosen by the client or architect for construct a building. This is because the opening of the reinforced concrete wall panel is usually modified in the factory. It need specialist to construct the opening design consideration. The cut-out opening in the wall panel changes the structural behaviour of the reinforced wall panel (EssayUK, 2008). Hence, reinforced concrete wall panel that can accommodate cut-out opening is desired in the market. The size and location of the opening affects the stress distribution and structural capacity of reinforced concrete wall panel (Lee at al., 2008, Guan et al., 2010). However, no design method for cut-out openings in reinforced concrete wall panel exist in current design codes especially for the cut-out opening on reinforced concrete wall panel at site (Eurocode 2 (2008), AS 3600 (2009), ACI (2011)). Eurocode 2 (2008) and AS 3600 (2009) provide limits for when an opening can be neglected and designed as a solid reinforced concrete wall panel, however, there are no agreed limits between large and small opening (Popescu et al., 2016). Most of the reinforced concrete wall panels were created at factory with existing mould and design that have been consult with specialist to save on production cost. This make difficulty for either contractor to create an opening during construction process or owner to make any renovation changing after the building was fully completely built.

The hypothesis tested analysis in this research include the significance difference between the strength of the concrete wall panel and the size of the opening. There are several factors which has significance impact on strength of the wall panel which included the size of the opening, shape of opening and location of the opening.

1.3 Research Aim and Objectives

The aim of this study is to determine the effect of opening shape ratio and location in reinforced concrete wall panel in order to evaluate the failure load, stress, strain and deformation of wall panel with cut-out opening on site. As this research study is aims to reveal the utilisation of the reinforced concrete wall panel in the construction industry especially the on-site cut off opening due to uncertainty situations on site, therefore, this research provides valuable knowledge on the effect of opening to the behavior of reinforced concrete wall panels.

The objectives of this study are focus on:

- i. To investigate the relationship between the failure load, stress and strain distribution to reinforced concrete wall panel with cut-out opening on site.
- ii. To evaluate the structural behaviour of reinforced concrete wall panel with cut-out opening on site with two-layer of reinforcement.
- iii. To relate the effect of the configuration of opening in shape and location in reinforced concrete wall panel towards the cut-out opening on site.

1.4 Scope of the Study

This research focuses on the effect of cut-out opening on reinforced concrete wall panel's strength. In order to obtain a more comprehensive evaluation on the behaviours of reinforced concrete wall panel with opening, several parametric manipulations have been included in this research study. These parametric studies included the opening with different shape, size and location.

In this research study, all the reinforced concrete wall panels with 150 mm thick and double-layered reinforcement are modelled using the ANSYS software and are subjected to

one-way axial loads. One-way axial loads is preferable to the two-way loads since it can provide more direct comparison on the effect of the opening since it is only limited to one-way deflection, therefore, the deflection and deformation patterns can be obtained clearly.

To investigate the structural behaviour of the reinforced concrete wall panel with various opening, the results for the maximum failure load retained by the wall panels, stress and strain distribution displayed by each of the wall modelling are determined. Meanwhile, the opening with size ratio of 10% in square shape is selected as the controlled sample in this study since square shape represented the most widely practiced cut-out shape in the construction industry. At the meantime, opening with size ratio of 10% is the limit of the opening size ratio in the wall panel since the opening with size ratio of 10% or less can be regarded as a solid wall. Previous studies showed that it did not raised significance cut-off effect on the wall. Therefore, 10% of opening size ratio is selected in order to extend previous studies and to reveal the effects of the 10% cut-out opening size towards the structural behaviour of the reinforced concrete wall panel.

To relate the effect of the configuration of opening in shape and location in precast concrete wall panel towards the cut-out opening on site, the opening has been manipulated into square shape with opening size ratio ranges from 0% to 20%. Apart from that, the shape of the opening is manipulated into square, fillet square, slit rectangular, wide rectangular and circle. The location of the opening is configured to shift vertically upwards and downwards, horizontally to the left and diagonally to the south-west and north-west directions. By the end of this research study, the configuration on the opening which raised the optimum performances in all the aspects of retained failure loads, maximum stress and strain distributions are determined.

1.5 Significance of the Study

In Malaysian construction industry, the precast concrete wall panel with 150 mm thick and double-reinforcement is widely installed in most building structures. However, previous research which involved the study of the behaviour of the concrete wall panel mostly focus on reinforced wall panel with thickness of less than or equal to 100 mm and reinforced in either single or double-layered reinforcement. Therefore, this study involved the design of the precast wall panel with thickness of 150 mm with double-layered reinforcement can extend the previous study and aims to contribute new design guideline for the precast industry.

As this research study is aims to reveal the utilisation of the reinforced concrete wall panel in the construction industry especially the on-site cut off opening due to uncertainty situations on site, therefore, it intends to provide useful knowledge and information on the effect of opening to the behavior of reinforced concrete wall panels. During the design and manufacture stage, the opening in the reinforced wall panel are usually customized into specific opening size, shape and also the location. All those attributes of the opening are being fixed in the wall panel. In fact, there exists some uncertainty during the installations stage in the site for instances some modifications of the building with ventilation system, door, window and renovation of the building. However, information which overcome this shortcoming of precast wall panel still lack. Thus, this research included all the possible geometric attributes of the opening in the reinforced concrete wall panel so that to obtain the full understanding and emphasise on the behaviour of double layer reinforced concrete wall panel in changing the shape, size and location of the opening.

In the sustainability aspect, the knowledge on the structural behaviour of concrete wall panel with opening could provide guidance on how to make a cut-out opening on

reinforced concrete wall panel without affecting the strength performances. The cut-out opening on the existing reinforced concrete wall panel could save the cost and no new material need to be produce. So, modification on the existing building gave less impact on the nature since the production of the concrete is energy consuming and affect the nature.

1.6 Summary of the Thesis

In the first chapter, the background, goal, scope and objectives of the work are presented. The literature review in Chapter 2 has reviewed the previously research on the concrete wall with opening and also the design formula for predicts the ultimate load of concrete wall panel with opening. In Chapter 3, description on modelling the reinforced concrete wall panel by using the ANSYS software is presented. The geometry, material, boundary condition, reinforcement ratio and loading integrated in the study are described in details. In Chapter 4, the result obtained from the calibration process and parametric study are presented. The results are analysed based on the opening ratio size, opening shape and opening location in the reinforced concrete wall panel. The results are discussed in comprehensive way. In the Chapter 5, conclusion is made based on the modelling analysis. Recommendations are suggested for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Reinforced concrete wall is a structural member with a length to thickness ratio of 4 or more and which the reinforcement is taken into account, Eurocode 2 (2008). If the loading is applied vertically on a wall, it is a load bearing wall. Experimental and modelling investigation in the previous researches show that cutting an opening from the reinforced concrete wall panel tends to decrease the load capacity of the wall panel. In this chapter, the findings in the previous researches are summarised in terms of effect of boundary condition on the strength, effect of opening size and number of opening, effect of reinforcement ratio, factor affecting the failure mode and cracking pattern, effect if eccentricity loading and design equations for reinforced concrete wall with opening.

2.2 Effect of Boundary Condition on Strength

A concrete wall can either be one-way wall or two-wall wall depending on the support conditions. A concrete wall panel that is supported laterally and restrained along top and bottom edges are referred to as one-way action panels. However, the wall panels restrained along three or four sides are referred to as two-way action panels. The supports of the concrete wall panel refer to the support from other wall, roof, floor slab and other forms in real structures as shown in Figure 2.1.

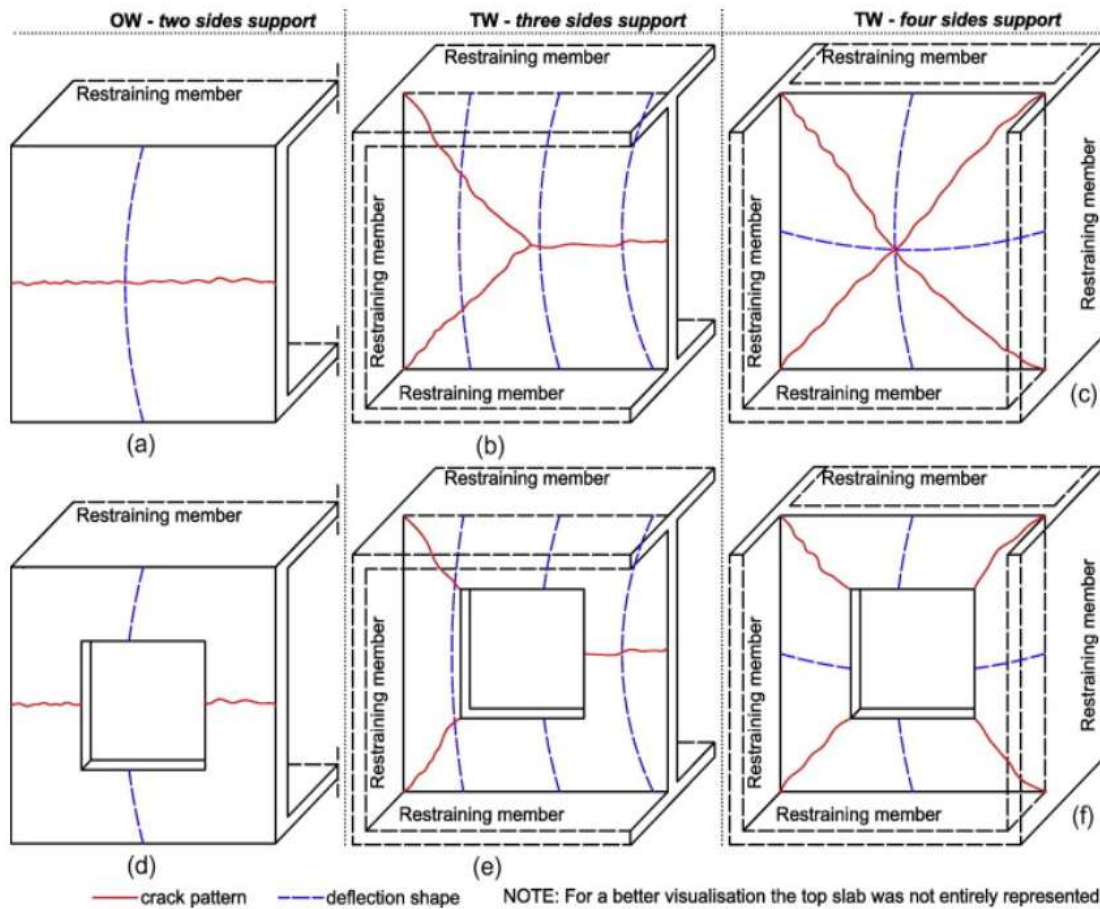


Figure 2.1: Typical crack pattern and deflection shape of axially loaded reinforced concrete walls (Cosmin et al., 2015)

Boundary conditions have a main influence on the failure mode and cracking pattern of the concrete wall panels (Saheb & Desayi, 1990a; Lee, 2008; Doh et al., 2010; Guan et al., 2010; Fragomeni et al., 2011; Doh et al., 2014). Eurocode 2 (2008) and AS3600 (2009) are the only major codes that consider lateral restraint along the side edges of a concrete wall.

Lee (2008) carried out both experimental study and LFEM analysis for high slenderness ratio wall panels. The experimental results showed that the strength for two-way wall is 2.5 to 3.5 times higher than one-way walls. LFEM analysis also showed the same results that the two-way walls increased strength due to side restrains. These results revealed that the strength of two-way concrete wall decreases when the opening area on the

wall panel increases. Additionally, Guan et al. (2010) also conducted a similar study in LFEM analysis. The results also showed that two-way walls gave an improved axial strength. Both researches concluded that the effect of the boundary condition can be ignored when the opening ratio is large, that is, $A_o/A \geq 0.67$, where A_o = area of opening; and A = wall area without opening.

Doh et al. (2010) studied and compared on six half-scale reinforced concrete walls with slenderness ratio of 30 supported on two, three or four sides with various opening configurations. All panels were subjected to a uniformly distributed axial load at an eccentricity. The results show lateral supports have changed the ultimate strength of wall panels with various opening location. Additional side support increases the strength of the wall. If the opening is near to an unsupported edge, it behaves like a two-way supported wall panel. The two-way wall panel has higher ultimate strength than the one-way wall panel. Doh et al. (2014) conducted the study using the same properties of wall panel in Doh et al. (2010) by comparing the strength ratio of solid panel and panel with central opening. The results concluded that there is an increase in axial strength of 40% to 70% by providing two-side and three-side supports. Fragomeni et al. (2011) also concluded that two-way walls have about 2 to 4 times higher failure load than one-way walls in an experimental study.

On the other hand, an experimental study carried out by Saheb and Desayi (1990a) revealed the opposite results as compared to the other researches. The deflection of two-way wall panels was reported to be 40.5% to 78.7% smaller than one-way wall panels. However, the cracking loads for one-way wall panels showed neglected effects with 7.3% to 16.2% higher than two-way wall panels and similarly to the ultimate loads with only 3.0% to 7.3% higher than two-way wall panels. It was concluded that the effect of the boundary

condition is small because the cracking loads and ultimate loads for one-way and two-way wall panels were almost equal.

2.3 The Effect of Opening on Strength

The opening in concrete wall panels refers to the provision of windows, doors and ventilation system. The ultimate strength of the reinforced concrete wall panel will be affected due to the creation of openings. The effect of small opening is not considered because the reinforced concrete walls have the ability to redistribute stress. However, the large opening created in a wall may change the stress distribution within the wall and adversely affects its behaviour due to considerable amount of concrete and reinforcing steel being removed. Figure 2.2 shows the maximum principal stresses in a wall panel of a computer simulation. It can be seen that the presence of the opening in precast wall panels will lead to stress concentrations resulting in cracking.

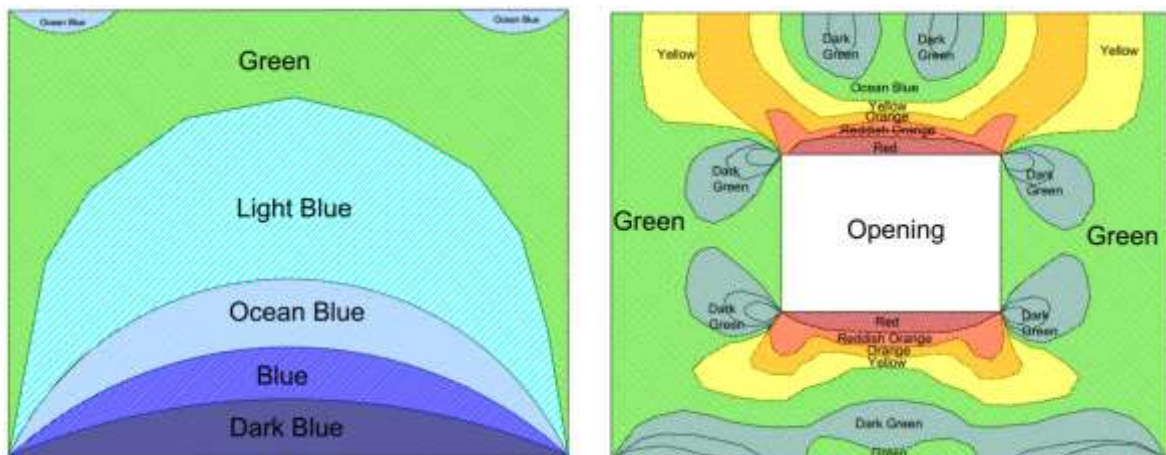


Figure 2.2: Stress contours in the wall panel with opening and without opening (Michael et al., 2002)

The varying configuration of the opening in reinforced concrete wall panel will also change the behaviour of the reinforced concrete wall panel. The change in location of the opening will change the eccentricity of the reinforced concrete wall panels and tend to influence the ultimate strength of wall panels, Popescu et al. (2015b).

2.3.1 The Effect of Opening Shape

Jaseela and Pillai (2017) continued the investigation of cut-out opening and study on the optimum shape of cut-out opening on concrete structural wall. A static structural linear analysis using ANSYS software to find the influence of cut-out opening in one-way and two-way wall panel was conducted. The results of the study were accomplished by twenty-eight wall panels with different opening shape. The shape is varied from rectangular with narrow height (wide rectangular opening) to narrow width (slit rectangular opening) and a comparison was also made with square opening. The study concluded that the optimum shape of the opening in a one-way wall panel is slit rectangular wall opening at the middle of the wall, whereas square opening is the most optimum shape that can be cut on the two-way wall panel. The behaviour of the wall panel is in ambiguity because the conclusion was made only on total deformation of the wall panel but not on ultimate strength, cracking pattern and failure mode. Jassela and Pillai (2017) found that the strength of the wall panel with opening was affected by the pier or the size of the remaining wall.

2.3.2 The Effect of Opening Size

There is no design guideline or recommended detailing in code of practice for concrete wall with opening. However, Eurocode 2 (2008) and AS3600 (2009) have recommended the limit for the height of the opening to be a third of the height of the wall or

the area of the opening is less than 1/10 of the area of the whole wall so that it could be designed as a solid wall. The effect of small opening is not significant because the reinforced concrete walls have the ability to redistribute stresses. However, a large opening created in a wall may change the stress distribution within the wall and adversely affects its behaviour because there are considerable amount of concrete and reinforcing steel removed. The varying configuration of the opening in reinforced concrete wall panel may change the behaviour of the reinforced concrete wall panel as well. These changes being size and location of the opening will change the eccentricity of the reinforced concrete wall panels and tend to influence the ultimate strength of the wall panels (Saheb & Desayi, 1990a; Lee, 2008; Guan et al., 2010; Fragomeni et al., 2011). Mohammed et al. (2013), Popescu et al. (2015a) and Jaseela and Pillai (2017) studied on the behaviour of cut out opening on reinforced concrete wall panels. On the other hand, the effect of the number of opening to the concrete wall panels was carried out by Fragomeni et al. (2012).

Saheb and Desayi (1990a) carried out a test on twelve concrete walls with opening in both one and two-way action. Each panel had a window or a door opening at different location. The wall panels used in the experiment have the slenderness ratio equal to 12 and aspect ratio equal to 0.67. The test parameters of the opening are number of opening, size and location of the opening. The walls were tested with uniformly distributed eccentric loads. The conclusion to this test was that the failure of the concrete panels with opening was induced by the buckling of the slender column strips adjacent to the opening.

Lee (2008) and Fragomeni et al. (2011) studied the effect of the number of opening on the ultimate strength of precast concrete wall panel. Both studies stated that the failure load decreases when the number of the opening increases. Lee (2008) conducted the experiment with seventeen two-way concrete wall panels with opening. The walls were

tested with both one and two window openings and concluded that the failure load decreases with the increasing number of opening. The decrease in axial strength ratio of wall was 77% for one opening and 54% for two openings when the opening ratio, A_o/A , was increased from 0.25 to 0.5. Lee (2008) also studied on the door-type openings and concluded that the axial strength decreased by 26% in two-way action. It was also found that an asymmetric opening location led to a decrease in axial strength ratio. However, both experimental studies did not have a control sample of solid wall without opening. Therefore, there is no relevant results to show how the openings affect the failure load of the walls.

Mohammed et al. (2013) and Popescu et al. (2015a) studied the effect of cross-sectional area of the cut-out opening to the wall panels. Both experimental studies concluded that the increase in cross sectional area of the opening will decrease the failure load

Mohammed et al. (2013) tested one-way concrete wall panel with cut-out openings of size varying from 5% to 30% of the solid wall panel. This study found that the disturbed zones formed due to the cut-out opening caused high stresses in the concrete. Discontinuities in the disturbed zones formed cracks at the corner if it is improperly reinforced. The results show that the failure load decreases as the cross-sectional area of the opening increases. However, this experimental study also did not include the control solid wall, so no conclusion can be drawn on how the opening size affects the failure load.

Popescu et al. (2015a) carried out an experimental study on high strength two-way walls and solid wall. The concrete wall panel with small opening which had cross sectional area of 25% registered a decrease in failure load by 36%. However, the concrete wall panel with large opening which had cross sectional area of 50% decreased in failure load by 50%. Popescu et al. (2015a) explains the decrease in the failure load could be affected by the piers of the concrete wall, where a pier is defined as the column-like cross section of the

remaining the wall area. The larger the opening, the smaller the piers. The decrease in the aspect ratio of the piers led to the restraints being more active and therefore the material strength is utilized more effectively. The decrease in the failure load does not decrease linearly with the increase of the size opening. This is because the results show that double the cross-sectional area in the wall from small to large opening does not give half the failure load. Pospescu et al. (2015a) found that the strength of the wall panel with opening was affected by the pier or the size of the remaining wall. The larger opening causes the piers width of the remaining wall to become narrow.

Linear finite element analysis (LFEM) was carried out by Lee (2008) and Guan et al. (2010) with the purpose to study how the dimensions of opening affect the axial strength of the wall. Guan et al. (2010) did a linear finite element analysis of two-way walls with window and door openings. The properties of the wall panel were identical with those in the experimental study conducted by Saheb and Desayi (1990a). A parametric study on the effect of the height and length of opening on wall panel was investigated. The results show that the strength of the wall panel decreases by 86% when the opening area of 25% was increased to 67%. The increase in length of the opening to the total length of the wall, L_o/L , from 0.25 to 0.67 decreases the load carrying capacity by 50% for two-way walls. However, the increase in height of the opening to the height of the wall from 0.25 to 0.67 reduces the ultimate load carrying capacity by 14% for two-way walls. Guan et al. (2010) found that the response of the ultimate load capacity to the variation in the opening size, height and length is approximately linear and that increasing the height together with the length of the opening has the most critical effect on the axial strength of the wall. This conclusion is in agreement with the LFEM analysis made by Lee (2008). Increasing only the height of the opening has a small effect on the ultimate load carrying capacity.

2.3.3 The Effect of Number of Opening

Fragomeni et al. (2012) studied the behaviour of concrete wall panels with one or two openings. There was a reduction in ultimate strength in the walls with two openings compared with identical walls with one opening. It was also reported that the failure loads of two-way panels with openings are about 2 to 4 times those of similar one-way panels with openings. In general, the test results indicate that failure loads decreased when the number of openings was increased from one to two.

2.4 The Effect of Reinforcement Ratio

According to BS8110 (1997), AS3600 (2009), Eurocode 2 (2010), and ACI318 (2014), reinforcement is provided in the concrete wall panels to offset creep and shrinkage effect when the reinforced concrete walls are subjected to axial load. It is generally proved that the contribution of steel reinforcement in a compression wall can be neglected but is necessary to provide the minimum requirement of reinforcement for each wall panel to control cracking. From the various design codes, the reinforced concrete wall panels can be designed by using simplified design method or method based on column theory. Simplified design method is used when only a single layer of reinforcement is provided.

Eurocode 2 (2010) categorises concrete walls to reinforced concrete walls or unreinforced and light reinforced concrete walls. A reinforced concrete wall should be designed according to a strut-and-tie model. Therefore, both horizontal and vertical reinforcement need to fulfil the minimum reinforcement requirement. Eurocode 2 (2010) specifies a minimum vertical reinforcement ratio of 0.2% in wall, and the maximum vertical reinforcement ratio is 4%. When the reinforcement ratio exceeds 2%, strut-and-tie should be used in the wall. The clear distance is mentioned in the design code and half of the amount

of reinforcement should be placed at each face. This requirement is used to satisfy structural and durability of walls. For the unreinforced and light reinforced concrete wall, it has less amount of reinforcement than the minimum reinforcement. The unreinforced and light reinforced concrete walls only have a single layer of reinforcement to control cracking due to shrinkage and creep effects in the walls. This single reinforcement does not account for the bearing capacity in the wall.

Experimental studies were carried out by Seddon (1956) and Pillai and Parthasarathy (1977) on single layer reinforcement concrete wall. Both results show the single reinforcement placed in the centre of the wall panel has negligible influence on the strength of the wall. Moreover, same conclusion was obtained from the finite element analysis. Indeed, one of the 3D finite element analysis studies conducted by Somiah et al. (2014) attempted to compare the stresses in concrete wall panels with minimum level of steel reinforcement and plain wall panel revealed that the stress in the reinforcement can be ignored. The results proved that the steel reinforcement in load bearing wall does not contribute to the strength of the wall since the principal stress only increased by 0.05% in the presence of steel reinforcement.

On the other hand, there are also some researches which found out that there is a significant effect of reinforcement to the strength of the wall. There are certain cases that the reinforcement provides additional strength to the wall panel. Seddon (1956) proved that double layers of reinforcement have more effect on the strength of the wall panel. Saheb and Desayi (1990b) conducted an experimental study on two-way wall panel. This study shows that the load capacity of the wall panel increased by 54% if the amount of the vertical reinforcement was increased from 0.33% to 0.85%. It was also concluded that the horizontal reinforcement did not contribute to the load carrying capacity of the wall panel.

Pospescu et al. (2015a) studied the effect of centric reinforcement placed in one layer in an experimental study. The study shows that the reinforcement only contributed to the strength at higher load. When the wall was about to fail, no yielding occurred in the vertical bar while only some horizontal bars yielded. The increase in geometric nonlinearities also led to large deformation of wall panels. The large deformation activated the yielding of the reinforcement and delayed the failure of the wall. So the failure of the wall only occurred in the pier with lower deformation.

Doh (2002) carried out a parametric study with LFEM of two-way walls with centric single-layer reinforcement. The results show that load capacity of the wall increased for low slenderness wall panel. However, the reinforcement can be negligible for high slenderness wall panel, that is, walls with height (H) to thickness (t_w) ratio of more than 40. For lower slenderness-ratio wall panels, the reinforcement placed in two layers can increase axial strength of the wall panel, instead of centric one-layer reinforcement. El-Metwally et al. (1990), Lee (2008) and Fragomeni et al. (2011) also deduced the same conclusion because the contribution of reinforcement in the tension zone increased the strength of the wall. Saheb and Desayi (1990b) and Fragomeni and Mendis (1997) also made the same conclusion that when the reinforcement is placed in two layers, a significant increase in ultimate strength can be achieved.

Another study on reinforcement in wall panels was carried out by Guan et al. (2010) through a nonlinear finite element analysis. The spacing of the bars differed depending on the opening arrangement for each wall. The spacing of the bar was closer when it was nearer to the opening, and the spacing became larger when it was away from the opening. This method was used to create a reinforced frame system around the opening to control cracking.

The results show the strength of the one-way wall models reduces by 92% as the opening dimension increases from 25% to 67% of the wall dimension.

2.5 Factors Affecting the Failure Mode and Crack Pattern

The cracks on a wall panel will lead to failure. Boundary conditions and slenderness ratio were found to be influencing the failure mode of concrete wall with opening (Lee, 2008; Fragomeni, 2011). The difference in concrete strength also to different failure mode (Doh & Fragomeni, 2010; Fragomeni et al., 2012; Doh et al., 2014).

2.5.1 Boundary Condition

An experimental study carried out by Doh and Fragomeni (2010) showed the majority of cracking propagated diagonally from the restrained corners to the opening and then horizontally from the opening to unrestrained edges, indicating typical two-way behaviour close to the restrained ends and one-way behaviour between unsupported edges. Similar investigation was conducted by Doh et al. (2014) with wall panels tested on three-side lateral supports. The results revealed that majority of cracking propagates diagonally from the restrained corners to the opening and then horizontally from the opening to the unrestrained edge. Both researches concluded that the cracking pattern will start from the corner of the opening and extend to the unrestrained edge of the wall panel.

Fragomeni et al. (2012) carried out an experimental study with forty-seven reinforced concrete walls with opening with both one-way and two-way actions. It was found that one-way wall panels with opening showed single curve bending failure and horizontal cracking at the centre of opening. However, the two-way wall panels with opening showed typical

curvature bending failure and diagonal cracking from corner edges of opening to the corner of the wall panel.

2.5.2 Concrete Strength

Concrete strength is also another factor that affects the cracking pattern and failure mode of the concrete wall panel with opening (Doh & Fragomeni, 2010; Doh et al., 2014). Doh and Fragomeni (2010) found out that the high strength concrete panels (>50 MPa) developed a single large crack, commencing at restrained corners at the tension face and then horizontally towards the unrestrained edge. This indicates a brittle failure mode, with possibly some yielding of reinforcement taking place. In contrast, the normal concrete strength panels tested exhibited more ductile behaviour with a number of parallel cracks. Biaxial curvature was evident as a result of the wall being supported on three sides.

Doh et al. (2014) compared the normal strength and high strength concrete wall cracking patterns and illustrated the differences in failure mode of two-way action with three-side lateral supports. The high strength concrete panel developed a single large crack, commencing at restrained corners at the tension face and then splitting in two separate parts near unrestrained region. This indicates that the high strength (>50 MPa) concrete panels possessed a more brittle failure mode, with some yielding of reinforcement taking place before concrete failure. In contrast, several minor cracks propagated in normal strength (30 MPa) concrete panel.

2.5.3 Slenderness Ratio

Slenderness ratio of a wall is defined as a function of the effective height divided by either the effective thickness or the radius of gyration of the wall section. The effect of

slenderness ratio on the ultimate strength of reinforced concrete walls with opening was investigated by Fragomeni et al. (2012) by testing forty-seven reinforced concrete wall panels with opening. In this investigation, it was found that the axial strength ratio for one-way panels gradually decreases when slenderness ratios were increased from 30 to 40. Same conclusion was deduced by Doh and Fragomeni (2006), where the investigation results show that axial strength decreases with increase in slenderness ratio. This conclusion was also proved by Philip and Guan (2006) from a parametric study on fifty-four one-way and two-way concrete wall panels with opening with slenderness ratios between 10 and 50. The results revealed that that axial strength ratio becomes lower for the slenderer wall.

In general, walls with a low slenderness ratio may fail by crushing on the compressed face and bending on the tension face, while those with high slenderness ratio may additionally fail through buckling. Brittle types of failure have been observed in all experimental studies performed on low slenderness-ratio walls (Doh & Fragomeni, 2006; Fragomeni et al., 2012).

2.6 The Effect of Eccentric Loading

Most of the researches subjected the concrete wall panel to a uniformly distributed axial load with an eccentricity of $t_w/6$. The loading with an eccentricity is used to simulate the imperfection of installation in construction. The wall develops tension within a certain zone when the load is applied on the wall with an eccentricity more than $t_w/6$. The portion of the wall cracks slightly at each corner in the section with the assumption of a no tension material. The geometry of the crack section changed with the varying value of eccentricity loading applied as depicted in Figure 2.3 (Kuddus, 2010).

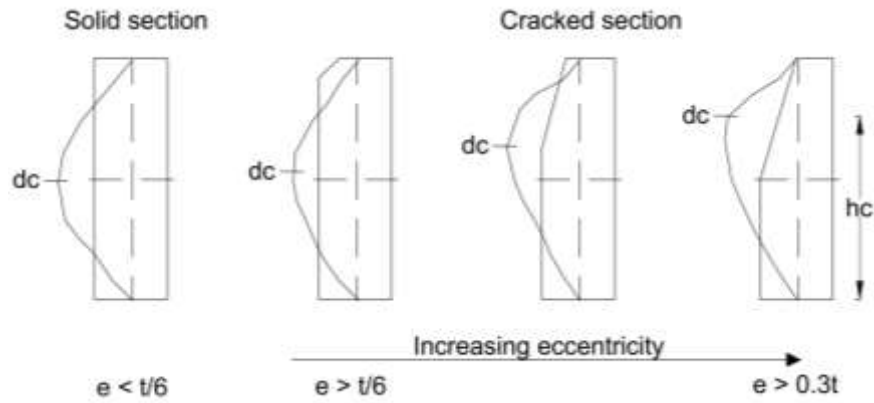


Figure 2.3: Effect of increasing eccentricity on the size of cracked section wall (Kuddus, 2010)

Eccentric load affects the ultimate load and the displacement of the wall panels. The eccentric axial load acting on the wall panel will provide an increase in bending moment resulting in out of plane curvature due second order effect. When the displacement of the wall panel is out of plane, and the eccentric load is continuously increasing, the second order effect occurs as shown in Figure 2.4.

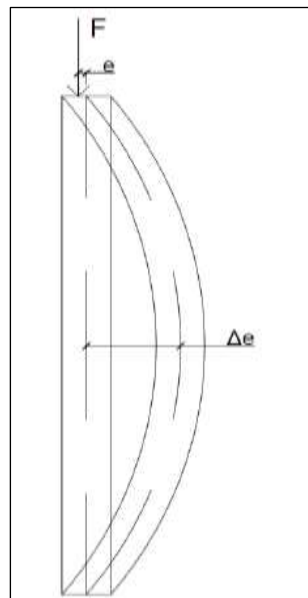


Figure 2.4: Second order effect due to eccentric loading (Johan & Sebastian, 2016)

Doh (2002) mentioned that only eccentric load acts on wall panels in practice. The centrically load can only be use in theory. Therefore, eccentric loading must be treated in the design procedure because eccentricity affects the failure type of the wall panel. A large curvature occurring in a slender wall and high eccentricity gives a catastrophic failure mode. Doh (2002) provided the results showing failure load for the centric loading was more than double compared to the eccentric loading. LFEM results showed the failure mode for lower eccentricity is crushing whilst buckling failure was recorded for higher eccentricity loading on wall panels.

2.7 Design Equations for Wall Panel with Opening

Many researches had carried out studies and investigations to improve the existing design method in the design code. There are different design formulae for one-way and two-way wall panels. However, study on the design formulae for one-way and two-way wall panel with opening is scarce (Saheb & Desayi, 1990a; Doh & Fragomeni, 2006; Philip & Guan, 2007; Guan et al., 2010). Most of the researchers studied on wall panels with low slenderness ratio (< 40) except for Philip and Guan (2007) who studied high slenderness-ratio wall panels with opening. Basically, the effect of the size and location of the opening is taken through a dimensionless parameter, α , accounting for the opening width. Only Guan et al. (2010) changed the reduction parameter from α_x to α_{xy} to include for the opening height. For the formulae contributed by each researcher, N_{uo} is the ultimate load (kN) for wall with openings; N_u is the ultimate load (kN) for solid wall; A_g is the gross cross sectional area of wall in plane (mm^2); f_v is the yield strength of steel (MPa); A_{sv} is the area of vertical steel in wall (mm^2); x is the opening geometry parameter; x_{xy} is the opening parameter defined by the opening size and location in both horizontal and vertical directions and the

spacing between opening; s_x is the opening spacing parameter for walls with two openings located side by side (mm); x_x and x_y is the opening parameter with respect to the influence of opening size and location in the horizontal and vertical direction respectively.

Saheb and Desayi (1990a) conducted an experiment on six two-way wall panels with different types of opening. Each wall panel was acted upon with eccentric load of eccentricity equals to $t_w/6$. The wall panels were insert with two layers of reinforcement symmetrically, one in each face of the wall. Figure 2.5 shows the definition of parameters in the design equations.

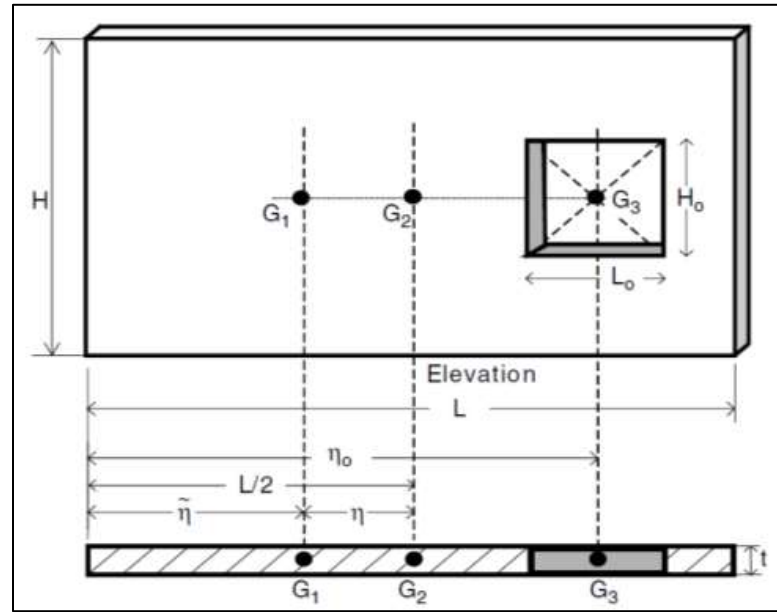


Figure 2.5: Definition of parameters in design equations, Saheb and Desayi (1990a)

The design formula for ultimate load is given by

$$N_{u0} = (k_1 - k_2 \cdot x) \cdot N_u \quad (2.1)$$

Where N_u for one-way wall panel

$$N_u = 0.55(A_g f'_c + (f_{yv} - f'_c)A_{sv}) \left(1 - \left(\frac{H}{32t_w}\right)^2\right) \left(1.20 - \left(\frac{H}{10L}\right)\right) \text{ for } \frac{H}{L} < 2.0 \quad (2.2)$$

$$N_u = 0.55(A_g f'_c + (f_{yv} - f'_c)A_{sv}) \left(1 - \left(\frac{H}{32t_w}\right)^2\right) \text{ for } \frac{H}{L} > 2.0 \quad (2.3)$$

And N_u for two-way wall panel

$$N_u = 0.67A_g f'_c \left(1 - \left(\frac{L}{120t_w}\right)^2\right) \left(1 + 0.12 \left(\frac{H}{L}\right)\right) \text{ for } 0.5 < \frac{H}{L} < 2.0 \text{ and } \frac{L}{t_w} < 60 \quad (2.4)$$

The constant k_1 and k_2 were obtained from test results by using curve-fitting techniques. It was found that $k_1 = 1.25$ and $k_2 = 1.22$ for one-way wall panels, while $k_1 = 1.02$ and $k_2 = 1.00$ for two-way wall panels. The non-dimensional quantity, x is a geometrical opening index which defined in Saheb and Desayi (1990a) is given by

$$x = \frac{A_0}{A} + \frac{\eta}{L} \quad (2.5)$$

where the area of the wall panel, $A = Lt_w$; the area of the opening, $A_0 = L_0 t_w$; $\frac{A_0}{A}$ accounts for the cross-sectional area of openings in the horizontal plane; $\frac{\eta}{L}$ corresponds to the location of the opening in the horizontal direction; η is the centre of gravity of wall panel with openings with respect to the wall centre, which $\eta = \left(\frac{L}{2} - \tilde{\eta}\right)$. However, $\tilde{\eta} = \frac{\frac{1}{2}t_w L^2 - t_w L_0 \eta_0}{Lt_w - L_0 t_w}$.

After that, Doh and Fragomeni (2006) introduced the new constant k_1 and k_2 based on their experimental result. Doh and Fragomeni tested wall panels with opening under one-way and two-way actions. The formula proposed for the ultimate load with openings, N_{uo} is same with the formula proposed by the Saheb and Desayi (1990a). The formula proposed for the ultimate load with openings is given by Equation (2.1).

In this case, $k_1 = 1.188$ and $k_2 = 1.175$ for one-way wall panels, while $k_1 = 1.004$ and $k_2 = 0.933$ for two-way wall panels. obtained from experimental results; the non-dimensional quantity α is defined in Saheb and Desayi (1990a); and the design axial strength

per unit length of the wall, N_u was same as the formula defined in Doh and Fragomeni (2005), which is

$$N_u = 2.0 * f'_c{}^{0.7} (t_w - 1.2e - 2e_a) \quad (2.6)$$

in which f'_c = the characteristic compressive strength of concrete from experiment ; e = eccentricity of load; and e_a = additional eccentricity due to the out-of-plane deflection of the wall during loading (the P-delta effect) given as $e_a = \frac{(H_{we})^2}{2500t_w}$; where $H_{we} = \beta H$.

For one-way wall panel, the effective height factor, β

$$\beta = 1 \text{ for } \frac{H}{t_w} < 27 \quad (2.7)$$

$$\beta = \frac{18}{\left(\frac{H}{t_w}\right)^{0.88}} \text{ for } \frac{H}{t_w} \geq 27 \quad (2.8)$$

For two-way wall panel, the effective height factor, β

$$\beta = \alpha \frac{1}{1 + \left(\frac{H}{L}\right)^2} \text{ for } H \leq L, \text{ and} \quad (2.9)$$

$$\beta = \alpha \frac{L}{2H} \text{ for } H > L \quad (2.10)$$

In these equations, the eccentricity parameter,

$$\alpha = \frac{1}{1 - \frac{e}{t_w}} \text{ for } H/t_w < 27, \text{ and} \quad (2.11)$$

$$\alpha = \frac{1}{1 - \frac{e}{t_w}} \times \frac{18}{\left(\frac{H}{t_w}\right)^{0.88}} \text{ for } H/t_w \geq 27 \quad (2.12)$$

A new empirical formula was introduced by Philip and Guan (2007) by their studies concrete wall panels with opening with slenderness ratio greater than 30. They studied the empirical formulae by linear finite element analysis. The formula for one-way wall panel

with opening is same with the formula given by Saheb and Deasayi (1990a) and Doh and Fragomeni (2006) because this formula was proven to give an accurate result with the LFEM. However, Philip and Guan (2007) introduced a restraint factor, λ for wall panel with two-way support, where the proposed design formula for ultimate load for wall panels with openings is given by

$$N_{u0} = \lambda(k_1 - k_2 \cdot x)N_u \quad (2.13)$$

where λ = restraint factor which is equal to 1 for one-way wall panels with opening, whereas for two-way wall panels with opening, λ is given by

$$\lambda = 0.038 \left(\frac{H}{t_w} \right) + 1.04 \quad (2.14)$$

The reduction parameter, x which considers the size, number and location of opening was same with the formula in Saheb and Desayi (1990), where $x = 0.25$ for one-way wall panels with opening and $x = 0.5$ for two-way wall panels with opening. Factors k_1 and k_2 are 1.188 and 1.175, respectively, which are constants derived from a calibration process.

From the previous researcher, the x parameter is used to compensate for the effects of opening, but the effect of opening neglects opening variations in the vertical cross-section of wall panels. Lee (2010) proposed the new formulae to simultaneously account for opening variations in both horizontal and vertical cross section of wall panels. In order to solve this, the existing parameter in Equation (5) is now referred to as x_x and a new parameter is proposed as x_y . The x_y is proposed as follows: $x_y = \left(\frac{A_{oy}}{A_y} + \frac{\eta_y}{H} \right)$ in which $\eta_y = \left(\frac{H}{2} - \tilde{\eta}_y \right)$ with $\tilde{\eta}_y$ being the distance from the left vertical edge to the center of gravity of the cross-

section of the panel with openings, or $\tilde{\eta}_y = \frac{\frac{1}{2}t_w H^2 - t_w H_0 \eta_0}{H t_w - H_0 t_w}$; and $A_{0y} = H_{0y} t_w$. The proposed new design equation for ultimate strength is as follow:

$$N_{uo} = \{k_1 - k_2(x_x + \lambda x_y)\}N_u \quad (2.15)$$

Where N_u was calculated as in Equation (2.6). The constant k_1 and k_2 are obtained from experimental results, and they are 1.19 and 1.30 for one-way action, and 0.83 and 0.2 for two-way action respectively. However, Guan et al. (2010) identified that increasing both the height and length of an opening has the most significant effect on the load carrying capacity. The analysis was conducted using a nonlinear finite element method. Guan et al. (2010) proposed new opening parameter, x_{xy} , which cover the both function of x_x and x_y in the effect of both the opening length and height. The proposed design formula for ultimate load is

$$N_{uo} = (k_1 - k_2 x_{xy})N_u \quad (2.16)$$

wher

$$x_{xy} = \frac{x_x + \lambda x_y}{1 + \lambda} \quad (2.17)$$

and

$$x_y = \frac{A_{oy}}{A_y} + \frac{d_y}{H} \quad (2.18)$$

in which $\frac{A_{oy}}{A_y}$ accounts for the opening size in the vertical plane, $\frac{d_y}{H}$ corresponds to the opening location in the vertical direction, and d_y is the distance between centres of gravity of the panel with and without an opening respectively, in the vertical plane. In Equation

(2.17), λ ($0 \leq \lambda \leq 1$) is the weighting ratio indicating the percentage of x_x in relation to x_y . However, λ together with the constants k_1 and k_2 can be determined by a standard regression analysis through a calibration process

2.8 Summary on Literature Review

Based on the previous literature review, there existed of several main points that can be concluded for the study on behaviour of reinforced concrete wall panel with opening. For wall panels assigned with axial load, most of the previous researchers focused on the design of concrete wall panels with opening in factory, but not consider the reinforced concrete wall panels with cut-out opening. So, more research is needed to carry out to study the behaviour of reinforced concrete wall panel with on-site cut out openings.

The boundary condition, aspect ratio and slenderness ratio will affect the load carrying capacity of the concrete wall panels with opening. Support condition affects the cracking pattern. Strength of wall panel affects the failure mode of reinforced concrete wall panel. The ratio of the reinforcement on previous research mostly focus on the single layer and the results showed that the single layer reinforcement has negligible effect in changing the ultimate strength. However, there existed a few results show two-layer of reinforcement obtained the opposite result against the single layer reinforcement.

Opening has decreased the load capacity of the wall panels depending on its size, shape and location. Through the analysis of existing experimental and modelling studies, it was found that the opening size ratio was studied in a very large gap with each ascending of 5% from 5% to 30%. More research is needed to study on the structural behaviour with each increasing of only 1% on the opening ratio.

The research also studies on the effect of the opening shapes and found that most of the opening shapes are focused on the right-angle opening shape. So, more shapes can be introduced to study the structural behaviour of reinforced concrete wall panel. The changes of the opening location in previous research mainly shift on the horizontal and vertically direction. Therefore, further research can be extended to study on the opening in the reinforced concrete wall which is shifting to diagonal direction. The research mostly focused on discussing the ultimate load capacity, cracking pattern and deformation cannot fully described the strength behaviours but in fact it also affected by the stress- strain relation.

The previous researches introduce the empirical formula for the reinforced concrete wall panel with opening. The proposed design formula for ultimate load is based on the formula that proposed by Saheb and Desayi (1990a), but the constant value in the formula was changed in the following research based on their own result from the experimental and modelling analysis. Hence, there was no empirical formula can comply to all type of reinforced concrete wall panel with opening.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter outlines all the relevant experimental and analytical techniques used in this research study. This research study involves the evaluation of the behavior of reinforced concrete wall panel with opening. The evaluation is focusing on the reinforced concrete wall panels under one-way axial load. The derivation of attributes and parametric studies for the openings in the LFEM wall modelling by using the ANSYS software (Version 19.1) are described in details in order to identify the effects on strength reduction and deformation of the reinforced wall panels due to the manipulation on its opening size, shape and location. Hence, this chapter aims to provide the detail of the methodology used to achieve the research objectives.

3.2 Research Workflow

This research project involves 5 phases of studies which involved the literature reviews, preliminary study, finite element model modelling, finite element model analysis and result. The research methodology flowchart is shown in Figure 3.1.

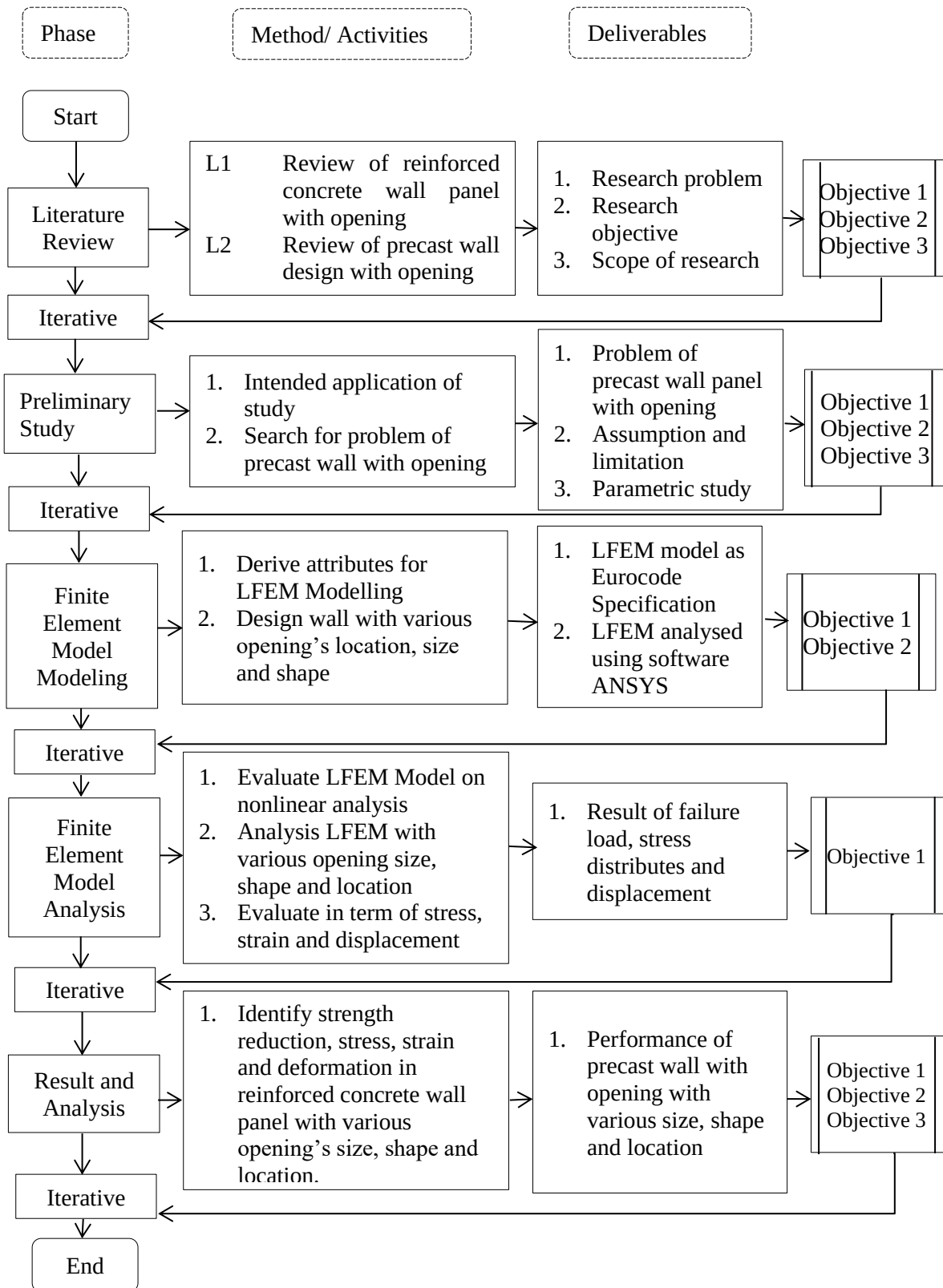


Figure 3.1: Research methodology flowchart

3.3 Geometry

The general dimension of the wall panels in this research are 1000 mm long, 750 mm tall and 150 mm thick as shown in Figure 3.2. This dimension for solid wall panel is based on the study conducted by Fragomeni and Mendis (1997). The thickness of 150 mm is modeled in this study since the reinforced concrete wall panel was assigned with two-layer of reinforcement. The study for the solid wall panel was then extended to the wall panels with opening with variation in size, shape and different location in order to evaluate for the effect of opening towards the strength of the wall panel. The wall modelling with 10% ratio of the opening was taken to configure the opening at different locations. The wall modelling with opening were designed with no additional steel reinforcement around the opening. This is deliberately simulating the on-site cut-out opening. The opening was first created centrally on the wall panel. Then, the opening manipulated for its shape and location. There are five set of precast wall models considered in the analysis: opening in different size, opening with different shape, change of opening location in vertical direction, change of opening location in horizontal direction and change of opening location in diagonal direction. In this research study, the LFEM was used to predict the failure load, the load- deflection response and the deformed shape for the walls with both opening and no opening respectively. Figure 3.3 shows the geometry attributes of the opening in the reinforced concrete wall panel which is derived from the calculation based on Equation (3.1) and Equation (3.2). Equation (3.1) was applied to calculate the distance between centre of gravity of solid wall and the centre of gravity of wall with opening in x direction whereas Equation (3.2) was applied to calculate the distance between centre of gravity of solid wall and the centre of gravity of wall with opening in y direction.

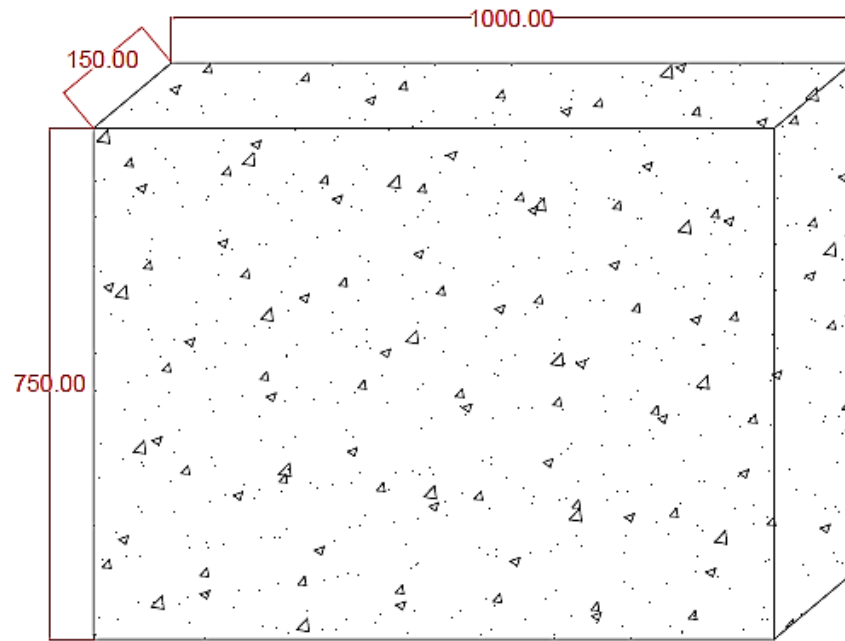


Figure 3.2: 3-Dimension of the concrete wall panel.

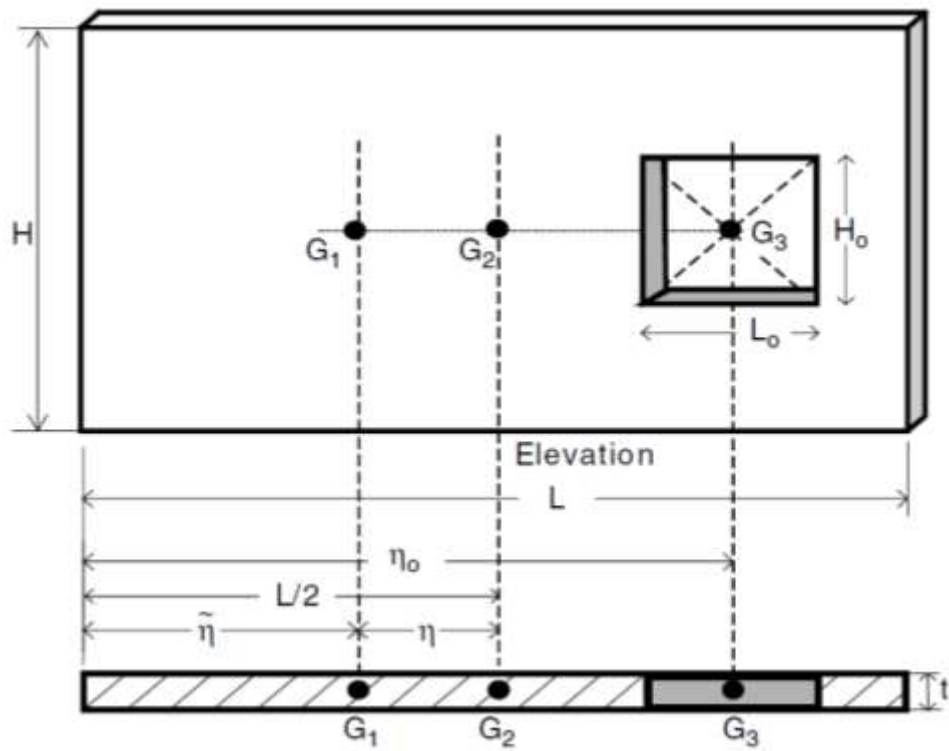


Figure 3.3: Geometry of reinforced concrete wall panels with opening

$$\tilde{n}x = \frac{\frac{1}{2}tL^2 - tL\eta_0}{Lt - Lot} \quad (3.1)$$

$$\tilde{n}y = \frac{\frac{1}{2}tH^2 - tH\eta_0}{Ht - Hot} \quad (3.2)$$

Where, ηx = Distance between centre of gravity of solid wall and the centre of gravity

of wall with opening in x direction

ηy = Distance between centre of gravity of solid wall and the centre of gravity

of wall with opening in y direction

H = Height of the wall

L = Length of the wall

t = Thickness of wall

H_o = Height of the opening

L_o = Length of opening

G_1 = Centre of gravity of wall with opening

G_2 = Centre of gravity of solid wall

G_3 = Centre of gravity of opening

3.3.1 Size of the Opening

In this research study, there are seven different geometry configurations of reinforced wall panel models with different opening size ratios as shows in Figure 3.4. The wall panels are named accordingly as Panel W0 as the solid reinforced wall panel; Panel W1 with 1% of opening size ratio; Panel W2 with 2% of opening size ratio; Panel W3 with 3% of opening size ratio; Panel W4 with 4% of opening size ratio; Panel W5 with 5% of opening size ratio; Panel W6 with 10% of opening size ratio and Panel W7 with 20% opening size ratio. Panel W0 is subjected to use as controlled modelling in this study. The geometry selection on these

seven reinforced wall panel modelling are purposely to represent the utilization of these configurations of precast wall panels in the nature of construction industry of which the wall panels W1, W2, W3 W4 and W5 are usually selected for ventilation system while panels W6 and W7 represent the window opening sizes. The opening size ratio is calculates based on Equation (3.3).

$$A_o = \frac{L_o \times H_o}{L \times H} \times 100\% \quad (3.3)$$

Where A_o = Opening size ratio (%)

H_o = Height of the opening (mm)

L_o = Length of opening (mm)

H = Height of the wall (mm)

L = Length of the wall (mm)

By taking the Panel W6 as an example for the detail calculation based on Equation (3.3),

$$A_o = \frac{L_o \times H_o}{L \times H} \times 100\%$$

$$A_o = \frac{275 \times 275}{1000 \times 750} \times 100\%$$

$$= 10\%$$

Therefore, the dimension of the 10% square opening size is with height of 275 mm and length of 275 mm. The detailed calculations with respect to the geometrical dimensions for each wall panels are in Appendix A.

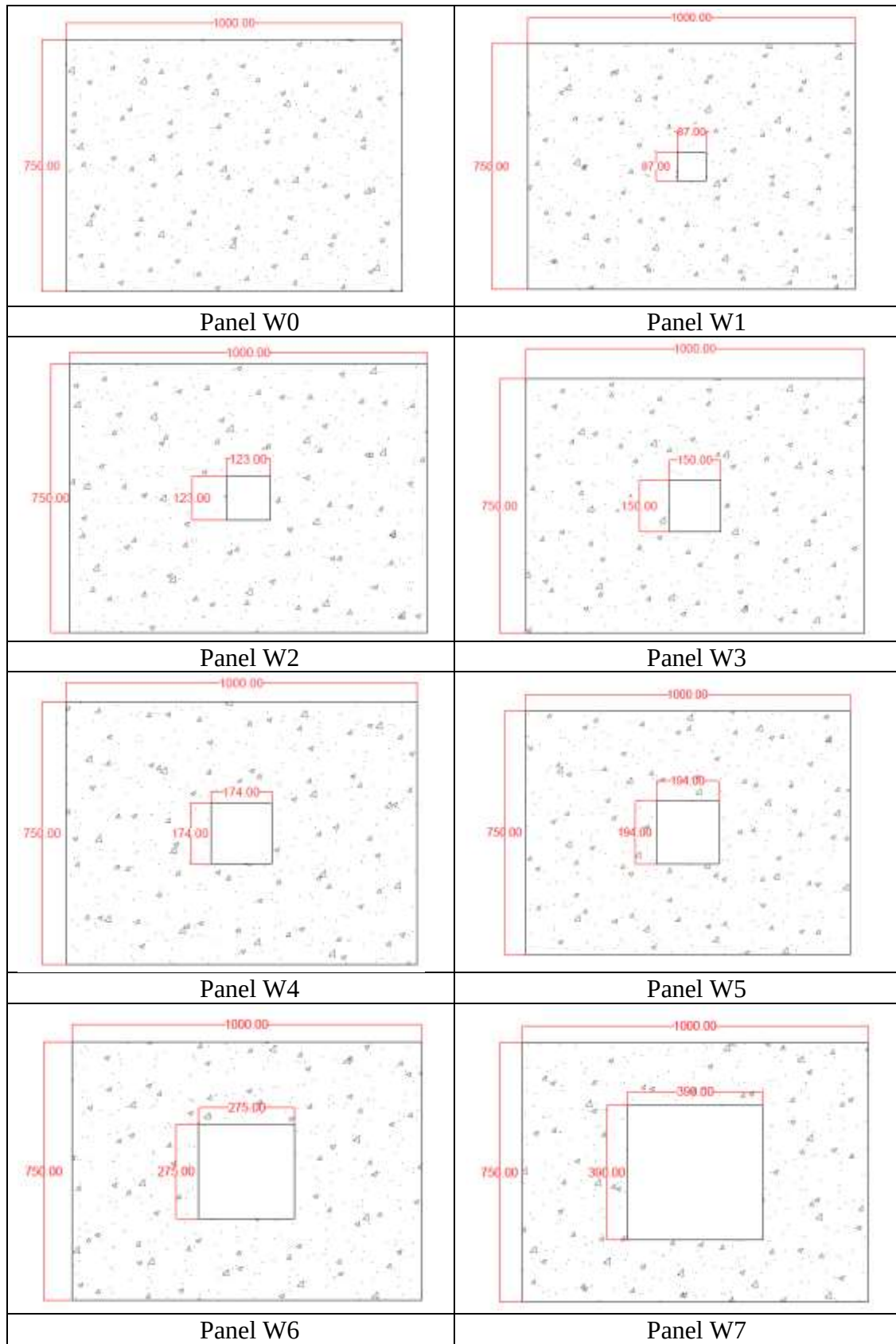


Figure 3.4: Geometry of reinforced concrete wall panels with different opening sizes ratio

3.3.2 Shape of the Opening

In order to evaluate on the shape of the opening in the reinforced concrete wall panel towards its behavior, the wall panel with 10% of opening (Panel W6) was selected for further study and converted into various opening shapes. Figure 3.5 shows the wall panel modelling with different shapes of opening. The 10% opening was designed into the fillet corner of which Panel W8 with radius of 45 mm fillet corner and Panel W9 with radius of 75 mm fillet corner. The circular opening namely Panel W10 with radius of 155 mm. The Panel 11 is the wide rectangular with length of 388 mm and height of 194 mm while Panel W12 is the slit rectangular opening with length of 194 mm and height of 388 mm. These modelling with different configurations of opening shapes are used to represent the aspect of functional or architectural designs and aesthetic value practiced in the construction of building structures. The configuration for each opening shape was derived by taking the 10% of opening size ratio as the reference. Equation (3.4) is used to calculate the dimension sizes for various shapes of opening.

$$A_o = \frac{\pi \times \left(\frac{L_o}{2}\right)^2}{L \times H} \times 100\% \quad (3.4)$$

Where A_o = Opening size ratio (%)

L_o = Length of opening (mm)

H = Height of the wall (mm)

L = Length of the wall (mm)

By taking the Panel W10 with circular shape as an example for the detail calculation based on Equation (3.4),

$$\begin{aligned} A_o &= \frac{\pi(155^2)}{1000 \times 750} \times 100 \\ &= 10\% \end{aligned}$$

Therefore, the circular dimension is with 155 mm radius. Appendix A shows the designated calculations for each shapes of wall opening in the reinforced concrete wall panels.

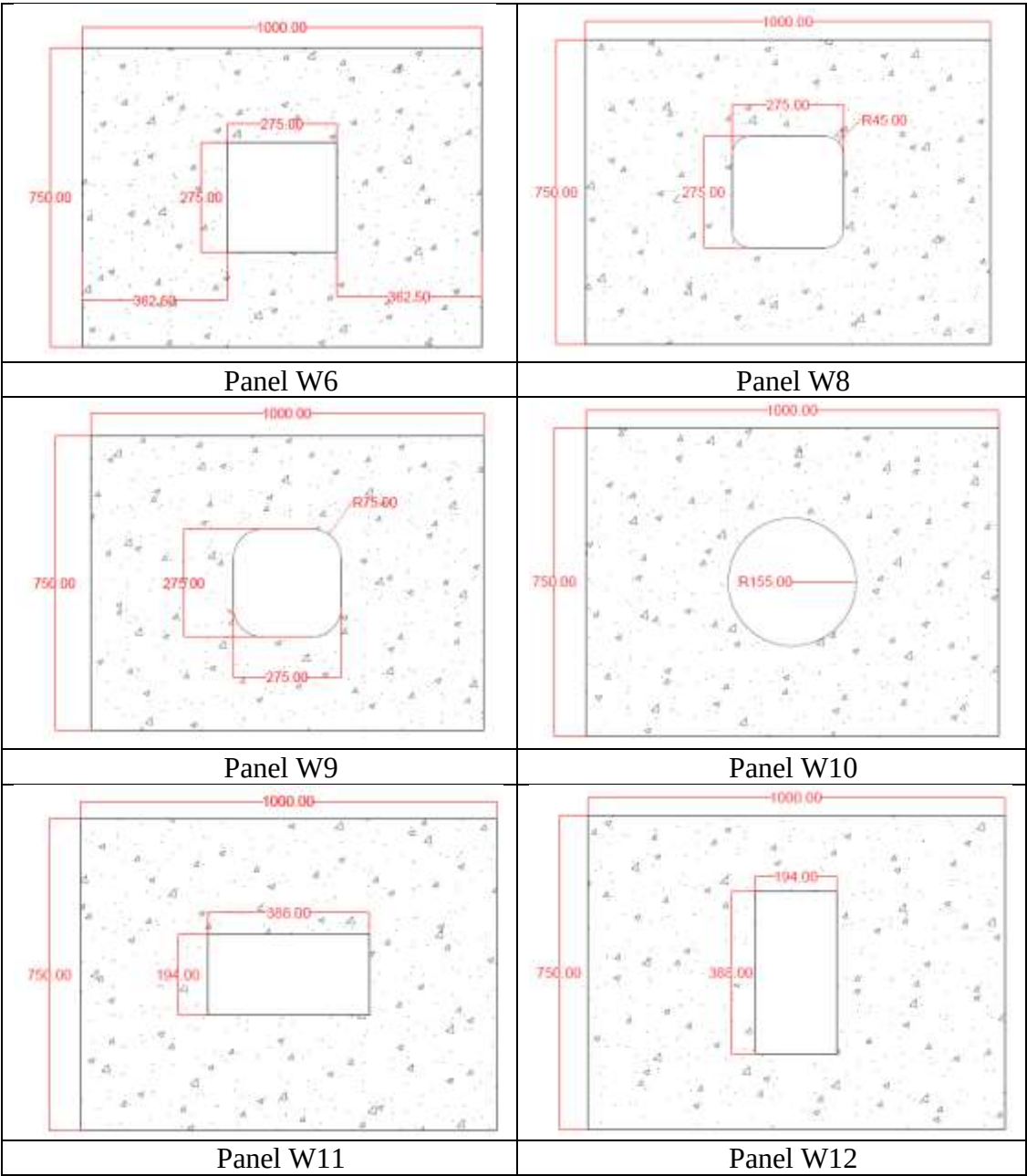


Figure 3.5: Geometry of reinforced concrete wall panels with different shape of opening

3.3.3 Location of the Opening

Figure 3.5, Figure 3.6 and Figure 3.7 illustrate the locations of the opening which were relocated in the direction towards horizontal, vertical and diagonal respectively. The different locations of opening in the reinforced concrete wall panels were modelled to represent the situations of which the opening utilized in the wall panel in real practice that is not exactly created at the centre of the wall panel. Same as the previous analytical techniques, the reinforced concrete wall panel with 10% of opening size, Panel W6 was selected to extend the study in this section.

As shown in Figure 3.6, the opening in the reinforced concrete wall panel is shifted in horizontal direction towards the left. Panel W6 is the wall panel with 10% opening at the centre. Then, the 10% opening size is shifted to the left from the centre by 50 mm as shown in Panel W13. Panel W14 with the 10% opening size is situated towards the left from the centre by 100 mm while Panel W15 with the 10% opening size is shifted to the left from the centre by 137.5 mm. Panel W16 with the 10% opening has opening position to the left from the centre by 150 mm and Panel W17 with the 10% opening size is located towards the left from the centre by 212.5 mm. The geometrical dimensions for each respective models of reinforced concrete wall panels are shown in Table A.3 (Appendix A).

Besides, Figure 3.7 shows the 10% of opening size is shifted vertically downward and upward. Same as previous, Panel W6 with the 10% of opening size located in the middle of the wall panels is acts as the control sample. There are all total of 8 samples of modelling with 4 samples of wall modelling undergoing the shifting of opening in vertical downward direction and the corresponding 4 samples which show the shifting of opening in vertical upward direction. For Panel W18, the 10% opening size in the wall panel is located at 30 mm in vertical downward direction from the centre. The opening is then moved 50mm

downward vertically in Panel W19 and 75 mm downward in Panel W20. Panel W21 shows the position of opening at 87.5 mm vertically downward direction. Meanwhile, panels, W22, W23, W24 and W25 each shows the location of opening in the reinforced concrete wall panel which are relocated by 30 mm, 50 mm, 75 mm and 87.5 mm in upward direction respectively. The derivation of the geometrical dimension for the wall panels with variety configurations are shown in Table A.4 (Appendix A).

Figure 3.8 shows the location of the 10% opening size shifting in diagonal direction towards the south-west and north-west directions. Panel W26 shows the 10% opening size which is shifting in south-west directions with 194.45 mm whereas Panel W27 shows the 10% opening size which is located at 265.17 mm in the south-west direction. The opening in Panel W28 has moved towards the south-west with 300.52 mm. Similarly, to the shifting of the 10% of opening size in the wall panels due to the south-west directions, the opening has relocated in 194.45 mm in north-west directions in the Panel W29 and 265.17 mm in the north-west direction for Panel W30. Panel W31 shows the location of opening size in 300.52 mm due to the north-west direction in the wall panel. Table A.5 in Appendix A tabulates the detailed calculations in obtaining the various locations for the opening in shifted in diagonal direction due to the south-west and north-west positions in the reinforced concrete wall panels.

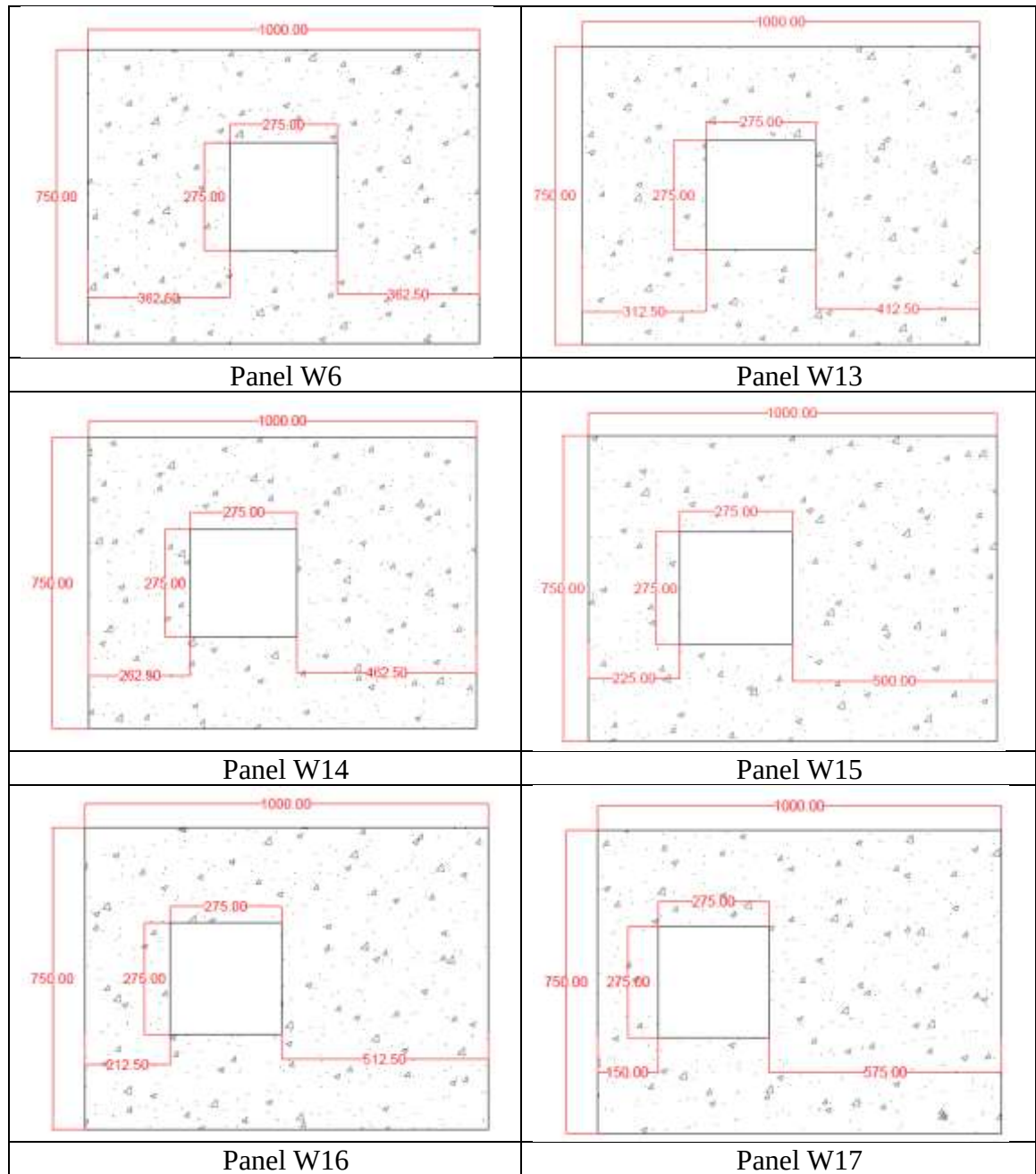


Figure 3.6: Geometry of reinforced concrete wall panels with opening shifting horizontally

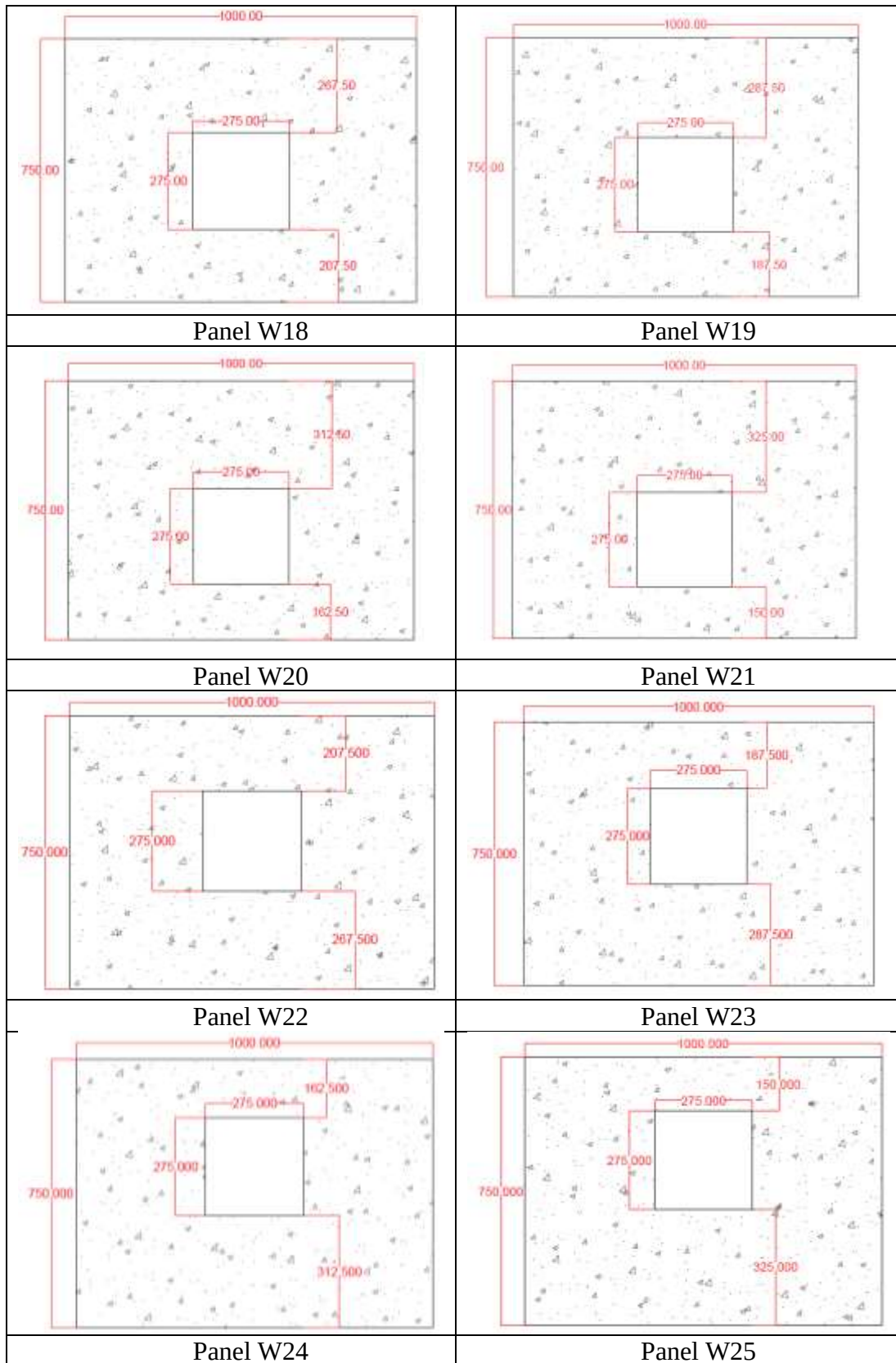


Figure 3.7: Geometry of reinforced concrete wall panels with opening shifting vertically

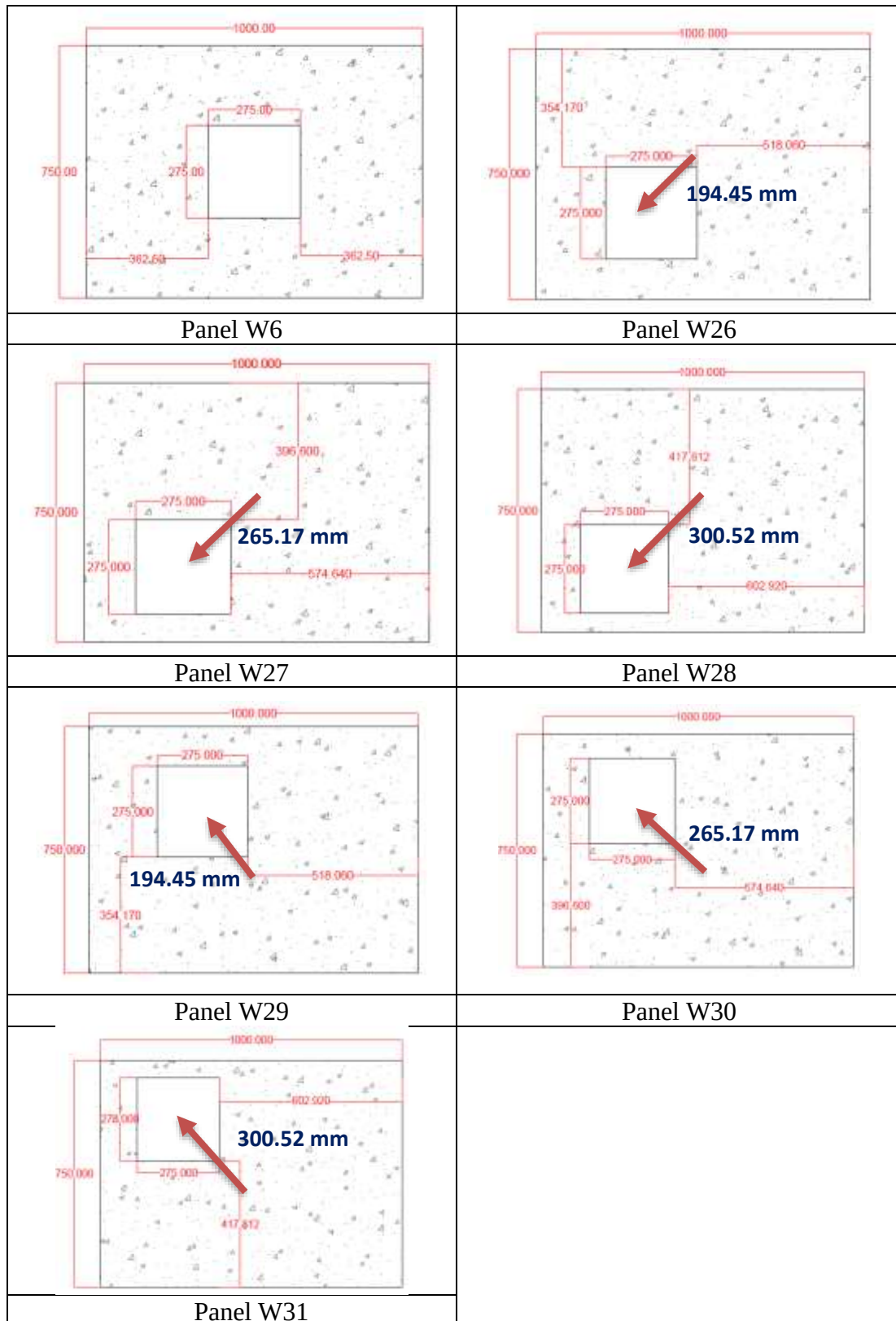


Figure 3.8: Geometry of reinforced concrete wall panels with opening shifting diagonally

3.3.4 Reinforcement Ratio

In this research study, the thickness of the wall models is subdivided into five layers of concrete and reinforcement with various thickness. The thinnest layer of concrete at both outer faces to act as the concrete cover while another thickest layer of concrete at the centre of the wall. Steel reinforcement layers were sandwiched at both faces respectively after the concrete layer. The wall has double layers of reinforcement ratio as shown in Figure 3.9. The reinforcement layers are modelled as a non-linear structural steel which are placed in each respective face with constituted of 0.15% from the 150 mm wall cross-sectional area. The concrete cover is 20 mm. The concrete strength was designed as 32 MPa.

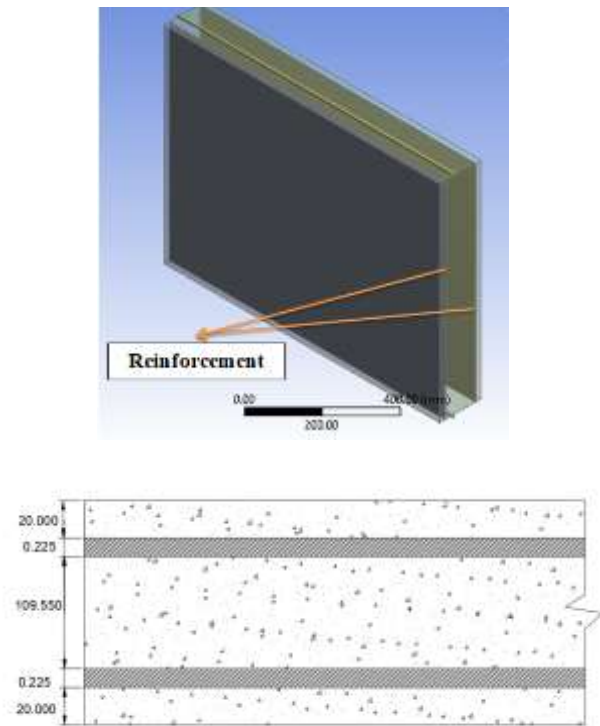


Figure 3.9: Double layers of reinforcement

The ratio of the reinforcement is depending on the thickness of the wall panel. Since the ratio of this modelling was fixed on 0.15% on each respective face. So, the design formula is shown as below.

$$\frac{A_R}{A_w} = 0.15\%$$

$$\frac{1000 \times t}{1000 \times 150} = \frac{0.15}{100}$$

$$t = 0.225\text{mm}$$

Where A_R = Area of reinforcement thickness

A_w = Area of wall thickness

3.3.5 Mesh

The modelling is assigned with the nonlinear mechanical properties to reveal the nonlinear properties of the composite reinforced concrete wall panel. The meshing covered the wall models was generated through the software and it must be controlled to ensure the entire nodes in each layer and slide of the different materials was connected. The mesh connections were generated by using the Detect Mesh Connections option as shown in Figure 3.10.

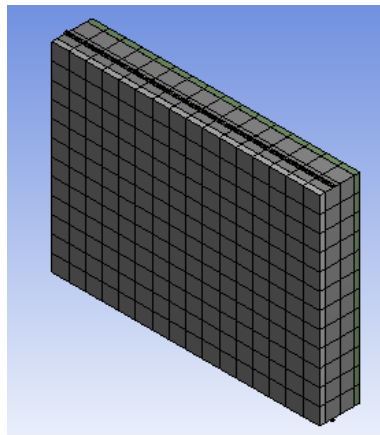


Figure 3.10: Meshing on the reinforced concrete wall

3.3.6 Modelling Considerations

There are several considerations and assumptions during the modelling process. These considerations were prior upon to create a model that is similar in both functionality and designation as the real practice of precast wall panel in the construction industry. These considerations included:

- i. The walls behave non-linearly where concrete and reinforcement behave as non-linear material.
- ii. Concrete was considered as homogenous material and the critical stress was analysed in the concrete.
- iii. Perfect bond was created between the reinforcement and concrete layers.
- iv. Vertical load was applied as uniform loads in an eccentricity of $t/6$.

3.3.7 Material Models

Table 3.1 shows the specified concrete material properties as the general non-linear material concrete material prototype in ANSYS software. However, Table 3.2 shows the specified steel material properties as the general non-linear structural steel material prototype in ANSYS software.

Table 3.1: Concrete strength parameter (Eurocode 2)

Density	Young's Modulus	Poisson's Ratio	Bulk Modulus	Shear Modulus	Compressive Strength
2300 kgm-3	30 GPa	0.18	15.625 GPa	12.712 GPa	25 MPa

Table 3.2: Reinforced steel strength parameter (Eurocode 2)

Density	Young's Modulus	Poisson's Ratio	Bulk Modulus	Shear Modulus	Tensile Strength
7850 kgm-3	200 GPa	0.3	166.67 GPa	76.92 GPa	350 MPa

3.3.8 Boundary Condition

In real practice, each precast wall must be supported at the bottom end of the wall. This is because the loading subjected to that wall will be transmitted downwards until it reaches the foundation. Same case in this study, the bottom edges of the concrete wall modelling were assigned with the fixed support.

For the model in ANSYS, the load was applied at an eccentricity of the $t_w/6$. A 10 mm radius steel rod is assigned on the top and bottom of the wall panel to achieve the same eccentricity of the loads. This was illustrated in Figure 3.11.

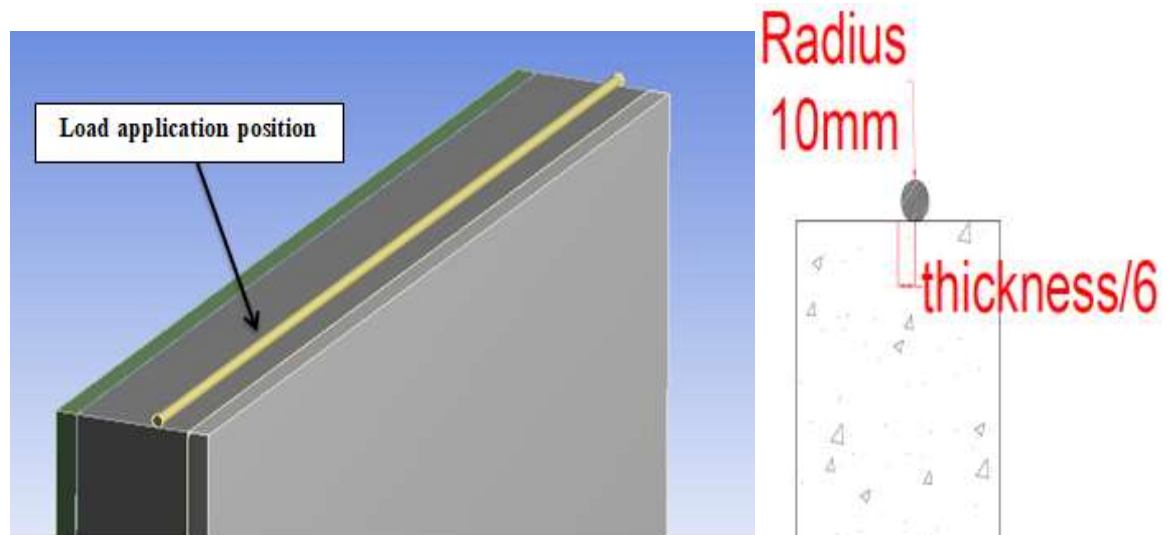


Figure 3.11: Steel rod applies on the top of the wall to achieve eccentricity load.

The loading in the model is subjected to structural loading. Axial force is chosen and applied to the underlying steel rod on the top of the wall panel to transfer the load to uniform eccentricity load. The loading per unit line is assigned as the uniform distributed load with $t/6$ eccentricity.

3.4 Terms for Result Analysis

3.4.1 Stress Distributions

ANSYS software provides three types of stress distribution results, namely, equivalent (Von-Mises) stress, shear stress and maximum principal stress. In this research, all the results shown for equivalent (Von-Mises) stress, shear stress and maximum principal stress will be recorded respectively with respect to its effects toward the wall panels with opening.

As the modelling structures of this research study involved the composite non-linear materials, which included the combination of concrete and reinforcement materials with perfect bond, therefore, the modelling walls behave as non-linear analysis. In the non-linear analysis, the wall panels subjected to fail when it is subjected to different types of stress and complex combination of stresses. Therefore, it gives rise to different types of stresses at different points in the structures. In this research study, the location of the maximum points for stress distributions will be analysed and evaluated for variety configurations of opening size and location.

Equivalent (Von-Mises) stress is used to measure and estimate the yield stress failure criteria mainly the fatigue properties of ductile materials for instance the steel reinforcement in this research study. However, the fatigue properties of the modelling structures are beyond the scope of study. Thus, the results displayed was aimed to provide complement for the information obtained.

Shear stress distributions will also not be used for the analysing of results since the modelling structures was assumed to be acted by normal axial forces. However, it was included in the results data as it can used to represent the imperfection of the acting force towards the modelling structures.

For maximum principal stress, it was referred to the normal stress acted upon the wall panel as discussed earlier of where the axial force will be applied uniformly on the panel. Therefore, in this aspect, the maximum and minimum stress distribution pattern existed on the software analysis will be identified and evaluated in this research study. In addition, the maximum value of normal stress can be referred as major principal stress whereas the minimum value of normal stress can be referred as the minor principal stress. In this research study, the 3D principal stress will be analysed. In the software analysis, the maximum principal stress always represented the most tensile stress whereas the minimum principal stress represented the most compressive stress in wall modelling. Therefore, the study of the location for the maximum principal stress distribution will be focused on steel reinforcement layer since it is the layer to provide the tensile strength with ductile material in nature for the concrete and the yield deformation will be achieved by the steel layer first in order to create a better bond with the concrete and go to a large extension before final collapse and it showed a prior indication of failure. However, the minimum principal stress which represented the most compressive stress will always occur at the concrete layer since the concrete performed as brittle properties and acted as axially loaded compression member in the composite wall modelling. Thus, this research will identify all the positions for the occurrence of minimum principal stress in all various types of wall modelling to undergo the evaluation and results analysis.

3.4.2 Strain Distributions

As stated in 3.4.1 for stress distributions, ANSYS software also provides three types of strain distribution results, namely, equivalent (Von-Mises) strain, shear strain and maximum principal strain. In this research, all the results shown for equivalent (Von-Mises)

strain, shear strain and maximum principal strain will be recorded respectively with respect to its effects toward the wall panel and prior to wall panel with opening.

Same as the method described for stress distributions, the positions of the points resulted from shear strain and equivalent strain will be recorded. But only the maximum principal strain distributions will be analysed and evaluated for variety configurations of opening sizes and locations. Apart from the same method to record the results of the stress distributions, it is important to focus on the positions of both points of maximum and minimum principal strains will be occurred at the concrete layer since the outcomes from the ANSYS software always showed the results of principal strain in terms of maximum and minimum compressive strains. In correspondence, compressive strains will only showed in concrete material since it is non-linear, non-elastic and brittle material which is strong in compression but very weak in tension.

3.4.3 Deformation

Deformation is another focused aspect need to be recorded in this research study. Deformation referred to the change in the shape of the wall modelling which was caused by the application of an external forces or stresses, and in this case was the normal axial forces that acted to the wall. Deformation is always related and proportional to the forces applied within the elastic limits of the material. In this research, it is importance to identify the types of support of the wall either fixed supported in order to direct the relationship towards the position of occurrence of maximum deformation. This is because the types of support will affect the deformation and failure axial loads of reinforced concrete wall panel. In this study, the value of deformation was analyses by the ANSYS software. The degree of deformation is measured from the neutral axis of the wall panel to the edge of bending of wall.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

In this chapter, the results obtained are presented into three main parametric studies, which include the data analysis on the variation of opening size, the configuration of different shape and the location of the opening on the reinforced concrete wall panels. In this research study, an LFEM analysis was used to carry out the data collection and analysis in order to explain the parameters that affect the behavior of reinforced concrete wall panel. Stress, strain and displacement which are obtained from the LFEM are used to explain the behaviour of the reinforced concrete wall panel due to the parametric geometric configuration on the reinforced concrete wall panels. In addition, the empirical results obtained are discussed and evaluated in order to investigate the relationship between the geometric parametric configurations towards the behaviour of the wall panels, particularly for wall panels with openings. The findings obtained in this research study can be used as a reference towards the practicable on-site modification or cut-off opening for precast wall panels.

4.2 Configuration of Reinforced Concrete Wall Modeling

Table 4.1 shows the configuration of reinforced concrete wall modeling used in this research study. As stated earlier in Chapter 3, this research study is aims to evaluate the behavior of the reinforced concrete wall panels with opening under one-way axial loads by extending the parametric studies into different size, shape and the location of the opening on the reinforced concrete wall panels. Therefore, a total of 31 samples of wall panels have been modeled by using the LFEM analysis. To identify the behavior of the reinforced concrete

wall panel with different size, a total of 7 wall panels have been configured. It included the W0 as the solid reinforced concrete wall panel without opening (controlled sample); W1 for reinforced concrete wall panel with 1% of square opening ratio; W2 with 2% of square opening ratio; W3 with 3% of square opening ratio; W4 with 4% of square opening ratio; W5 with 5% of opening ratio; W6 with 10% of square opening ratio and W7 with 20% of square opening ratio.

To assess the effects due to the shape of opening on the performance of the reinforced concrete wall panels, there existed a total of 5 different shapes of opening being cut-out on the reinforced concrete wall panels. By taking the Panel W6 as a reference, the 10% opening size ratio has been converted into 10% of square opening ratio with fillet 45 mm as W8 and fillet 75 mm as W9. The panel W10 is the 10% of circle opening ratio while W11 is the panel with 10% of wide rectangular opening ratio and W12 is the wall panel with 10% of slit rectangular opening ratio.

In order to identify the effects on the strength of the reinforced concrete wall panels due to the location of opening, three different movement of opening have been configured. These included the shifting of the opening towards horizontally to the left, vertically upwards and downwards, and inclined to south-west and north-west. Constantly, the opening with 10% of square opening ratio is taken as the reference in this part of study. Panel W13 with 10% of square opening ratio has been shifted 50 mm to the left and W14 involved the movement of the opening 100 mm to the left. For Panel W15, the opening has been allocated 137.5 mm to the left and the opening in W16 is allocated 150 mm to the left and continued to move to the left by 212.5 mm in W17. There existed a total of 8 samples used to study the effects of opening when it is shifted upwards and downwards. These included W18 of which the opening shifted 30 mm downward; W19 with opening shifted 50 mm downward; W20 with

opening shifted 75 mm downward and W21 with opening shifted 87.5 mm downward. In corresponding, the opening is shifted in same distance of 30 mm upward in W22; shifted vertically 50 mm upward in W23; 75 mm upward in W24 and shifted 87.5 mm upward in W25. In addition, 6 samples were used to manipulate the opening in the incline direction. Panel W26 involved the inclination of opening towards the south-west with distance of 194.45 mm moved away from the center of the wall panel. The same distance has been moved towards the north-west in Panel W29. Besides, the panel W27 involved the movement of opening at a distance of 265.17 mm towards the south-west and north-west in panel W30. For panel W29, the opening is shifted 300.52 mm inclined south-west. Comparable, the opening is allocated in the same distance of 300.52 mm which is inclined north-west in panel W31.

Table 4.1: Configuration of reinforced concrete wall modelling with different opening sizes

Wall Panel	Configuration
W0	Solid reinforced concrete wall panel without opening
W1	Reinforced concrete wall panel with 1% of square opening ratio
W2	Reinforced concrete wall panel with 2% of square opening ratio
W3	Reinforced concrete wall panel with 3% of square opening ratio
W4	Reinforced concrete wall panel with 4% of square opening ratio
W5	Reinforced concrete wall panel with 5% of square opening ratio
W6	Reinforced concrete wall panel with 10% of square opening ratio
W7	Reinforced concrete wall panel with 20% of square opening ratio

Table 4.2: Configuration of reinforced concrete wall modelling with different opening shape

Wall Panel	Configuration
W6	Reinforced concrete wall panel with 10% of square opening ratio
W8	Reinforced concrete wall panel with 10% of square opening ratio (Fillet 45mm)
W9	Reinforced concrete wall panel with 10% of square opening ratio (Fillet 75mm)
W10	Reinforced concrete wall panel with 10% of circle opening ratio
W11	Reinforced concrete wall panel with 10% of wide rectangular opening
W12	Reinforced concrete wall panel with 10% of slit rectangular opening

Table 4.3: Configuration of reinforced concrete wall modelling with opening shifting horizontally

Wall Panel	Configuration
W6	Reinforced concrete wall panel with 10% of square opening ratio (Centre)
W13	Reinforced concrete wall panel with 10% of square opening ratio (shift 50 mm left)
W14	Reinforced concrete wall panel with 10% of square opening ratio (shift 100 mm left)
W15	Reinforced concrete wall panel with 10% of square opening ratio (shift 137.5 mm left)
W16	Reinforced concrete wall panel with 10% of square opening ratio (shift 150 mm left)
W17	Reinforced concrete wall panel with 10% of square opening ratio (shift 212.5 mm left)

Table 4.4: Configuration of reinforced concrete wall modelling with opening shifting vertically

Wall Panel	Configuration
W6	Reinforced concrete wall panel with 10% of square opening ratio (Centre)
W18	Reinforced concrete wall panel with 10% of square opening ratio (shift 30 mm downward)
W19	Reinforced concrete wall panel with 10% of square opening ratio (shift 50 mm downward)
W20	Reinforced concrete wall panel with 10% of square opening ratio (shift 75 mm downward)
W21	Reinforced concrete wall panel with 10% of square opening ratio (shift 87.5 mm downward)
W22	Reinforced concrete wall panel with 10% of square opening ratio (shift 30 mm upward)
W23	Reinforced concrete wall panel with 10% of square opening ratio (shift 50 mm upward)
W24	Reinforced concrete wall panel with 10% of square opening ratio (shift 75 mm upward)
W25	Reinforced concrete wall panel with 10% of square opening ratio (shift 87.5 mm upward)

Table 4.5: Configuration of reinforced concrete wall modelling with opening shifting diagonally

Wall Panel	Configuration
W6	Reinforced concrete wall panel with 10% of square opening ratio (Centre)
W26	Reinforced concrete wall panel with 10% of square opening ratio (shift 194.45 mm inclined south west)
W27	Reinforced concrete wall panel with 10% of square opening ratio (shift 265.17 mm inclined south west)
W28	Reinforced concrete wall panel with 10% of square opening ratio (shift 300.52 mm inclined south west)
W29	Reinforced concrete wall panel with 10% of square opening ratio (shift 194.45 mm inclined north west)
W30	Reinforced concrete wall panel with 10% of square opening ratio (shift 265.17 mm inclined north west)
W31	Reinforced concrete wall panel with 10% of square opening ratio (shift 300.52 mm inclined north west)

4.3 Ratio of the Opening Size

4.3.1 Failure Load based on Ratio of the Opening Size

In this research study, the failure load of a reinforced concrete wall panels represents the load bearing capacity of the reinforced concrete wall panel of which it is used to predict the conditions under which the reinforced concrete wall panel fail due to the action of external load. The failure of material is commonly classified into brittle failure or knows as fracture and otherwise classified into ductile failure or yield. As stated earlier in Chapter 3 of which the reinforcement mesh is considered as ductile and the concrete is classified as brittle material. Therefore, the failure load in this case is considered as either brittle or ductile. The failure loads are then used to discuss the maximum loads to be supported by different wall panels. In this research study, seven different reinforced wall panels have been designed. The solid reinforced concrete wall panel denoted as W0 has modelled as a controlled wall panel of which the parametric results obtained from the solid wall panel is used as a controlled result and it shows the typical practice load-bearing wall panel in construction

industry. Another six models of reinforced concrete wall panel are designed with different opening ratios, which includes wall panel W1 with 1% of opening size, W2 with 2% of opening size, W3 with 3% of opening size, W5 with 5% opening size, W6 with 10% opening size and W7 with 20% of opening size as shown in Table 4.1. Figure 4.1 shows the failure loads withstood by each of the designed reinforced concrete wall panel with different opening ratio respectively. Based on the results, it shows that the failure load for the 1% opening (W1) is same as the failure load obtained from solid wall panel, which is 2400 kN. The result shows that the 1% of opening ratio is insignificance towards the strength of the wall panels without reducing the failure load. It can be considered as a small opening of which the 1% of opening size causes negligible effect on the reinforced concrete wall panel. Therefore, it is predicted that the behaviour for 1% of opening ratio will always behave as a solid wall panel. The result obtained is concurrent with the previous result obtained from Michael et al. (2002) as stated earlier in Chapter 2.

However, it shows a drastic decline of the failure loads to only 542 kN for the wall with 2% (W2) of opening ratio. The failure load drops 77% across the opening ratio from 1% (W1) to 2% (W2) of opening size. Therefore, it shows that the opening has considerable effect on the behaviour of reinforced concrete wall panel starting from opening with size of 2% onwards.

As compared across the 3%, 4% and 5% opening ratios, 3% of opening size (W3) shows lower failure load of 450 kN as compare to the 4% (W4) and 5% (W5) opening which are 508 kN and 461 kN respectively. The behavior of the opening size of 3% (W3) can be further explained in section 4.3.2 through its maximum principal stress and maximum strain. It is because the maximum principal stress and maximum strain are located at the same point

and it forms the concentrating area of where it creates the weakest point for concrete and reinforcement which leads to cracking and failure happened prematurely.

Apart from wall panel W3 with opening ratio of 3% showing outlying result, the failure loads drop across the wall panels with increasing size of openings. Based on Figure 4.1, the wall panel, W7 with the opening ratio of 20% shows the lowest failure load. Therefore, it can be concluded that the larger opening size on the reinforced concrete wall panel reduces the strength of the reinforced concrete wall panel. Consequently, the failure load decreases when the opening ratio increases.

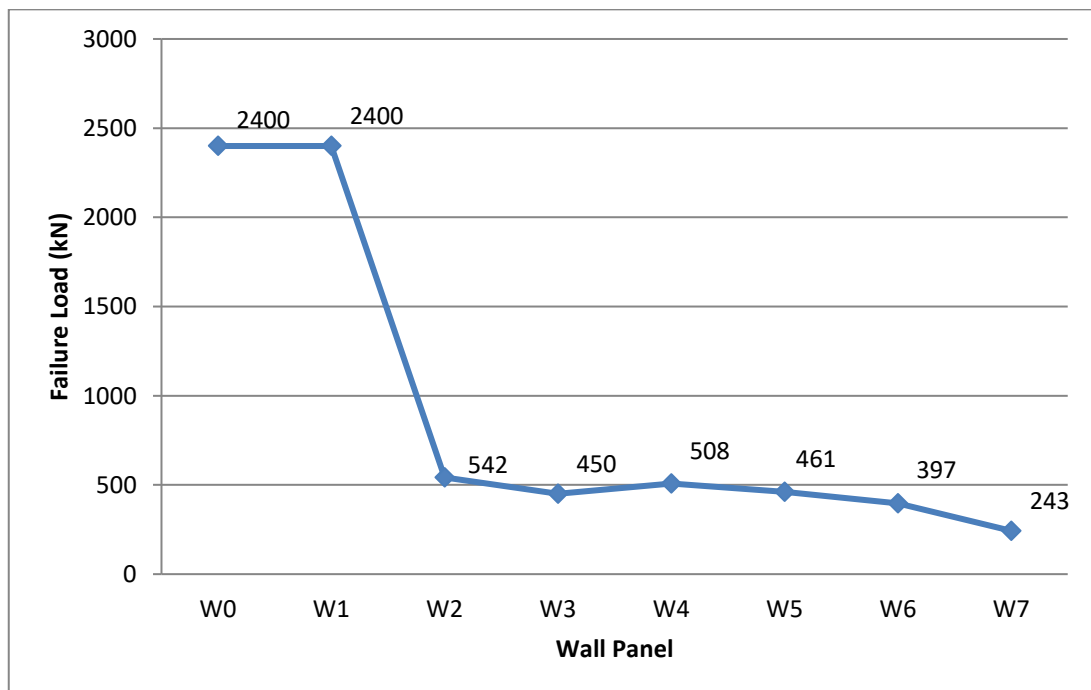


Figure 4.1: Failure load versus Opening Ratio

4.3.2 Principal Stress based on Ratio of the Opening Size

As discussed earlier in Chapter 3 in Section 3.3.1, the maximum and minimum principal stress are used to explain the behaviour of the reinforced concrete wall panel with variety configurations of opening size. Figure 4.2 shows the locations of maximum and

minimum principal stress located in variety of opening size ratio. For all of the opening size ratios, the maximum principal stress located at the steel reinforcement layer while the minimum principal stress located at the concrete layer. This is due to the ability of the reinforcement layer to perform as a ductile material of which intends to resist the distribution stress while the concrete layer with its brittle properties in nature can only use to resist minimal stress level. Therefore, the maximum principal stress always occurs at the reinforcement layer for all the models of reinforced concrete wall panels.

In this research study, the reinforced concrete wall panels are designed in one-way wall support condition. As stated in Chapter 3, one-way wall support boundary condition refers to the wall which is supported laterally and restrained along the top and bottom edges. Therefore, the designed boundary condition has greatly influenced the failure mode of the reinforced concrete wall panel. Due to the fix boundary condition of the wall panel, the solid wall panel and the wall panel with 1% opening (Figure 4.2(b)) showed that the maximum principal stress occurs at the bottom corner of the reinforcement layer in the wall panel. Again, the results emphasis on which the 1% of opening size in the wall panel tends to follow the behaviour of the failure mode as the solid wall panel.

However, for the wall panel with larger opening, namely the 2% opening ratio and onwards (Figure 4.2 (a), (b), (c), (d), (e), (f)), the maximum principal stress distributes at around the opening and positions in the reinforcement layer. Instead, the minimum principal stress locates in the concrete layer. For reinforced concrete wall panel with opening ratio of 2% onwards, all of the positions of maximum principal stress located in parallel ways with the minimum principal stress. The significance of the maximum principal stress is interrelated to the failure loads of the reinforced concrete wall panel.

Referring to Figure 4.1, the solid reinforced wall panel shows highest failure load and the maximum principal stress positions at the bottom edge of the wall panel. It is therefore allowing the solid wall panel to be able to withstand the maximum loads until the failure start to occur at the maximum principal stress at bottom edge. For the concrete wall panel with opening ratio of 3% (Figure 4.2(d)), it shows lower failure loads as compared to opening size with 4% (Figure 4.2(e)) and 5% (Figure 4.2(f)). It can be explained that the position of the maximum principal stress locates symmetrically at the middle above the 3% opening of the reinforced concrete wall panel (Figure 4.2(d)). Thus, the stress concentrating area leads to premature failure for the reinforced concrete wall panel. On the other hand, the larger opening ratio of 4% (Figure 4.2(e)) and 5% (Figure 4.2(f)) create an unsymmetrically regions once the eccentricity loads are applied since the opening size are larger and cause accountable loss of reinforcement areas and thus it does not lead to symmetrical distribution of principal stress as compared to W3 with 3% of opening size.

Figure 4.2 clearly illustrates the consequences of the creation of openings in wall panels. Although the small size of opening, in this case the 1% opening ratio does not cause adverse changes of the position of stress distribution in the wall panel, but it shows deviation in stress distributions in the wall panels with larger opening ratio. The distributions of stress have shifted towards the top of the opening in the wall panels. This is mainly due to the reduction of reinforcement area which causes the decreases in axial strength of the wall panels and impacts on unsymmetrical load distributions while accountable reinforcing steel being removed and causes it to have less ductile properties.

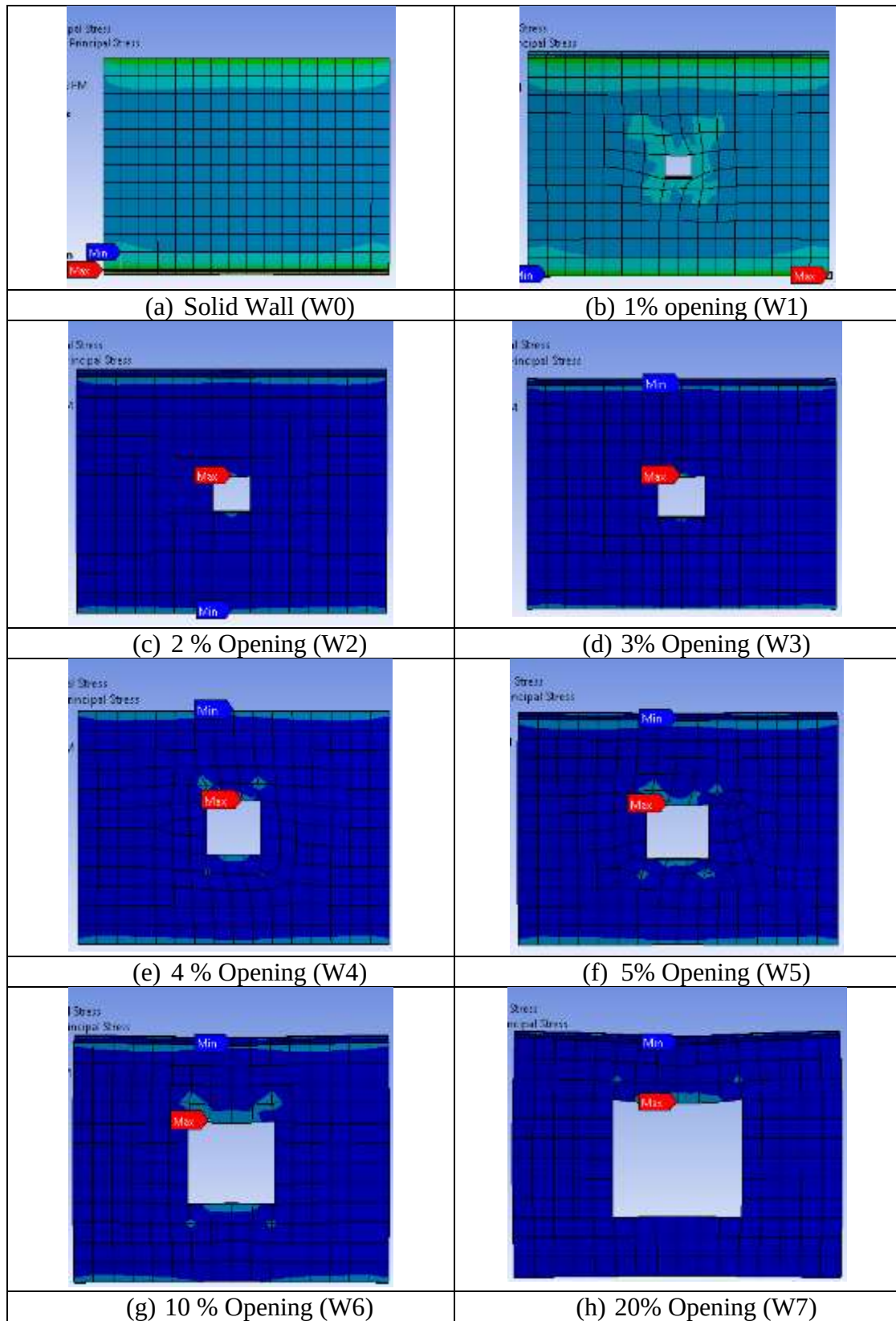


Figure 4.2: Maximum and minimum principal stress for variety configuration of opening size ratio

4.3.3 Principal Elastic Strain based on Ratio of the Opening Size

The maximum principal elastic strain happened at the concrete since the concrete layer is the compression side of the reinforced wall panels. The maximum principal elastic strain for solid wall panel (Figure 4.3(a)) and 1% wall opening ratio (Figure 4.3(b)) is higher as compared to the wall panel with others opening ratio. Therefore, it shows that solid wall panel (Figure 4.3(a)) has the highest compressive force in order to achieve the highest failure loads. The location of the maximum principal strain was located at the bottom edge of the wall panel for the solid wall, wall panel with 1% opening ratio (Figure 4.3(b)) and 2% opening ratio (Figure 4.3(c)).

However, the lower maximum principal elastic strain recorded at the wall panel with 3% of opening ratio (Figure 4.3(d)). The strain value has dropped as much as 80% as compared to solid wall panel (Figure 4.3(a)). Due to the increasing size ratio of opening on the reinforced concrete wall panel, it causes the maximum principal strain to occur at the top of the opening. As analysed across the relationship between the failure loads and maximum principal strain, it shows that the wall panel with 20% of opening size (Figure 4.3(h)) shows the lowest failure loads since the largest opening size caused all the axial loads to concentrate at the layer of concrete and this occurs at the top of the opening size which shows the maximum of principal strain of which the wall panel undergoes the most deformations when it is loaded beyond the yielding point of the concrete wall panel.

Since the maximum principal strain theory always refers to as the yielding in a member when it becomes equal to the strain corresponding to the yield point under the tension in the material which is subjected to complex stress system. In this research study, the maximum principal strain results from the three-dimensional state of stress. Thus, the results outcome from Figure 4.3 represents the geometrical co-related between stress and

strain since strain results from the actions of stresses and for the wall panels, namely W3, W4, W5, W6 and W7, the results clearly show that the maximum principal stress and maximum principal strain are located at the same position of each wall when the axial load is applied on the wall. Consequently, the failure mode occurs at those positions. For W0, W1 and W2, the interrelationship between the locations due to the maximum principal stress and strain can be seen in Appendix B. The deformation is measured by the AnSYS software from the neutral axis to the maximum bending of wall panel.

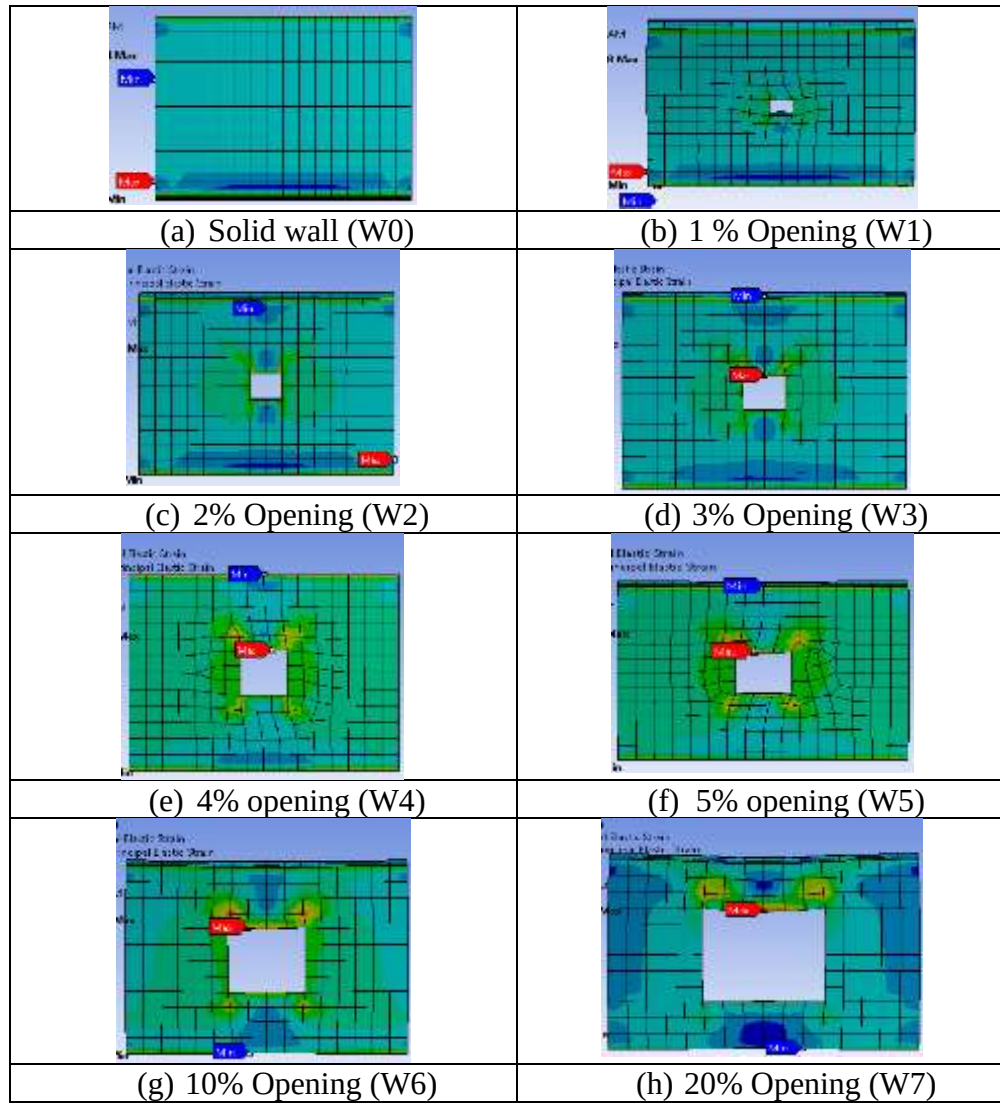


Figure 4.3: Maximum and minimum principal elastic strain for variety configuration of opening size ratio

4.3.4 Deformation based on Ratio of the Opening Size

In this research study, the deformation is used to measure the degree of change of shape of the reinforced concrete wall panels. The deformation of the reinforced concrete wall panels are due to the application of axial loads, results of tensile stress and compressive strain. In general, deformation is often described as strain. The deformation refers to the permanent structural failure. Since all the wall panels are assigned with the eccentric loads, therefore, the direction of the deformation occurred at the sides of where the loads imply. The deformation is measured from the centre to the compression side of concrete wall. The parameter that influences the behavior of the walls is the eccentricity of the load. Solid wall panel can deform in higher magnitude before failure. The magnitude of deformation decreases when the opening ratio increases.

In this research study, the results from Figure 4.4 shows the deformation for the solid wall panel and the wall panel with 1% opening ratio (W0) has dropped from 4.855 mm to 1.926 mm. Although the result values shown for failure loads and maximum principal strain are the same for both solid reinforced concrete wall panel and the wall panel with 1% of opening ratio (W1), but the results for deformation values show great differences between the two types of wall panels. The results indicate that behavior of solid wall panel with non-opening raise the benefit in term of gradual cracking failure or deforms and only will leads to fracture when the loads apply achieves the yielding value or in this case describes as maximum principal stress and strain. However, the lower deformation value registered in reinforced concrete wall panel with 1% of opening ratio (W1) expresses that the wall behaves with the potential of sudden failure or fracture due to the applied load going beyond its maximum principal stress and strain.

As evaluated across the reinforced concrete wall panels with 2% (W2), 3% (W3), 4% (W4), 5% (W5) and 10% (W6) of opening ratios, the wall panel with 3% of opening ratio shows the lowest magnitude of deformation with only 0.388mm as compared to the wall panel of opening sizes with 2% (0.452 mm), 4% (0.454 mm), 5% (0.418 mm) and 10% (0.417 mm). Referring to Figure 4.2 and Figure 4.3, the opening ratio of 3% has created a considerable opening size in very symmetrical way in the reinforced concrete wall panel. Therefore, the axial loads have applied in the concentrate areas in the middle top of the wall panel. Since the wall panel are the composite structures from reinforcement and concrete, it undergoes the symmetrical strain or deformation as the surrounding concrete in order to prevent discontinuity, slip or separation of the two materials under load. Maintaining composite action requires transfer of load between the concrete and steel. The direct stress is transferred from the concrete to the bar interface so as to change the tensile stress in the reinforcing bar along its length. In consequences, it has created a notable earlier deformation in the symmetrical way and thus shows either lower failure loads, maximum principal strain and also the magnitude of deformation. This symmetrical meet point of maximum principal stress and strain at the same section hence weaken the strength of the concrete wall panel and cause premature failure when compare to concrete wall panel with 4% and 5% opening. However, the wall panels with larger opening ratios of 4% (W4), 5% (W5) and 10% (W6) do not cause symmetrical distribution of maximum principal stress and strain happening at the same time in these wall panels since the axial loads cause the deformation happened in the reinforcement layer first than the deformation in concrete layer. This is because the considerable loss of amount of reinforcement areas in these opening ratios have greatly reduced the tensile stress which is used to overcome the axial loads and therefore it tends to extend the magnitude of deformation in the concrete layer. By using the same theoretical

explanation to analyse on the results of deformation value in the wall panel with 20% of opening ratio (W7), it shows the least of magnitude of deformations among all the manipulated types of reinforced concrete wall panels, it deforms only 0.344 mm before failure. This is because the 20% of opening ratio (W7) leads to the highest reduction in the total areas of both reinforcement and concrete of the wall panel and hence reduce the failure load. Thus, the reduced area of the reinforced concrete wall panel causes the small spandrel beam area on the wall panel easily to bend downward and lead to fracture when it is loaded to the maximum load.

As a conclusion between the relationships of failure loads and deformation of the reinforced concrete wall panel, it can be analysed that from Figure 4.1 and Figure 4.4, the profile of both the line graphs show the same pattern of which the solid reinforced concrete wall panel (W0) shows the highest failure loads with highest degree of deformations. Whereas, the magnitude of both failure loads and deformations drops sharply at the model W2 with 2% of opening size in the wall panel. W3 with 3% of opening ratio shows both lower failure loads and deformations as compared to W4 with 4% of opening ratio and W5 with 5% of opening ratio. The least failure load and deformation are in W7 with 20% of opening ratio. Thus, it can be concluded that, the creation of openings in the wall panel can affect the behaviour of the wall. The bigger the size of the opening in the wall panel, the weaker the strength of the wall. The changes of behaviour of the walls are notify as the opening size is larger or equal to 2% of opening ratio as obtained in this research study.

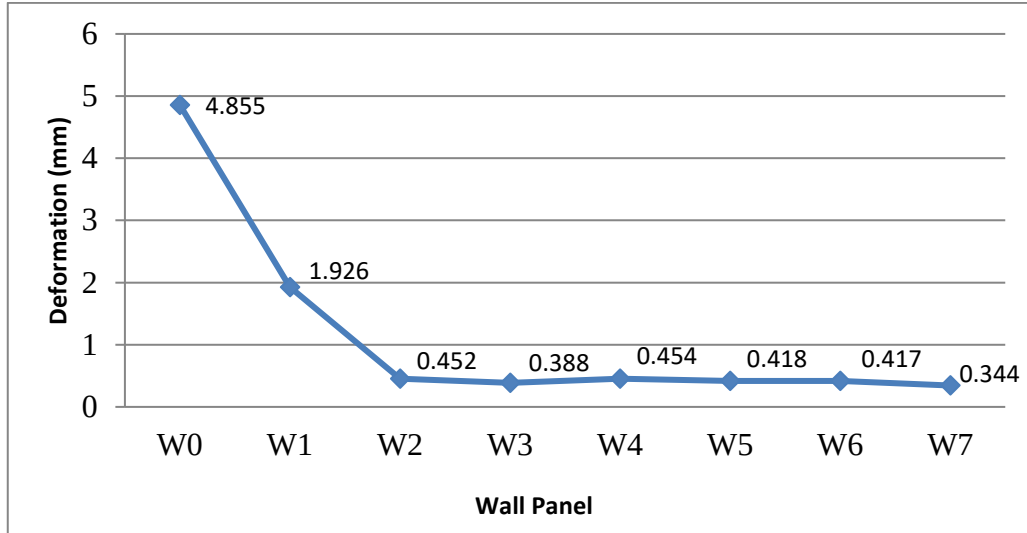


Figure 4.4: Deformation for variety configuration of opening size ratio

4.4 Shape of Opening

4.4.1 Failure Load based on Shape of Opening

The shape of the opening is designed into four typical types of shape, which are square, rectangular, circle and square with fillet. The 10% of the opening was taken for the further study by changing into different shapes of the openings. Figure 4.5 shows the results for the failure loads due to various shapes of openings.

As analysed across the results from Figure 4.5, the wall panel with 10% fillet 45 mm opening (W8) shows the highest failure load of 460 kN. Besides, the reinforced concrete wall panel with the 10% fillet 75 mm opening (W9) also registered the same failure load as 460 kN. The failure load decreases to 408 kN in wall panel with 10% slit rectangular opening (W12). The decreasing percentages of failure loads are about 11%. Then, the failure loads tend to decrease gradually about 3% to 397 kN in 10% of square opening (W6). For the 10% wide rectangular opening (W11) in reinforced concrete wall panel, it only success to withstand the failure loads up to 336 kN. The 10% of circular opening (W10) in reinforced concrete wall panel recorded the least failure loads of 318 kN.

Since the opening ratio for each types of opening shapes is set constant as 10%, therefore, the necessity for the analysis to carry out is particularly to focus on the clear distance creates between the top and bottom spandrel beams to the openings and also both sides clear distance between the piers to the openings. As stated in Chapter 2, when an opening is created in the wall panel, a pier is defined as the column-like cross section of the remaining the wall area (Pospescu et al., 2015a).

By taking the wall model with 10% of square opening (W6) as the control sample since it is the typical practicable shape in the construction industry, it can be seen that the 10% fillet 45 mm (W8) opening and 10% fillet 75 mm (W9) opening can resist higher failure loads. This is mainly due to the 10% of square opening (W6) creating sharp perpendicular edges with 90° and therefore the edges easily cause cracking when the apply loads keep increasing. However, the fillets openings create more smooth edges and have decrease the clear area of the opening at the same time. Consequently, the wall panels can resist higher failure loads since the remaining larger area of spandrel beams and piers with composite tensile and compressive properties are able to withstand the axial loads. In addition, the 10% slit rectangular opening (W12) also can resists failure loads with 3% higher than 10% of square opening (W6). Although the slit rectangular opening also has the sharp perpendicular edges, but it shows higher strength to one-way loads, this is because the slit rectangular opening provides a larger section of structural walls between openings which can function as piers as compare to square opening. The square opening with same length of each sides creates a concentrate area for the distribution of stress and strain when the one-way is apply. Due to this, the wall fails earlier. Yet, the wall panel with 10% wide rectangular opening shape (W11) does not grant higher failure loads as compared to square opening (W6) and slit rectangular opening (W12). This is due to the small piers area provided by the wall panel.

The pier areas usually behave as the column-like structural part to resist the loads applied on it. Based on the results from Figure 4.5, the reinforced concrete wall panel with 10% of circular opening (W10) shows the lowest value of failure loads as compared to the other types of opening shapes. This is because the circular opening with a circle diameter causes the uniform wider opening areas due to wider diameter of opening as compared to square, fillet and rectangular openings. The wider diameter of opening causes all the areas for spandrel beams and piers to decrease. Consequently, the wall panel is unable to resist higher amount of the uniform axial load applied on the wall panel.

The change of the shape of the opening from square to circular decreased the failure load by 20%. The change of the square opening to fillet opening increased the failure load by 16%. The change of square opening to the slit rectangular opening increased the failure load by 3%. The change of the square opening to the wide rectangular opening decreased the failure load by 15%. The comparison between the square and rectangular opening can be concluded that, the slit rectangular opening is better than square opening in one-way wall panel. The results obtained are congruent to the study of Jaseela and Pillai (2017) of which rectangular opening raises the optimum failure loads.

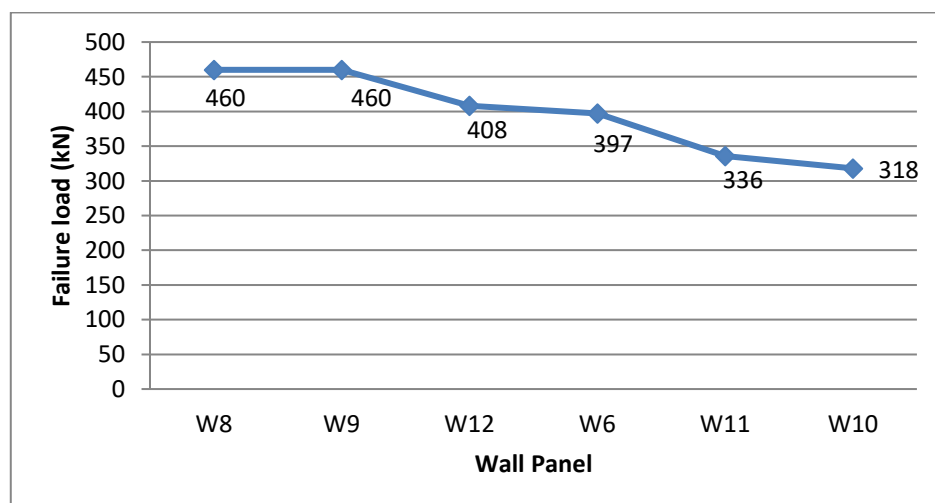


Figure 4.5: Failure load for variety configuration of 10% opening shape

4.4.2 Principal Stress based on Shape of Opening

Figure 4.6 shows the results for the maximum stress distributions in all the models of reinforced concrete wall panels with various opening shape. As stated in Section 4.3.2, the maximum stress distributions occur in the reinforcement layer while the minimum stress distributions happen in the concrete layer. Since different types of opening shapes have shown different values of failure loads, therefore, the location of maximum point for the stress distributions is useful to explain the behavior of the wall panels.

From Figure 4.6, it shows the location for the maximum principal stress in wall panel with 10% of 45 mm fillet opening (Figure 4.6 (b)) is same as the wall panel with 10% of 75 mm fillet opening (Figure 4.6 (c)). Therefore, it justifies the results for both panels of which obtain the same failure loads. For the wall panel with 10% of square opening (Figure 4.6 (a)), it shows the location of which the point for maximum principal stress happens at the top edge of the opening and therefore the failure happen at the top parts of the wall since the distribution of stress concentrate at the top part areas of the wall and shows parts of light-blue based on Figure 4.6. Meanwhile, the wall panel with 10% wide rectangular shape (Figure 4.6 (e)) also shows that the position of the maximum principal stress is located at the top edge of the opening in the wall panel. This has caused the wall to resist the stress concentrations at this area and leads to premature failure.

In comparison, the wall panel with 10% of slit opening (Figure 4.6 (d)) shows the point of the maximum principal stress located at the middle top of the opening. However, it shows less light blue areas as shown in Figure 4.6 with less concentration of stress distribution in the top spandrel beam of the wall panel. This can be explained of which the piers areas at the left and right is wider and provides the stress resistant and thus the wall panel shows higher failure load. Nevertheless, the 10% of circular opening (Figure 4.6 (d))

shows the highest degree of distortion of the reinforcement areas when the circular opening is created. The cut-off of circular shape has distorted the original reinforcement with square-grid forms into disturbed zone. Hence, it causes the discontinuities in the disturbed zone to form cracks easily and this support the results found of which all the wall area due to the circular opening is in light-blue areas as referred to Figure 4.6 of which subjects to higher stress distributions with the maximum principal points located at the top of the opening in the wall panel.

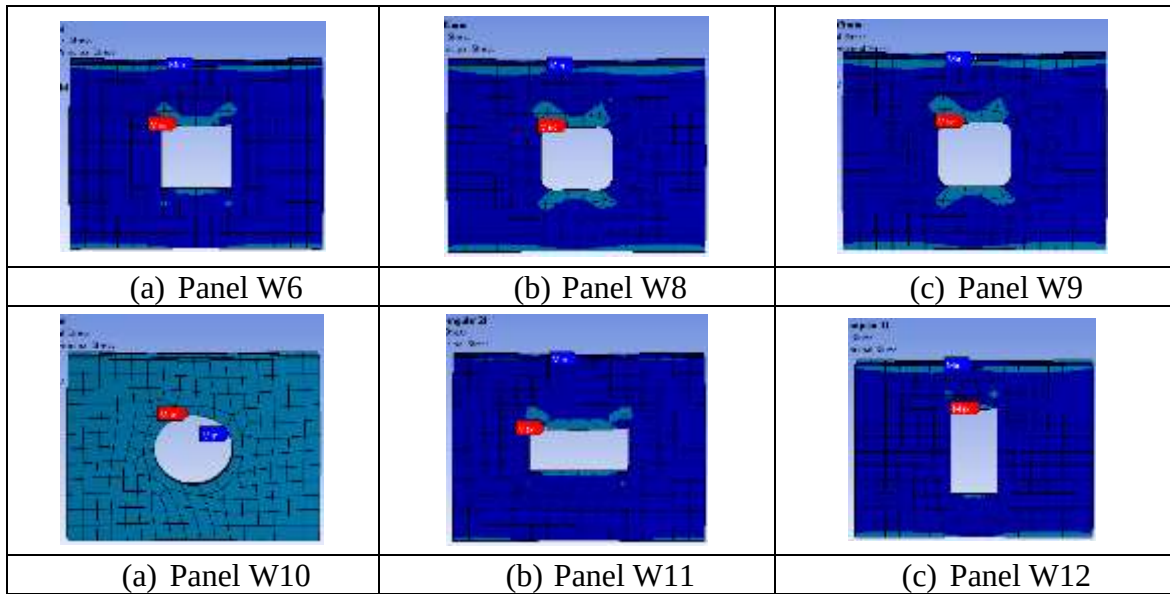


Figure 4.6: Maximum principal stress for variety configuration of 10% opening shape

4.4.3 Principal Elastic Strain based on Shape of Opening

Figure 4.7 shows the maximum strain distribution patterns in the reinforced concrete wall panels with different shape of opening. For the wall panel with 10% of square opening (Figure 4.7(a)), the position of the maximum strain distribution occurs at the same position as the maximum stress distribution as referred to Figure 4.6. Both the reinforced concrete wall panels with 10% of 45 mm fillet opening (Figure 4.7(b)) and 10% of 75 mm fillet opening (Figure 4.7(c)) shows the same position for the occurrence of maximum principal

strain distributions. The location of the maximum principal strain occurs at the top edge of the walls. This is also happening to the wall panels with 10% of slit rectangular opening (Figure 4.7(f)) and 10% of wide rectangular opening (Figure 4.7(e)). The maximum principal stress and strain take place at the same location in the wall panels. Dissimilarly, the wall panel with 10% of circular opening (Figure 4.7(d)) does not show the same locations for the maximum principal stress and strain. Referring to Figure 4.7, the maximum principal strain points at the left edge of the opening.

As compared across the maximum value of principal strains in all the wall panels, the wall panel with 10% of 45 mm fillet (Figure 4.7(b)) and 10% of 75 mm fillet openings (Figure 4.7(c)) show higher strain values with 0.00036 and 0.00022 each respectively. These values indicate the two opening shapes retain the higher failure loads as stated in Figure 4.5 since the wall panels have extend its principal yield strain towards the elastic strain in order to resist the one-way axial loads. Although the 10% of circular opening (Figure 4.7(d)) shows the lowest failure load, but it does not show the lowest strain value. The strain value obtain from 10% circular opening (Figure 4.7(d)) is same as the 10% square opening (Figure 4.7(a)) as 0.00015. These results signify that the strain distributions area are concentrated around the opening region so causes the strain to achieve the yield strain early and thus lowers the failure load. It is worth to mention the result of the wall panel with 10% of slit rectangular (Figure 4.7(f)). Although it shows higher failure load but it shows the least maximum principal strain with only 0.00014. This is mainly due to the shape of the slit opening of which has decreased the upper clear distance between the spandrel beam to the opening, for that reason all the distributions of strain are accumulated at this area and consequently shows least value of maximum strain.

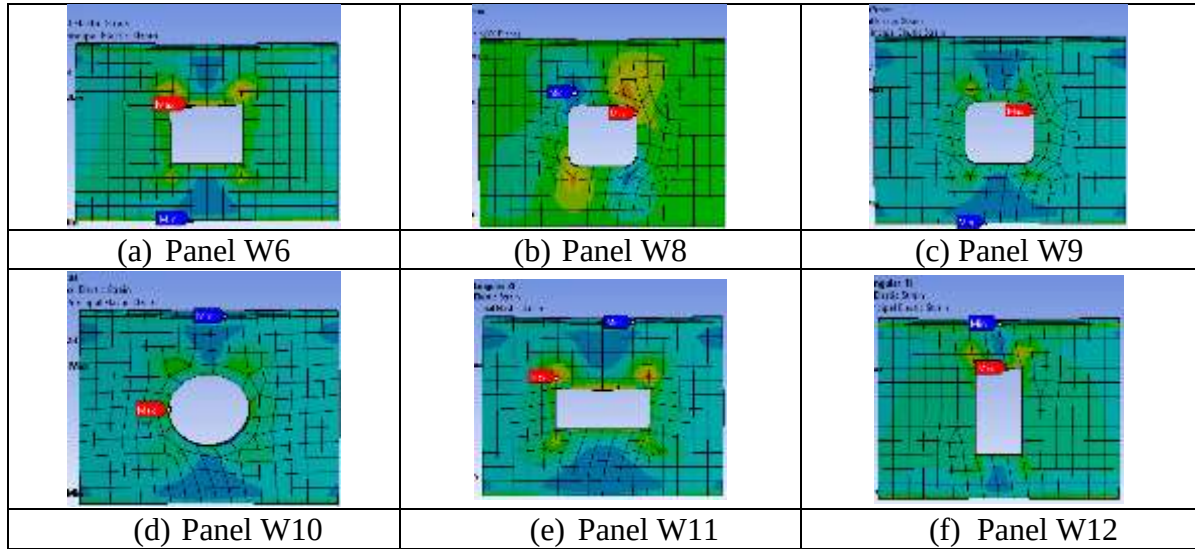


Figure 4.7: Maximum principal elastic strain for variety configuration of 10% opening shape

4.4.4 Deformation based on Shape of Opening

Figure 4.8 shows the results of the deformation value versus the different design of opening shapes in the concrete wall panels. The wall panels, namely W8 with 10% of 45 mm fillet opening and W9 with 10% of 75 mm fillet opening show the same deformation values of 0.475 mm. The slope of the line graph shows the deformation values encounters drastic decrease of 12% to 0.417 mm for wall panel W6 with 10% of square opening. It continues to show gradual decrease to 0.414 mm for W10 with shape of 10% of slit rectangular shape and then decreases again for 0.008 mm to deform at only 0.406 mm for W11 with 10% of wide rectangular shape. Intensely, it deforms at only 0.328 mm for W10 with 10% of circular opening.

From the results shown, its emphases again for both the wall panels with 10% of 45 mm fillet opening and 10% of 75 mm fillet opening have the same behavior due to the effect of shapes of openings. Both wall panels resist the same amount of failure loads and also show the deformation in the same order with the same value. Hence, both wall panels exhibit the highest strength in oppose the one-way axial loads. Besides, the benefits gain from the

wall panel with 10% of slit rectangular shape can also be confirmed as it behaves to retain the higher degree of deformations as compare to the wall panels with 10% of square opening and 10% of wide rectangular opening. Therefore, the wall panel W6 can receive more failure loads as compare to W11 and W12. By gathering all the results for failure loads, maximum principal stress and strains, it complies that the W10 with 10% of circular opening behaves the least strength in counteracting the one-way axial loads.

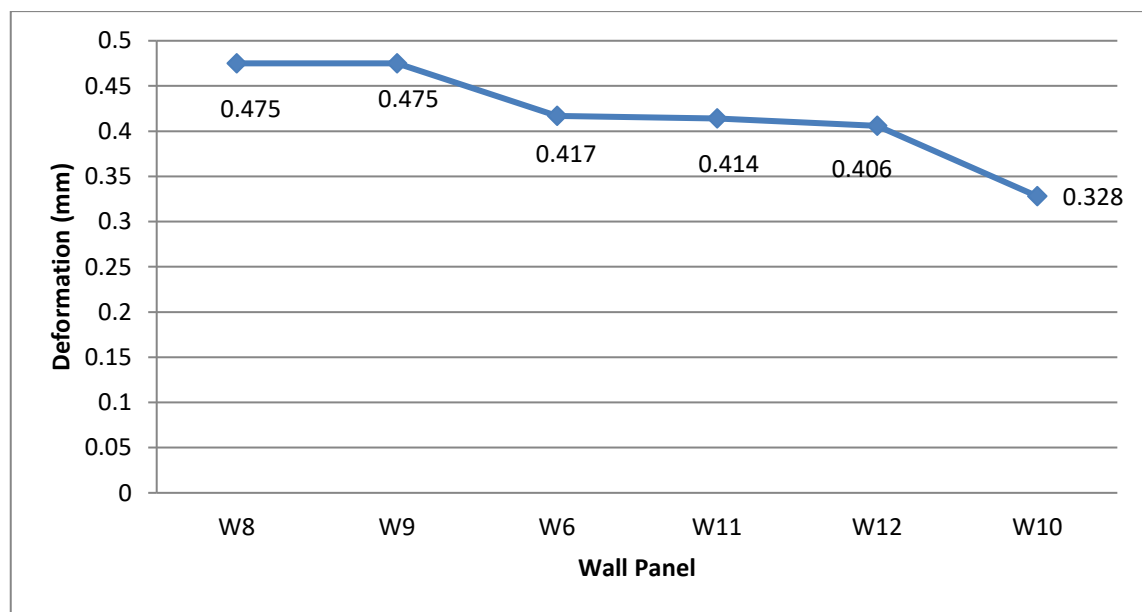


Figure 4.8: Deformation for variety configuration of 10% opening shape

4.5 Location of Opening

This section clarifies the results obtained from the manipulations on locations of opening in the reinforced concrete wall panels. In this research study, the opening in the reinforced concrete wall panel has been configured to three different locations. These involve the shifting of opening horizontally towards the left side of the wall panels, vertically upwards and downwards, and also inclined towards the north-west and south-west directions. 10% of square opening has been constantly used throughout the study on locations of

opening in the wall modelling. In this research study, the results for the failure load obtained from the shifting of opening towards the left also used to represent the results for right shifting configurations since it is theoretical applicable for the conditions to study the behavior of the wall panels with one-way axial loads. In accordance, the shifting of the opening in inclined directions to north-west and south-west also represented the results for shifting the opening in north-east and south-east directions. Both shifting of opening in horizontally and inclined directions were aimed to study the effects of the remaining area for side column-like piers towards the behavior of the wall panels. However, the allocations of opening in the upwards and downwards directions are use to indicate the significance of clear distance between the top spandrel beam and opening towards the behavior in resisting the one-way axial loads.

4.5.1 Opening Shifting Horizontally

4.5.1.1 Failure Load based on Opening Shifting Horizontally

Figure 4.9 shows the results obtained due to the shifting of the 10% of square opening size horizontally towards the left side of the wall panels. Wall panel, W6 consisted of the 10% of square opening cut-out at the center of the wall panel. For the wall panel W13, W14, W15, W16 and W17, the 10% of square opening has shifts to the left by 50 mm (5%), 100 mm (10%), 137.5 mm (13.75%), 150 mm (15%) and 212.5 mm (21.25%) each respectively.

Wall panel, W6 with the 10% square opening cut in the center of the wall showed the failure load of 397 kN, which is the highest reading as compared to other wall panels. When the opening is shifted to the left by 50 mm (W13), the failure load drops from 397 kN to 385 kN. The failure loads decreased by only 3%. The failure load dropped to 380 kN (4% of W6) when the opening is shifted by 100 mm to the left. As the opening shift towards the

left by 137.5 mm, the failure loads dropped sharply to 354 kN (11% of W6) and it continued to drop significantly to only 335 kN (16% of W6) as the opening is shifted to 212.5 mm towards the left side of the wall panel.

The failure load was decreased when the opening in the wall panel is shifted towards left side of the wall panel. This is because to the shifting of locations of the opening also tended to shift the eccentricity of the wall panel. When the opening is shifted to the left side, it has caused the eccentricity of the wall panel to shift to the right side of the wall panel. This condition has created an unbalance point of eccentricity. Consequently, the wall panel undergone premature failure. As referred to the previous manual calculations done in Table 3.3 in Chapter 3, the wall panels which involved the alteration on the location of opening, for instance the W15, W16 and W17 in this case, the shifting of opening's location by more than 100 mm to the left side of the wall have tended to shift the eccentricity of the wall panel to more than 50 mm, which indicated the eccentricity has shifted from center towards the right side in the wall. The deviation of the eccentricity of the wall panel impacted on the decreased in failure loads of wall panels. In conclusion, when the opening is shifted to the left, the width for the left pier has decreased and become narrow. As analysed across the results for the wall panel W15, W16 and W17, it clearly indicated that the width of the left pier decreased to less than $\frac{1}{4}$ of the reinforced concrete wall length. Therefore, the failure load dropped at around 16% from wall panel W6 to wall panel W17.

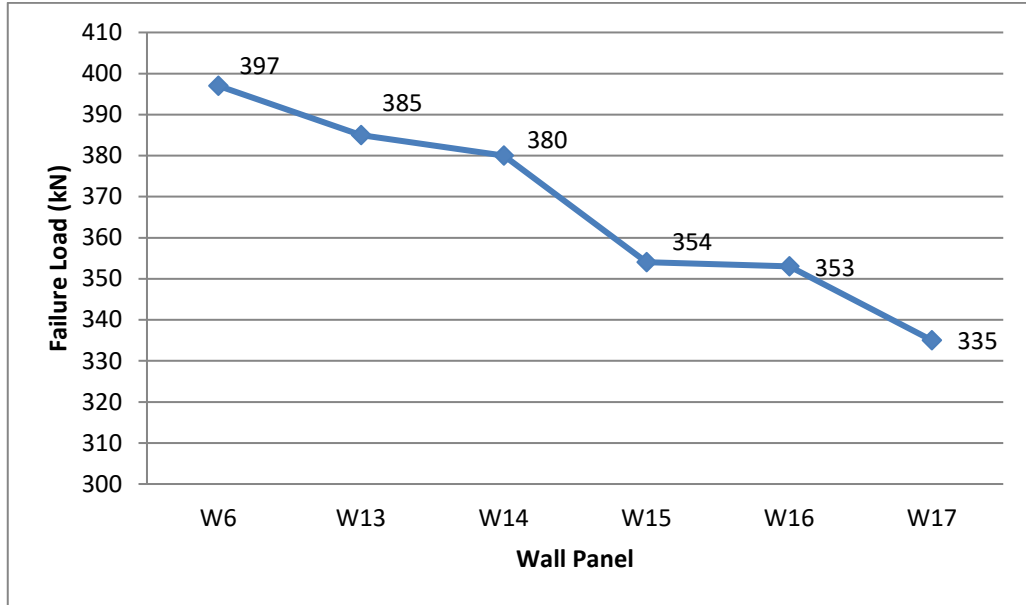


Figure 4.9: Failure load for variety configuration of 10% opening shifting horizontally

4.5.1.2 Principal Stress based on Opening Shifting Horizontally

Figure 4.10 shows the results for the various location of maximum principal stress occurred in the reinforced concrete wall panels. As an overall, the position of the maximum principal stress is existed at the top of the opening in all of the wall panels modelling disregarding the configurations on the location of opening. Same as the previous results obtained, the maximum principal stress was occurred at the reinforcement layer. Therefore, it signified that the reinforcement layer exhibited the tensile stress to resist against the one-way axial loads.

Since the maximum principal stress is located at the edges of the opening, the wall panel becomes critical at the point. The maximum principal stress criterion postulates that the growth of the crack and happened in a direction perpendicular to the maximum principal stress. As stated early in Chapter 2, the results gained from the previous research showed that the opening cracking patterns will be started from the corner of the opening and extended to the unrestrained edge of the wall panel (Doh & Fragomeni, 2010; Doh et al., 2014).

Therefore, the results obtained in this study affirmed the previous research study on the theoretical effects of cracking at the corner of opening was due to the maximum principal stress located near the edges of the opening.

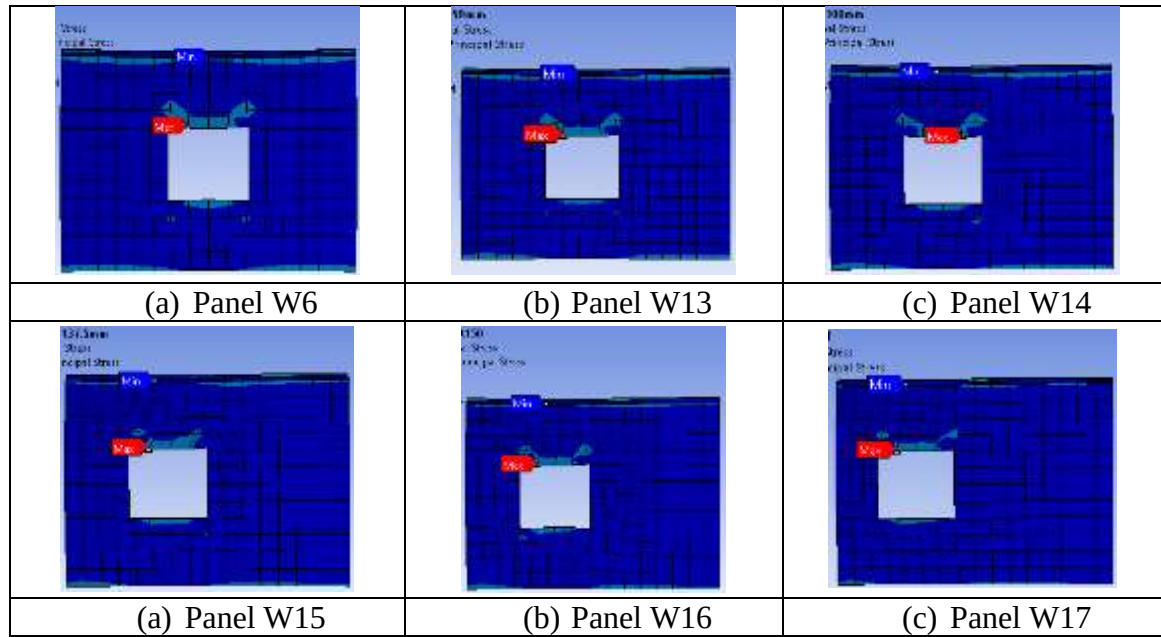


Figure 4.10: Principal stress for variety configuration of 10% opening shifting horizontally

4.5.1.3 Principal Elastic Strain based on Opening Shifting Horizontally

Figure 4.11 represents the results for the maximum principal strain occurred in the reinforced concrete wall panels. The results analysed that the wall panels W6, W13, W14, W15, W16 and W17 have the same maximum principal elastic strain, which are 0.00015. It shows that the magnitude for the maximum principal strain is not affected when the opening is configured to the left side of the wall panel. In addition, the locations for the maximum principal stress and strains are located at the same position in the wall panel. The only differ is that the point for the maximum principal strains is located in the concrete layer while the maximum principal stress is happened at the reinforcement layer.

Since all the wall panels displayed the same value of maximum principal strain disregarding the locations of the opening. Thus, it can be concluded that when the location of opening is shifted towards the left sides of the wall, the wall panels experienced the increasing principal stress rather than strains. Therefore, the maximum principal strains remain the same in the wall panels and at the same time recorded very least strain can be resisted by the concrete layer. However, it behaved to resist the one-way axial tensile stress through its reinforcement layer.

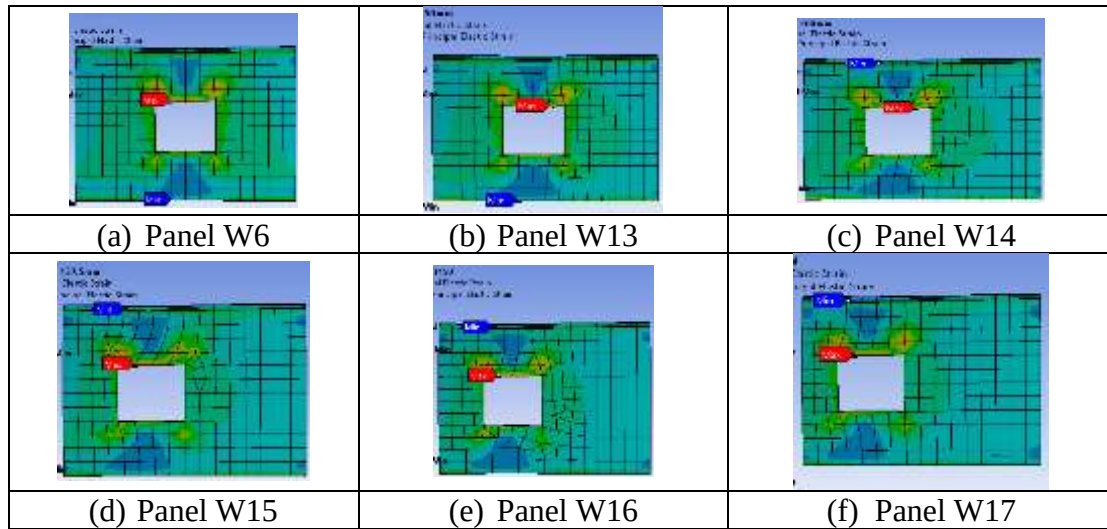


Figure 4.11: Principal elastic strain for variety configuration of 10% opening shifting horizontally

4.5.1.4 Deformation based on Opening Shifting Horizontally

Figure 4.12 shows the tendency of graph for the deformation values against the opening's location in the reinforced concrete wall panels. It tended to slope downwards across the wall panels W6 to W15. Wall panel (W6) with square opening located in the center of the wall showed the deformation as much as 0.417 mm when the one-way axial loads is applied. Then, it has gradual decreased to 0.415 mm when the opening moved to the left by 50 mm (W14). There was a decreased of maximum principal strains to only 0.385

mm (8% of W6) when the opening of the wall panel is shifted to the left by 150 mm. It continued to decrease to 0.378 mm in W17 (shifts 212.5 mm to the left) and W15 showed the least values of only 0.375 mm when it configured about 137.5 mm to the left sides of the wall. As referred to the results obtained from Figure 4.9, the least failure load is recorded in W17 but it behaves to deform the more on displacement. The results indicated that W17 has achieved the ultimate strengths of which it displaced the most whereas W15 has failed in deformations before reached the highest failure load.

As evaluates across the performances of the wall panels towards the failure load, maximum principal stress and strains, and the deformations achievements, it can be concluded that the reinforced concrete wall panels showed different failure load and deformation merely due to the ability of the wall panels to retain its principal maximum stress but not to its maximum principal strains since all of the wall panels showed the same maximum principal strains disregarding of the configurations on the location of the openings in the wall. This is also the reason to explain the behavior on W15 which shows the least values of deformations in this research study.

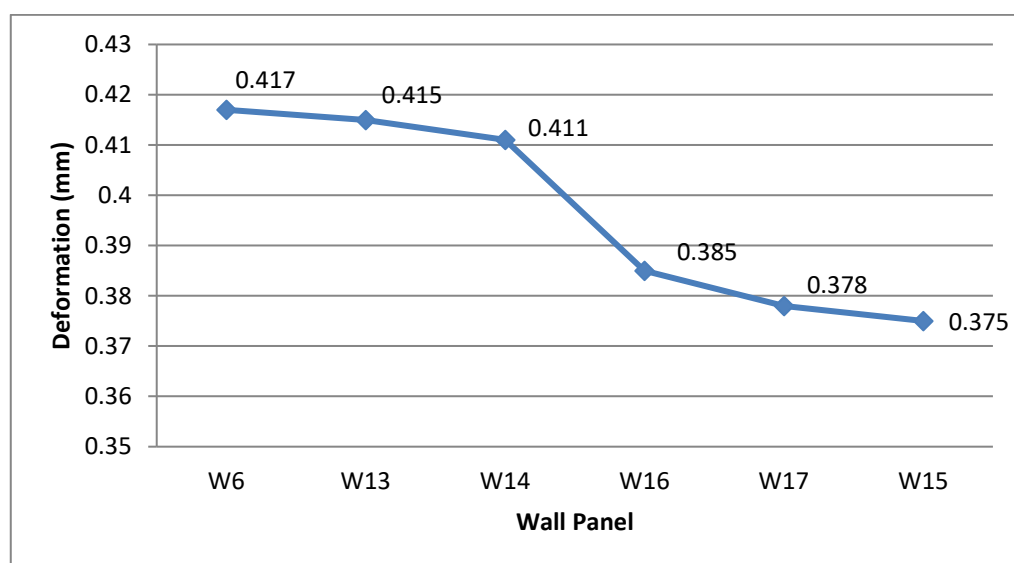


Figure 4.12: Deformation for variety configuration of 10% opening shifting horizontally

4.5.2 Opening Shifting Vertically

4.5.2.1 Failure Load based on Opening Shifting Vertically

Figure 4.13 shows the comparison on the failure load between the wall panels when the opening in the wall panels are shifting vertically upwards and downwards. The wall panel with 10% of square opening at the center of the wall is compared with other wall panels of which the 10% of square opening has shifted downwards and upwards with 30 mm, 50 mm, 75 mm and 87.5 mm each respectively. The blue line graph shown in the Figure 4.13 represented the failure load achieved by each wall panels when the opening is shifting vertically upwards while the red line graph represented the failure load attained by each wall panels when the opening is shifting vertically downwards. The wall panel (W6) with 10% of square opening ratio located at the middle of the wall and is used as the control wall model in this research study.

When evaluates across the failure loads reached by the wall panels W6 and W18, it showed the failure load has increased from 397 kN to 442 kN when the opening is shifted by 30 mm downwards in W18. This failure load has increased at about 11%. But, when the opening is shifted by 30 mm downwards in wall panel W22, the failure load decreased at around 14% from 397 kN to 341 kN. When the opening is configured vertically downwards, for instances the wall panels W18, W19, W20 and W21, the failure load are increased. However, when the opening is shifts vertically upwards from W6 to location in W22, W23, W24 and W25, the failure load is decreased.

From the data analysis, as compared across the wall panels W18, W19, W20 and W21, the wall panel W19 shows the lower failure load of 410 kN. On the other side, when the opening is shifted upward, as compared across W22, W23, W24 and W25, wall panel W23 shows higher failure load of 359 kN. Both wall panels W19 and W23 with opening

located 50 mm vertically downwards and upwards displayed the prominent results with extremely lowest failure loads with 410 kN (W19) and highest failure loads of 359 kN (W23) as compared to others wall panels.

From the Figure 4.13, it can be concluded that when the opening is shifted vertically downwards, the value of failure load is increased because of the spandrel beam area above the opening is also increased. Instead, when the opening is shifted vertically upwards, the values of failure loads is decreased because the spandrel beam areas above the opening is decreased. This is confirmed through the results obtained of which the wall panel W21 with the location of opening at 87.5 mm vertically downwards in the wall panel showed the highest ultimate strength whereas W27 with the location of opening at 87.5 mm vertically upwards the wall panel exhibited the lowest ultimate strength and failed at lowest failure loads of 294 kN. This can be explained in the principal elastic strain, the location of the maximum elastic strain is better on the top of opening while compared to the location at near the bottom edge of the reinforced concrete wall panel.

Hence, it can be summarized that when the opening is shifted downward, the value for the failure load is increased because the spandrel area above the opening is increased. When the opening shifts upward, the failure load value is decreased since the spandrel area above the opening is decreased.

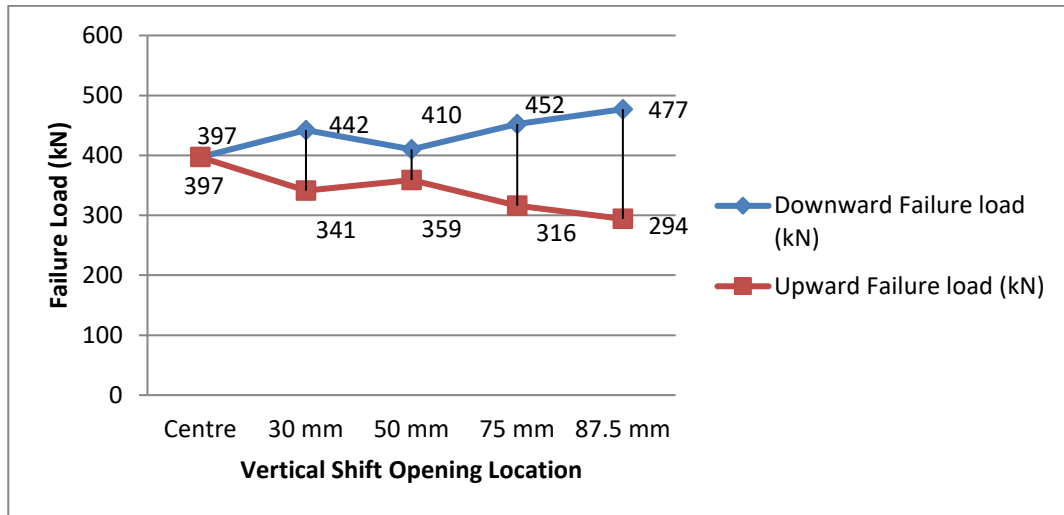


Figure 4.13: Failure load for variety configuration of 10% opening shifting vertically

Table 4.6: Configuration of reinforced concrete wall panel with 10% opening shift vertically

Wall Panel	Centre	30 mm	50 mm	75 mm	87.5 mm
Opening shift downward	W6	W18	W19	W20	W21
Opening shift upward	W6	W22	W23	W24	W25

4.5.2.2 Principal Stress based on Opening Shifting Vertically

Figure 4.14 tabulates the results obtain for the location of maximum principal stress occurred in various types of wall panels when the opening is shifted vertically upwards and downwards in the wall panel. When analyse across the results, it showed that the position of the maximum principal stress is located at the top edges of the opening in the wall panels W6, W19, W20, W21, W23, W24 and W25. However, the position of the maximum principal stress has located at the middle top edges of the opening for wall panels W18 and W22.

For all of the wall panels, the occurrence of the maximum principal stresses is existed in the steel reinforcement layer. Therefore, it affirmed the behavior of the reinforcement layer is to react as tensile strength in the composite wall panels. In addition, the location of the

maximum principal stress constantly occurred at around the top corners of the opening disregarding the configurations on the position of the opening. Hence, the principal stresses always accumulate at the top areas of the opening in the wall panels.

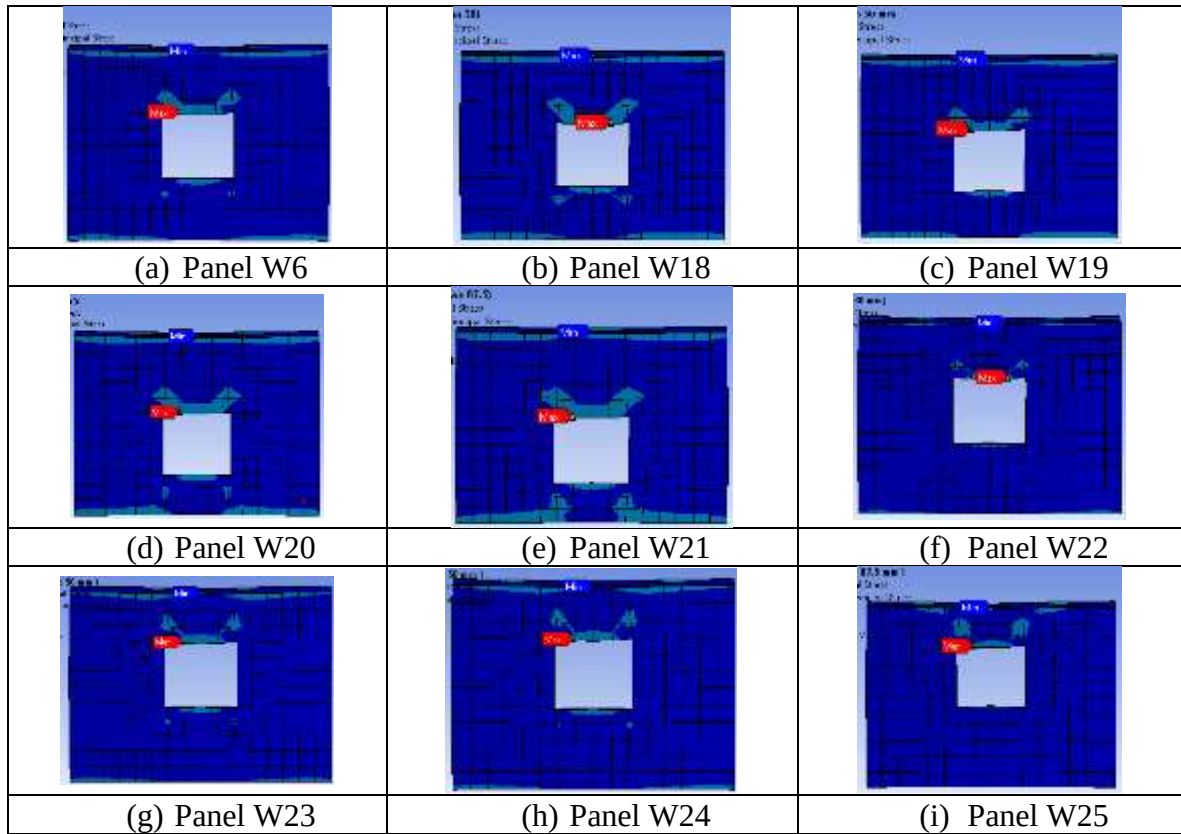


Figure 4.14: Principal stress for variety configuration of 10% opening shift vertically

4.5.2.3 Principal Elastic Strain based on Opening Shifting Vertically

As evaluates across the maximum principal strains in the reinforced concrete wall modelling, it showed that the patterns for the distributions of strains is scattered and not followed in order. For the wall panels W6, W19 and W22, the maximum principal strain happened at the top edges of the opening in the wall panel while the position for the maximum principal strain is located at the middle top of the opening in wall panels W23, W24 and W25. For wall panel W18, the maximum principal strain took place at the bottom

left corner of the wall whereas it located at the right corner of the wall for wall panels W20 and W21.

All the maximum principal strain happened at the concrete layer since it behaved to resist the compressive strains due to the one-way axial loads. The further the position of which the maximum principal strain allocated from the opening area, the more strength the wall panel. Thus, the wall panels W18, W20 and W21 have displayed higher failure loads as referred to Figure 4.13. In corresponding, when the opening is located vertically upwards which is nearer to the top, it caused the top spandrel beam areas to reduce. Therefore, the critical strains happened closer to the top edges of opening in the wall panel.

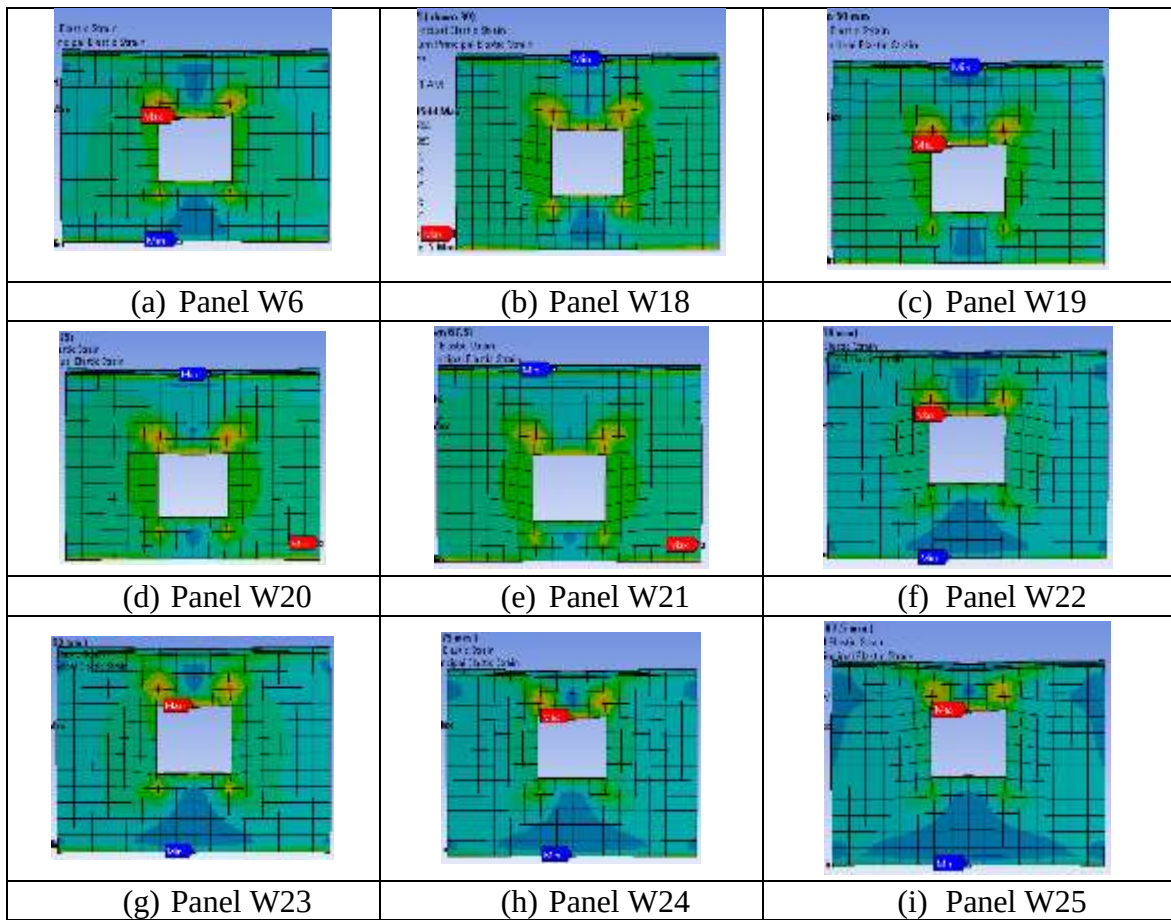


Figure 4.15: Principal elastic strain for variety configuration of 10% opening shifting vertically

4.5.2.4 Deformation based on Opening Shifting Vertically

As a supportive result to clarify the behaviour of the wall panels with the shifting of opening vertically upwards and downwards, Figure 4.16 collected the values of deformations for each of the wall panels. The same tendency of results are obtained as the previous results shown by the failure load in various wall panels as in Figure 4.13.

It shows that the magnitude of deformations are increased across the wall panels W18, W20 and W21 when the opening is shifted vertically downwards from 30 mm to 87.5 mm. But the W19 (50 mm vertically downwards) has showed the extraordinary results with a sudden decreased to 0.443 mm, about 7% as compare to W18. This is same happened to W23 (50 mm vertically upwards) of which it has sudden increased to 0.387 mm, about 6% as compared to W22. However, when the opening shifted vertically upwards from 30 mm to 87.5 mm across the other wall panels W22, W24 and W25, it displayed the decreases in values of deformations. The W21 with the opening shifted to 87.5 mm vertically downwards in the wall panel showed the highest values of deformation of 0.517 mm whereas the W25 with the opening shifted to 87.5 mm vertically upwards in the wall panel showed the lowest values of deformation of 0.312 mm. Thus, the results obtained is compiled to the results obtained for the failure load in Figure 4.13. The wall panel with highest failure load can lead to the highest degree of deformations in order to achieve its ultimate strength. In addition, the wall panel with the opening which is located vertically further away from the one-way axial loads can withstand more loads since the top spandrel beam areas can increase the strength of the wall by providing necessary tensile strength in the reinforcement layer.

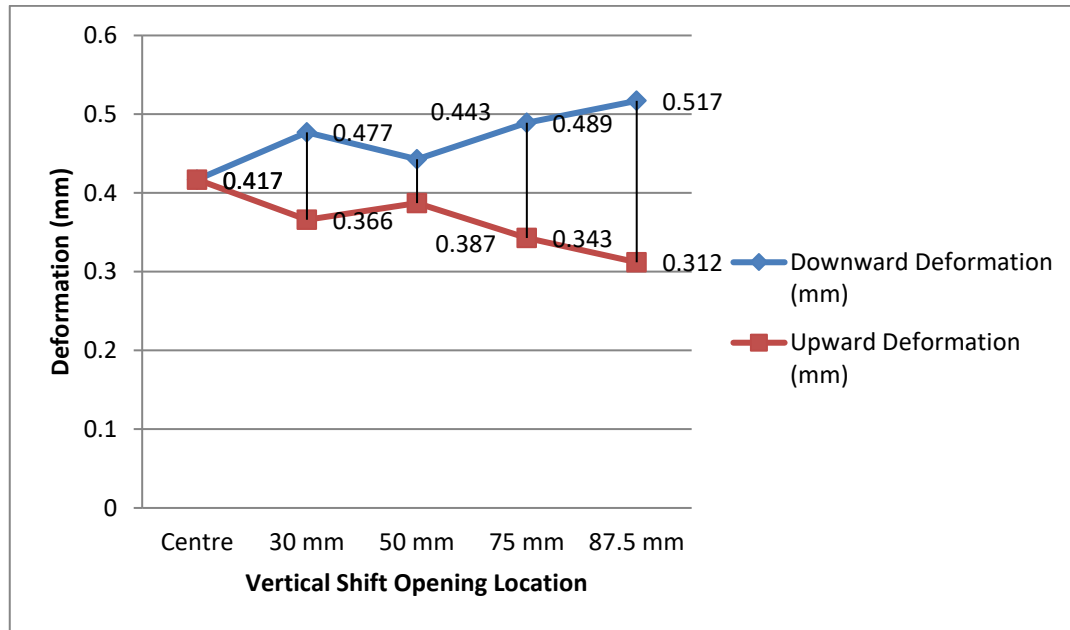


Figure 4.16: Failure load for variety configuration of 10% opening shift vertically

4.5.3 Opening Shifting Diagonally

4.5.3.1 Failure Load based on Opening Shifting Diagonally

Figure 4.17 shows the results of failure load due to the opening in the reinforced concrete wall panel when the opening is configured by manipulated to incline in direction towards south-west and north-west. The wall panel W6 with the opening located at the center is used as the references modelling corresponded to other wall panels. The failure load showed in the W6 is 397 kN.

When the opening in the wall panel is inclined to south-west by 194.45 mm, the failure load have increased to 451 kN with 14% more than W6 with opening at the center. However, when the opening is shifted by increased its distance to 265.17 mm due to south-west (W27), the failure load has decreased to 413 kN. It shows the least failure load by W28 of only 349 kN when the opening is inclined 300.52 mm south-west in the wall panel.

In contrast, the wall panel (W29) with inclination by 194.45 mm towards north-west exhibited lower failure load of 231 kN with 42% less than the failure load shown in the W6.

In between, the failure load tended to decrease to 136 kN when it is shifted to 265.17 mm towards north-west in W30. The lowest failure load shown in W31 with only 65 kN as inclined at a distances 300.52 mm towards the north-west since it is the farthestmost location from the center. Thus, it can be concluded that, the failure load tended to decrease as the opening is moved farther to north-west and south-west.

The results indicated the wall panels with opening located at a distance of 194.45 mm and 265.17 mm due to south-west have higher strength as compared to wall panel with opening at the center. This was mainly due to the larger area provided by both the piers and spandrel beams of which it can provide more strength. However, when the opening is inclined upwards due to the north-west, it did not provide an increase in failure loads. Instead, it showed lower failure loads. Since the inclination of opening towards the north-west has caused the opening to move closer towards the area of where the axial loads are applied. It is therefore, the wall is easier to fail and showed lower failure loads.

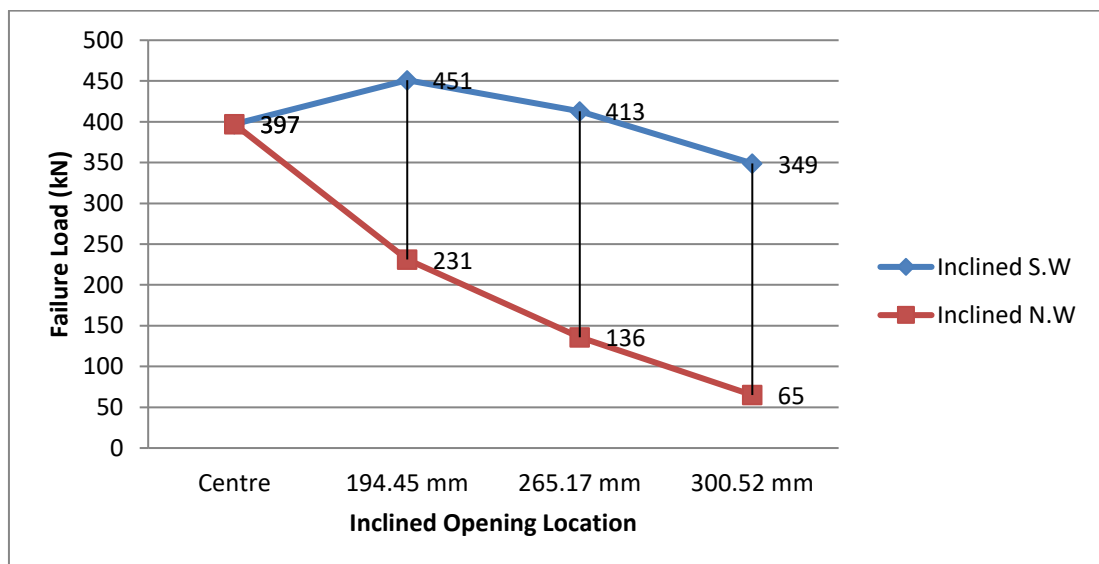


Figure 4.17: Failure load for variety configuration of 10% opening shifting diagonally

Table 4.7: Configuration of reinforced concrete wall panel with 10% opening shift inclined

Wall Panel	Centre	194.45 mm	265.17 mm	300.52 mm
Opening shift inclined South West downward	W6	W26	W27	W28
Opening shift inclined North West upward	W6	W29	W30	W31

4.5.3.2 Principal Stress based on Opening Shifting Diagonally

Figure 4.18 shows the positions of maximum principal stress located in the reinforced concrete wall panels under the one-way axial loads. The results showed that the position of the maximum principal stress occurred at the top edge for the wall panels W6 and W27. For wall panels W26, W29, W30 and W31, the point of maximum principal stress located approximately at the middle top of the opening. Differ from those wall panels, the point of occurrence of maximum principal stress located at the bottom corner of the opening in W28. Same as the previous results obtained, the maximum principal stress in this case also took place in the reinforcement layer. Therefore, it affirmed the behavior of the reinforcement layer to resist against the tensile stress raised by the axial loads.

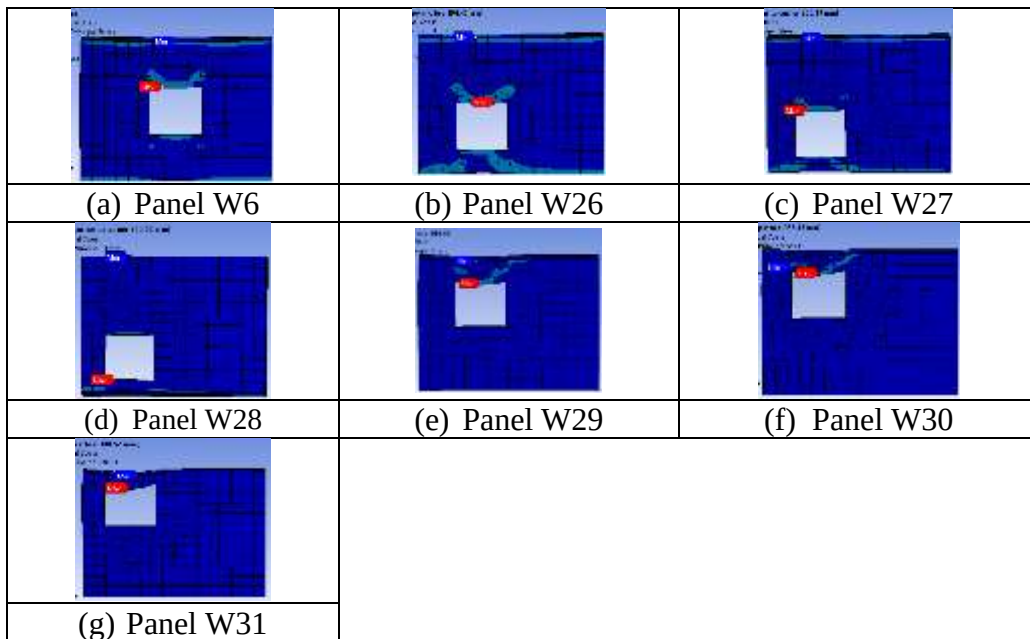


Figure 4.18: Principal stress for variety configuration of 10% opening shifting diagonally

4.5.3.3 Principal Elastic Strain based on Opening Shifting Diagonally

Figure 4.19 shows the location of maximum principal strains in the reinforced concrete wall panels. For the wall panel W6, the point of maximum principal strains located at the top corner of the opening, which is the same position with the maximum principal stress. The point of maximum principal strains located approximately in the middle top of the opening in the wall panels W29, W30 and W31. In addition, as referred to Figure 4.17, these wall panels displayed the same positions for both of the occurrence of maximum principal stress and strains. However, the wall panels W26, W27 and W28 showed discrete points of which the maximum principal strain is located at the bottom corner regions in the walls. The maximum principal strain happened in the concrete layer for all of the reinforced concrete wall panels. Thus, the concrete layer exhibited the compressive strength in resisting the one-way axial loads.

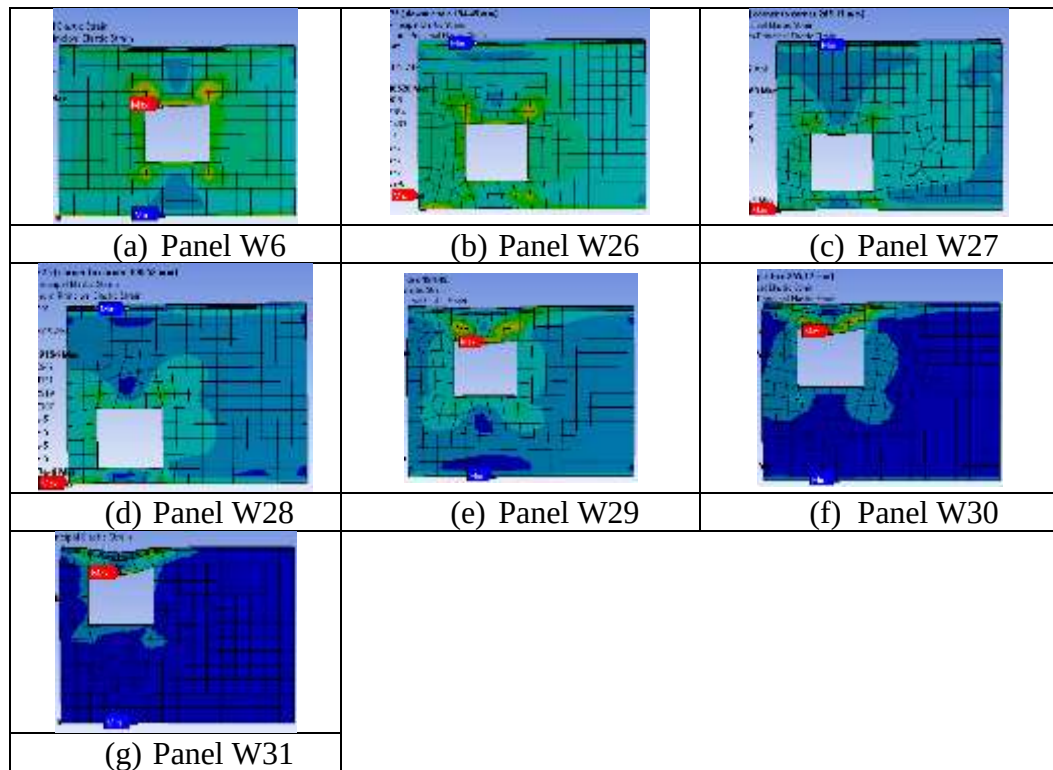


Figure 4.19: Principal elastic strain for variety configuration of 10% opening shifting diagonally

4.5.3.4 Deformation based on Opening Shifting Diagonally

Same as the previous results indicated in Figure 4.17, the wall panels experienced in decreasing in deformation values when the opening in the wall panels is inclined farther towards the north-west and south-west. The W6 with deformation values of 0.417 mm is used as the reference result, it showed that when the opening in the wall panel is inclined by 194.45 mm towards the south-west (W26), the deformation values is increased to 0.502 mm. This result can use to define the result obtained for the failure load of the wall as referred to Figure 4.17 of which the failure load for W26 is higher than W6. The wall panel which exhibited higher failure loads will tended to exhibit higher deformation values too. For the opening which inclined north-west from the center, wall panel (W31) has displayed the lowest of deformation values of 0.098 mm since the opening is located farthest with 300.52 mm due to north-west in the wall panel. This is same happened to W28 of which it showed the least values of deformation of 0.399 mm since it is located 300.52 mm farthest due to south-west in the wall panel.

When the location of the opening has been oriented to a position farther from the centre of the wall panel, it has altered the point of eccentricity in the wall. Therefore, it leaded to an unbalance distribution of loads in the wall panel and most of the loads will be accumulated closer to the opening area and therefore it created the critical point of which the maximum combinations of principal stress and strains will be happened simultaneously. When the opening is located farther from which the axial loads are acted, it can increase the ultimate strength of the wall panel since it provided larger surface areas of concrete which can be used to resist the strains whereas larger surface areas of reinforcement are provided to resist the stress. From Figure 4.20, it showed that the configurations on the location of the openings in wall panels W26 and W27 have taken the benefits as stated.

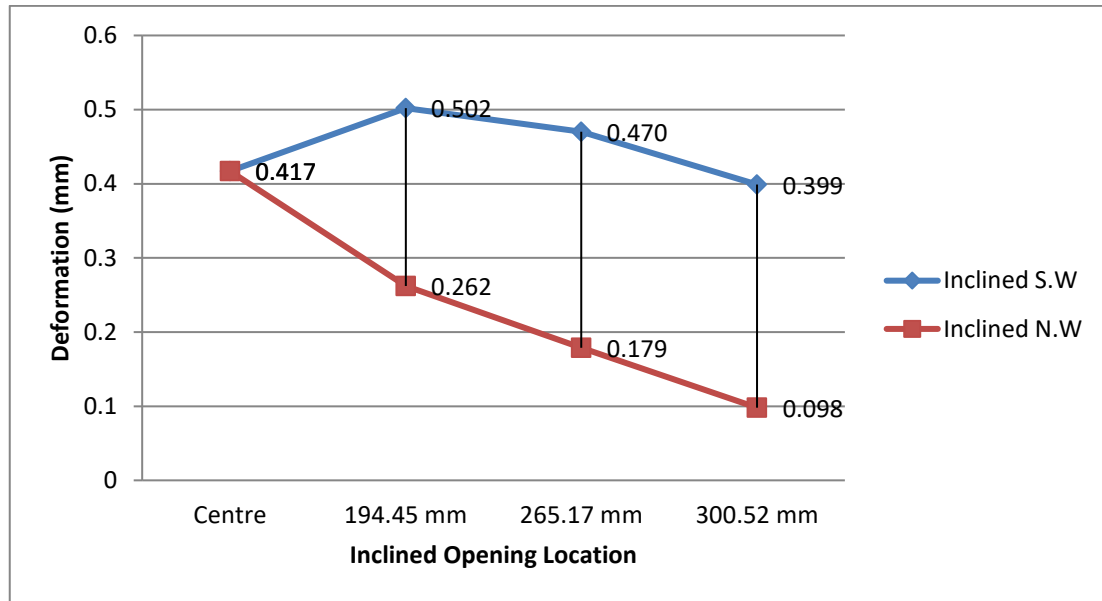


Figure 4.20: Deformation for variety configuration of 10% opening shifting diagonally

4.6 Summary

The structural behaviour of the reinforced concrete wall with opening was affected by the cut-out opening. When the opening sizes ratio was increases from 1% to 20%, the results show the 1% cut-out opening has negligible effect on the failure load. This result can be explained when the 1% cut-out opening ratio share the same stress and strain behaviour. The failure load drops drastically when the opening is increased from 2% till 20% opening ratio. The result shown different results with the design code because as there are huge change in failure load for 2% cut-out opening whereas the Eurocode 2 (2008) and AS3600 (2009) have recommended the limit for the area of the opening which is less than 1/10 of the area of the whole wall can be designed as a solid wall. This was due to the cut-out opening did not have any reinforcement reinforced around the opening and not due to the effect of the two-layer reinforcement ratio.

The shape of the opening was study with the 10% cut-out opening ratio by changing the opening shape in square, slit rectangular, wide rectangular, circular and fillet square. The

results show the same with Jessela and Pillai (2017) of which the optimum shape of the opening in a one-way wall panel is slit rectangular wall opening. However, fillet square opening was introduced in this research and the result showed the fillet square opening shape have greater failure load than slit rectangular opening in reinforced concrete wall panel.

The structural behaviour of reinforced concrete wall panel was studied by shifting the location of the 10% cut-out opening ratio in horizontally, vertically and diagonally. The result showed the same finding with Popescu et al. (2015b), the change in the location of the opening will change the eccentricity of the reinforced concrete wall panels. These results shown in the failure load graphs for reinforced concrete wall panel with opening changed in location in Section 4.5. However, there is no limit in changing the eccentricity of the opening. In order to discuss the effect of the change of eccentricity of the opening, the important factor that influenced the failure load is the spandrel area at the top and bottom of the opening and pier area at the left and right of the opening. This research has introduced the 10% cut-out opening ratio by shifting it diagonally, which is different in the previous research that only shift in horizontally and vertically, the result given a range in shifting the eccentricity of the cut-out opening in 300 mm. The result show in Section 4.5.3.1 that when opening shift diagonally more than 300 mm from the centre, the failure load drops by 83%.

The results of the stress distribution showed the stress are critical or maximum around the opening when the cut-out opening is created in the reinforced concrete wall panel. The failure load will be decreased when the maximum stress and maximum elastic strain are at the symmetric top of the opening. The maximum principal stress happened in steel reinforcement layer whereas the maximum principal strains occurred in the concrete layer. When these two maximum points happened at the same location, the reinforced concrete wall panel with cut-out opening will lead to a premature failure as shown by the reinforced

concrete wall panel with 3% of cut-out opening. When shifting the location of the opening, the maximum stress point shifted to the corner edge of the opening. This finding showed the location of maximum stress shift to the edges of opening away from the centre when the eccentricity of the wall panel is changing due to the changing of location of opening.

The deformation graph follows the trend of the failure load graph. Deformation is the ability of the reinforced concrete wall panel to retain its principal maximum stress but not the maximum principal elastic strain. This conclusion come from the results obtained in Section 4.5.1 since all the reinforced concrete wall panels showed the same maximum principal strains disregarding of the configurations on the location of the openings in the reinforced concrete wall panel.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 General Review of Work Done

This chapter presents the conclusion, research findings and also the recommendation of this research. The conclusion represents the summarization of this research results and several recommendations are suggested by the end of this chapter.

In general, opening in reinforced concrete wall panel can be regarded as an area of weakness in the wall panel. In this research study, the reinforced concrete wall panels with openings were analysed by using the Layered Finite Element Method (LFEM). The study on the behaviors of solid wall panel has then extends to the wall panels with opening with various geometrical configurations of sizes, shapes and different locations in order to evaluate for the effect of opening towards the behaviours of the wall panels. The research findings are discussed based on the failure loads, maximum principal stress, maximum principal elastic strain and deformation as analysed from the ANSYS software. Structural analysis is important because it can evaluate whether a specific structural design will be able to withstand external and internal stress and forces to achieve the expectation of the design.

5.2 Research Findings

The aim of this research was to find out how the configuration of the opening size, shape and the location can influence on the behaviour of the reinforced concrete wall panels with two-layers of reinforcement. Based on the results, the failure load of the wall panel is affected by the configuration of the parameter studies of opening size, shape and position. For the two-layers reinforced concrete wall panel with opening, the failure load decreases

with the increase in opening ratio. The 1% opening ratio on the concrete wall panel can be neglected and the reinforced concrete wall panel will perform as a solid wall panel. When the reinforced concrete wall panel was cut-out at 2% opening ratio, the failure load drops by around 77%. This result shows that the 2% opening raises significance effects for concrete wall panel with double layer of reinforcement. The failure loads tend to decrease when the opening size become larger. However, the result changes abruptly when the maximum principal stress and the maximum principal elastic strain are located at the same point on the reinforced concrete wall panel as stated in the results for the 3% opening size in this research study.

As the 10% opening ratio is used to conduct further study by changing the opening shape, the results show that by changing the shape of the opening, the failure load can either increase or decrease. The failure load can increase up to 15% when fillets are created at the corner of the opening. However, the failure load can be decreased by 20% when changing the square opening to the circular opening. Thus, the opening with fillet corner can increase the wall panel to achieve its optimum strength but circular opening reduces its strength.

When the wall panel is manipulated by shifting the opening locations, the failure load increases when the opening is shift away from the load applied and near to the boundary restraint. The pier and the spandrel area above the opening become the important keys to affect the failure load and the deformation of the reinforced concrete wall panel with opening. Yet, shifting the opening horizontally, the pier should not be less than $\frac{1}{4}$ of the reinforced concrete wall length since it will decrease the failure load up to 10%.

In conclusion, when the reinforced concrete wall panel contains discontinuity, such as the opening that causes sudden change in the cross-section areas of the wall, the maximum principal stress and strain will occur near the discontinuity. Thus, the results display on the

figures of stress and strain in Chapter 4 shows the distribution of the maximum principal stress and strain occur at the area where it is near to the opening and the load attributions. Since the modeling includes the combination of different material which are concrete and reinforcement, the results of the maximum principal stress and strain happen at different layer in the modeling, for instance, the maximum principal stress has happened in steel reinforcement layer whereas the maximum principal strains occurs in the concrete layer.

5.3 Recommendation

The result in this thesis shows how the behaviour of the reinforced concrete wall panel is affected by a cut-out opening. Further work on how to predict the failure load for a wall with cut-out opening can be carried out as follows:

- Perform variability investigation to identify the stress and strain concentration for non-linear opening wall with combination of different material.
- Perform a parametric study on reinforced concrete wall with more than one cut-out opening.
- More experimental test should be carried out to compare behaviour of the modelling and the actual situation in the stress and strain distribution.

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APPENDICES

Appendix A

Table A.1 Geometrical dimension of wall with different ratio of opening area

Wall	Geometrical Dimensions (mm)															
	Wall panel					Opening			Wall with opening		Coordinate					
	H	t	L	$\frac{H}{L}$	λ	H ₀	L ₀	A _o (%)	η(x)	η(y)	G1		G2		G3	
x	y	x	y	x	y											
W0	750	150	1000	0.75	6.67	0	0	0	0	0	500	375	500	375	500	375
W1	750	150	1000	0.75	6.67	87	87	1	0	0	500	375	500	375	500	375
W2	750	150	1000	0.75	6.67	123	123	2	0	0	500	375	500	375	500	375
W3	750	150	1000	0.75	6.67	150	150	3	0	0	500	375	500	375	500	375
W4	750	150	1000	0.75	6.67	174	174	4	0	0	500	375	500	375	500	375
W5	750	150	1000	0.75	6.67	194	194	5	0	0	500	375	500	375	500	375
W6	750	150	1000	0.75	6.67	275	275	10	0	0	500	375	500	375	500	375
W7	750	150	1000	0.75	6.67	390	390	20	0	0	500	375	500	375	500	375

Indication:

Slenderness, $\lambda = \frac{L}{t}$

Table A.2: Geometrical dimension of wall with different shape of opening

Wall	Geometrical Dimensions (mm)															
	Wall panel					Opening			Wall with opening		Coordinate					
	H	t	L	$\frac{H}{L}$	λ	H ₀	L ₀	A ₀ (%)	$\eta(x)$	$\eta(y)$	G1		G2		G3	
											x	y	x	y	x	y
W6	750	150	1000	0.75	6.67	275	275	10	0	0	500	375	500	375	500	375
W8	750	150	1000	0.75	6.67	275	275	9.85	0	0	500	375	500	375	500	375
W9	750	150	1000	0.75	6.67	275	275	9.44	0	0	500	375	500	375	500	375
W10	750	150	1000	0.75	6.67	310	310	10	0	0	500	375	500	375	500	375
W11	750	150	1000	0.75	6.67	150	150	10	0	0	500	375	500	375	500	375
W12	750	150	1000	0.75	6.67	174	174	10	0	0	500	375	500	375	500	375

Table A.3: Geometrical dimension of wall with opening shifting horizontally

Wall	Geometrical Dimensions (mm)															
	Wall panel					Opening			Wall with opening		Coordinate					
	H	t	L	$\frac{H}{L}$	λ	H ₀	L ₀	A ₀ (%)	$\eta(x)$	$\eta(y)$	G1		G2		G3	
											x	y	x	y	x	y
W6	750	150	1000	0.75	6.67	275	275	10	0	0	500	375	500	375	500	375
W13	750	150	1000	0.75	6.67	275	275	10	18.97	0	518.97	375	500	375	450	375
W14	750	150	1000	0.75	6.67	275	275	10	37.93	0	537.93	375	500	375	400	375
W15	750	150	1000	0.75	6.67	275	275	10	52.16	0	552.16	375	500	375	362.5	375
W16	750	150	1000	0.75	6.67	275	275	10	56.90	0	556.90	375	500	375	350	375
W17	750	150	1000	0.75	6.67	275	275	10	80.60	0	580.60	375	500	375	287.5	375

Table A.4: Geometrical dimension of wall with different downward and upward location of opening

Wall	Geometrical Dimensions (mm)															
	Wall panel					Opening			Wall with opening		Coordinate					
	H	t	L	$\frac{H}{L}$	λ	H ₀	L ₀	A ₀ (%)	η (x)	η (y)	G1		G2		G3	
											x	y	x	y	x	y
W6	750	150	1000	0.75	6.67	275	275	10	0	0	500	375	500	375	500	375
W18	750	150	1000	0.75	6.67	275	275	10	17.36	0	500	392.36	500	375	500	345
W19	750	150	1000	0.75	6.67	275	275	10	28.94	0	500	403.94	500	375	500	325
W20	750	150	1000	0.75	6.67	275	275	10	43.42	0	500	418.42	500	375	500	300
W21	750	150	1000	0.75	6.67	275	275	10	50.65	0	500	425.65	500	375	500	287.5
W22	750	150	1000	0.75	6.67	275	275	10	17.37	0	500	357.63	500	375	500	405
W23	750	150	1000	0.75	6.67	275	275	10	28.95	0	500	346.05	500	375	500	425
W24	750	150	1000	0.75	6.67	275	275	10	43.42	0	500	331.58	500	375	500	450
W25	750	150	1000	0.75	6.67	275	275	10	50.66	0	500	324.34	500	375	500	462.5

Table A.5: Geometrical dimension of wall with different inclined location of opening

Wall	Geometrical Dimensions (mm)															
	Wall panel					Opening			Wall with opening		Coordinate					
	H	t	L	$\frac{H}{L}$	λ	H ₀	L ₀	A _o (%)	η (x)	η (y)	G1		G2		G3	
											x	y	x	y	x	y
W6	750	150	1000	0.75	6.67	275	275	10	0	0	500	375	500	375	500	375
W26	750	150	1000	0.75	6.67	275	275	10	59.01	67.55	559.01	442.55	500	375	344.44	258.33
W27	750	150	1000	0.75	6.67	275	275	10	80.47	92.11	580.47	467.11	500	375	287.86	215.90
W28	750	150	1000	0.75	6.67	275	275	10	91.19	104.39	591.19	479.39	500	375	259.58	194.69
W29	750	150	1000	0.75	6.67	275	275	10	59.01	67.55	559.01	307.45	500	375	344.44	491.67
W30	750	150	1000	0.75	6.67	275	275	10	80.47	92.11	580.47	282.89	500	375	287.86	534.10
W31	750	150	1000	0.75	6.67	275	275	10	91.19	104.39	591.19	270.61	500	375	259.58	555.31

Appendix B

Table B.1 Maximum point for principal stress and principal elastic strain

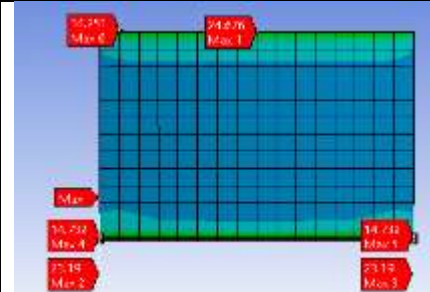
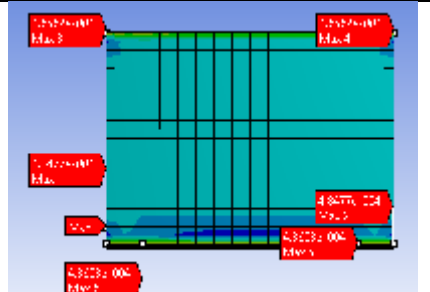
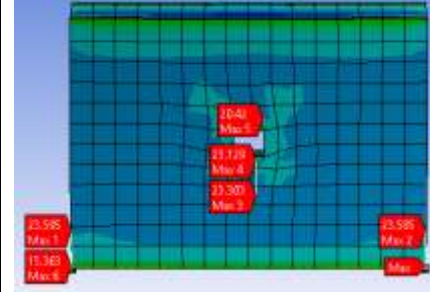
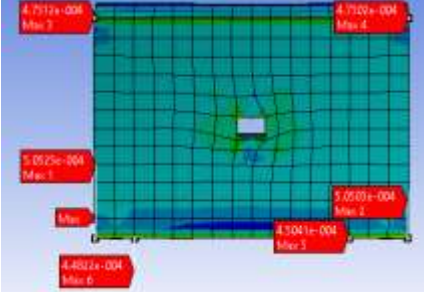
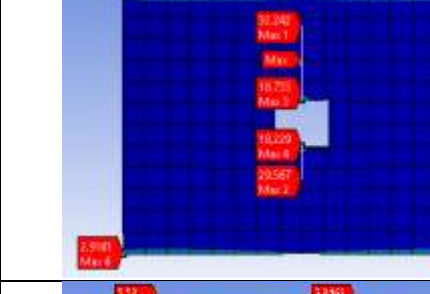
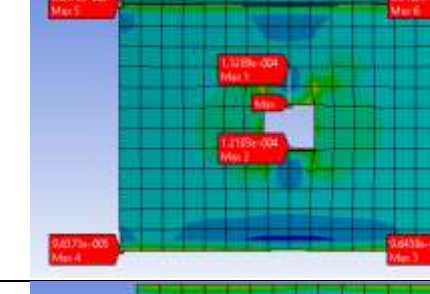
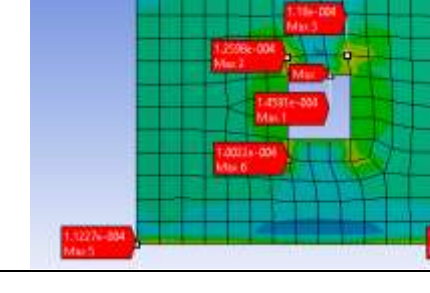
WALL PANEL	MAXIMUM PRINCIPAL STRESS	MAXIMUM PRINCIPAL ELASTIC STRAIN
W0		
W1		
W2		
W3		
W4		

Table B.1 continued

W5		
W6		
W7		
W8		
W9		

Table B.1 continued

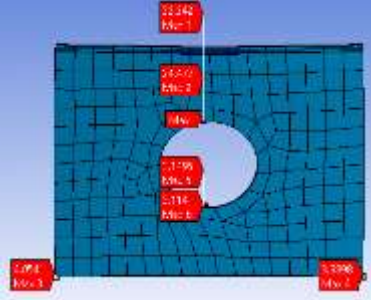
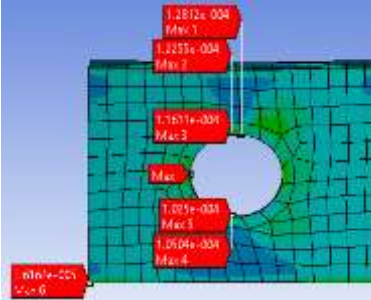
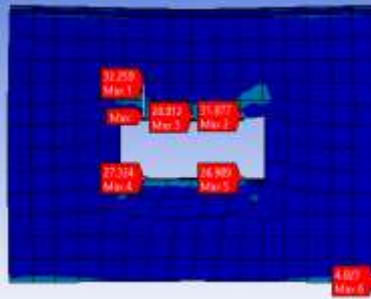
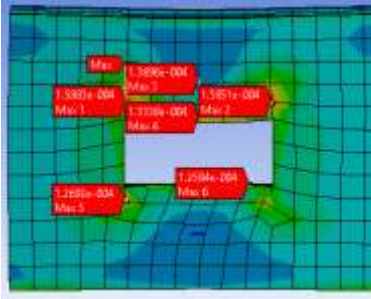
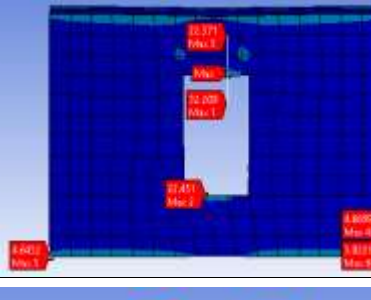
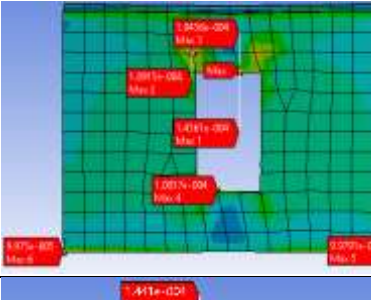
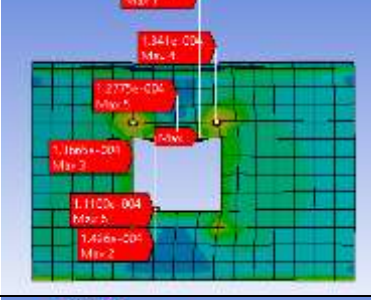
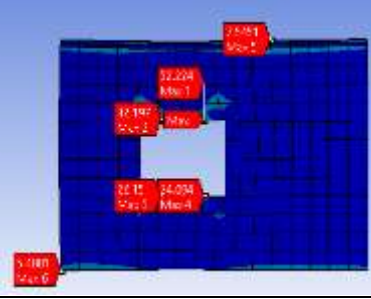
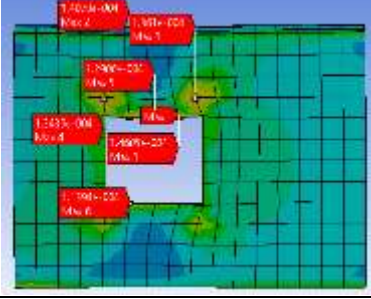
W10		
W11		
W12		
W13		
W14		

Table B.1 continued

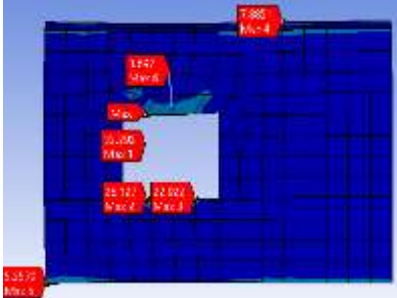
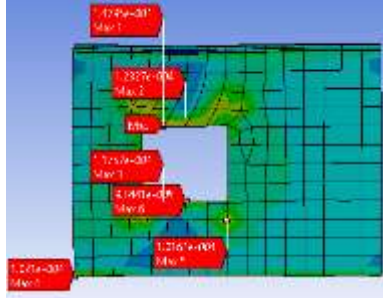
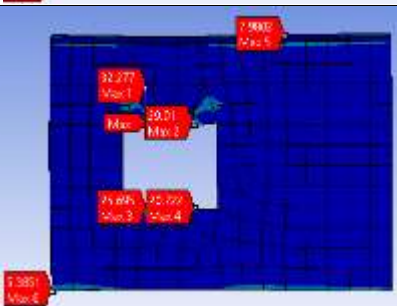
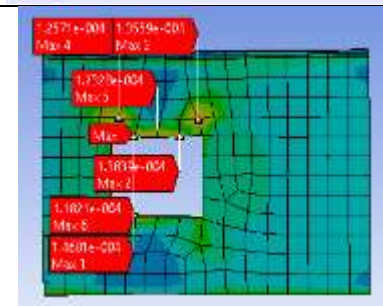
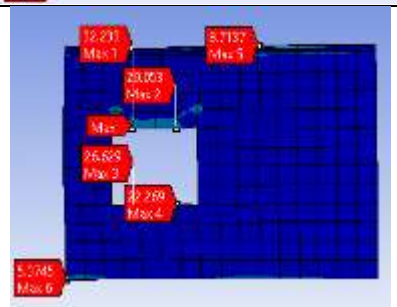
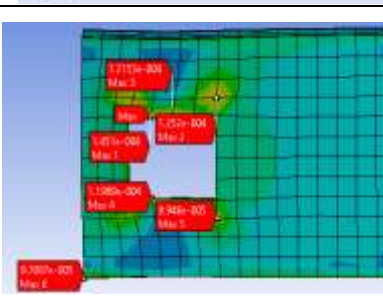
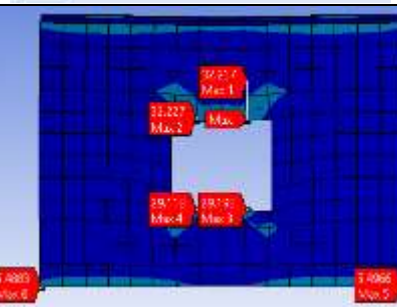
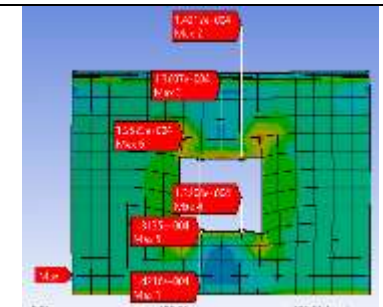
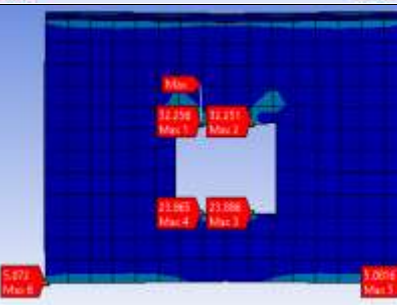
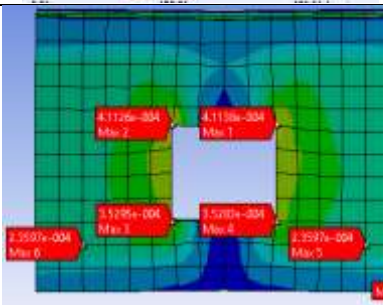
W15	 Stress contour plot for W15 (left). The plot shows a rectangular domain with a central square hole. The color scale ranges from blue (low stress) to red (high stress). Key stress values are labeled in red boxes: Max 1 (12.06), Max 2 (25.12), Max 3 (22.04), Max 4 (7.88), Max 5 (1.44), and Max 6 (1.17).	 Stress contour plot for W15 (right). The plot shows a rectangular domain with a central square hole. The color scale ranges from blue (low stress) to red (high stress). Key stress values are labeled in red boxes: Max 1 (1.21e+01), Max 2 (2.37e+01), Max 3 (1.52e+01), Max 4 (4.04e+01), Max 5 (1.21e+01), and Max 6 (1.21e+01).
W16	 Stress contour plot for W16 (left). The plot shows a rectangular domain with a central square hole. The color scale ranges from blue (low stress) to red (high stress). Key stress values are labeled in red boxes: Max 1 (32.27), Max 2 (20.01), Max 3 (25.05), Max 4 (25.05), Max 5 (7.88), and Max 6 (1.17).	 Stress contour plot for W16 (right). The plot shows a rectangular domain with a central square hole. The color scale ranges from blue (low stress) to red (high stress). Key stress values are labeled in red boxes: Max 1 (1.460e+01), Max 2 (1.183e+01), Max 3 (1.183e+01), Max 4 (1.257e+01), Max 5 (1.750e+01), and Max 6 (1.257e+01).
W17	 Stress contour plot for W17 (left). The plot shows a rectangular domain with a central square hole. The color scale ranges from blue (low stress) to red (high stress). Key stress values are labeled in red boxes: Max 1 (12.21), Max 2 (20.03), Max 3 (26.62), Max 4 (20.29), Max 5 (8.11), and Max 6 (1.17).	 Stress contour plot for W17 (right). The plot shows a rectangular domain with a central square hole. The color scale ranges from blue (low stress) to red (high stress). Key stress values are labeled in red boxes: Max 1 (1.183e+01), Max 2 (1.183e+01), Max 3 (1.183e+01), Max 4 (1.183e+01), Max 5 (1.183e+01), and Max 6 (1.183e+01).
W18	 Stress contour plot for W18 (left). The plot shows a rectangular domain with a central square hole. The color scale ranges from blue (low stress) to red (high stress). Key stress values are labeled in red boxes: Max 1 (32.27), Max 2 (32.27), Max 3 (20.12), Max 4 (20.12), Max 5 (7.88), and Max 6 (1.17).	 Stress contour plot for W18 (right). The plot shows a rectangular domain with a central square hole. The color scale ranges from blue (low stress) to red (high stress). Key stress values are labeled in red boxes: Max 1 (1.183e+01), Max 2 (1.183e+01), Max 3 (1.183e+01), Max 4 (1.183e+01), Max 5 (1.183e+01), and Max 6 (1.183e+01).
W19	 Stress contour plot for W19 (left). The plot shows a rectangular domain with a central square hole. The color scale ranges from blue (low stress) to red (high stress). Key stress values are labeled in red boxes: Max 1 (32.27), Max 2 (32.27), Max 3 (20.12), Max 4 (20.12), Max 5 (7.88), and Max 6 (1.17).	 Stress contour plot for W19 (right). The plot shows a rectangular domain with a central square hole. The color scale ranges from blue (low stress) to red (high stress). Key stress values are labeled in red boxes: Max 1 (4.112e+01), Max 2 (4.112e+01), Max 3 (3.530e+01), Max 4 (3.530e+01), Max 5 (3.530e+01), and Max 6 (3.530e+01).

Table B.1 continued

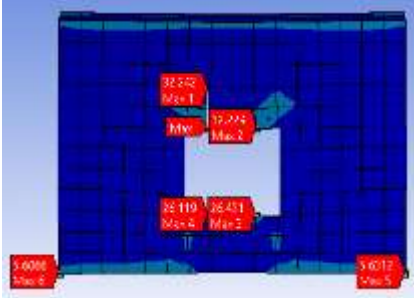
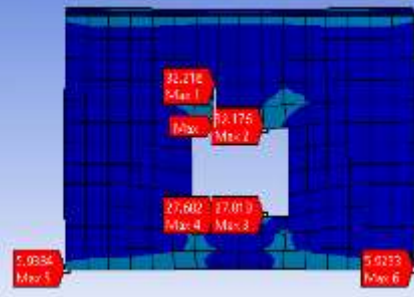
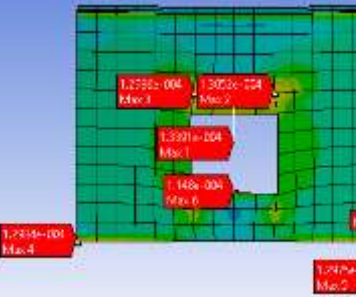
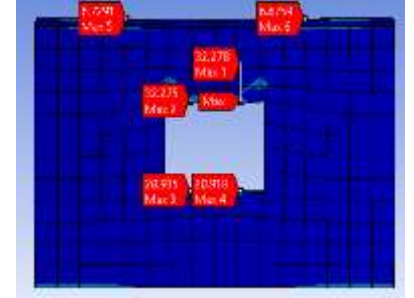
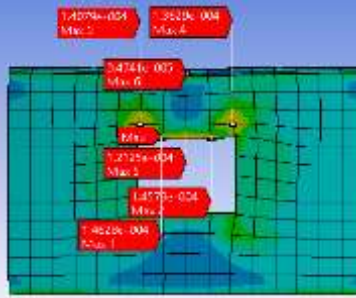
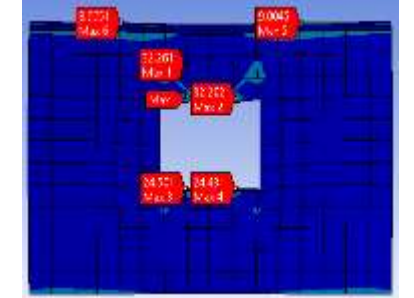
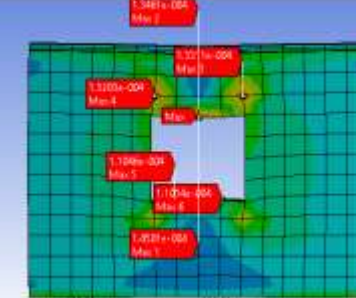
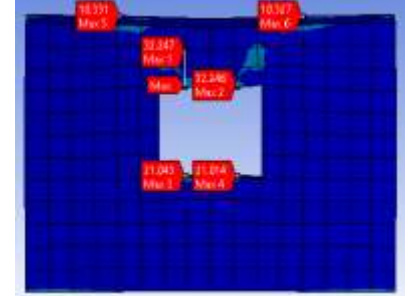
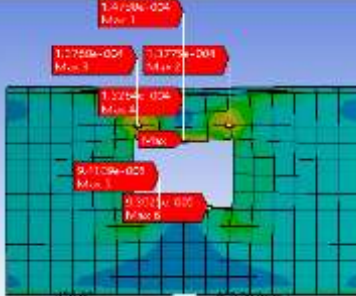
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W21		
W22		
W23		
W24		

Table B.1 continued

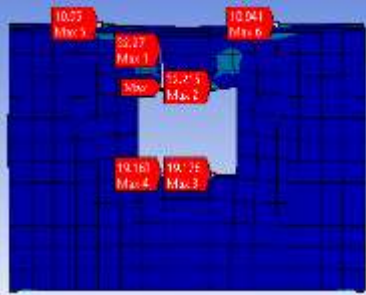
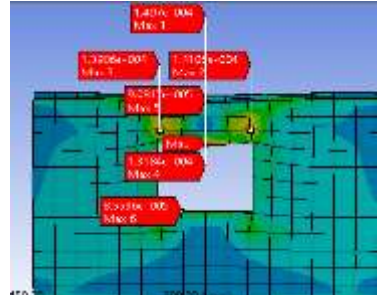
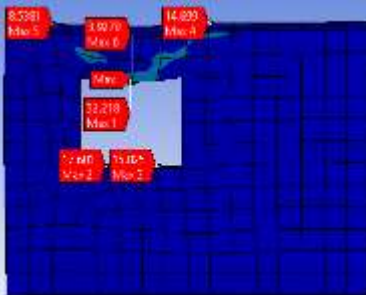
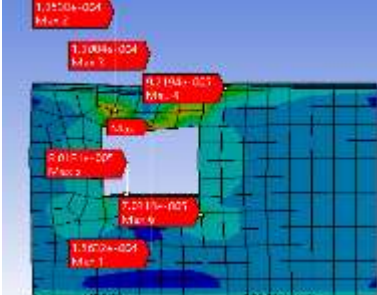
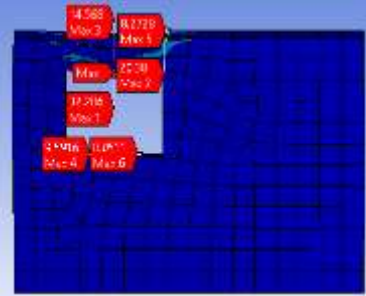
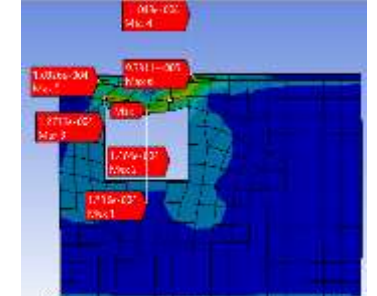
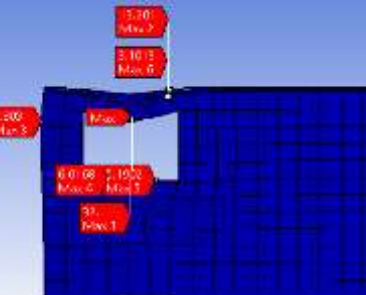
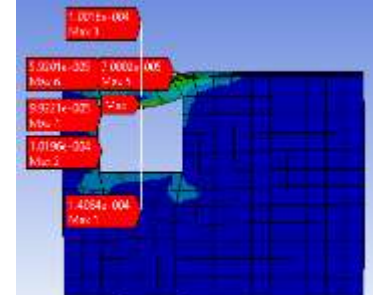
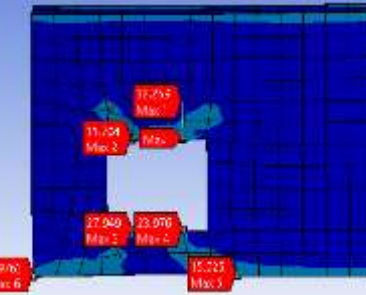
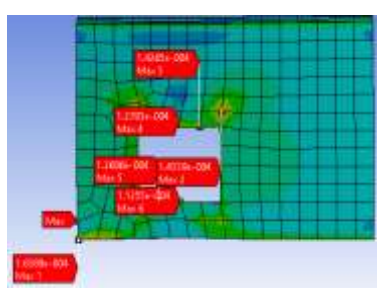
W25		
W26		
W27		
W28		
W29		

Table B.1 continued

