



THESIS APPROVAL

GRADUATE SCHOOL, KASETSART UNIVERSITY

Master of Engineering (Civil Engineering)

DEGREE

Civil Engineering

FIELD

Civil Engineering

DEPARTMENT

TITLE: Study of the Effect on the Shear Strength by the Openings in Flat Plate

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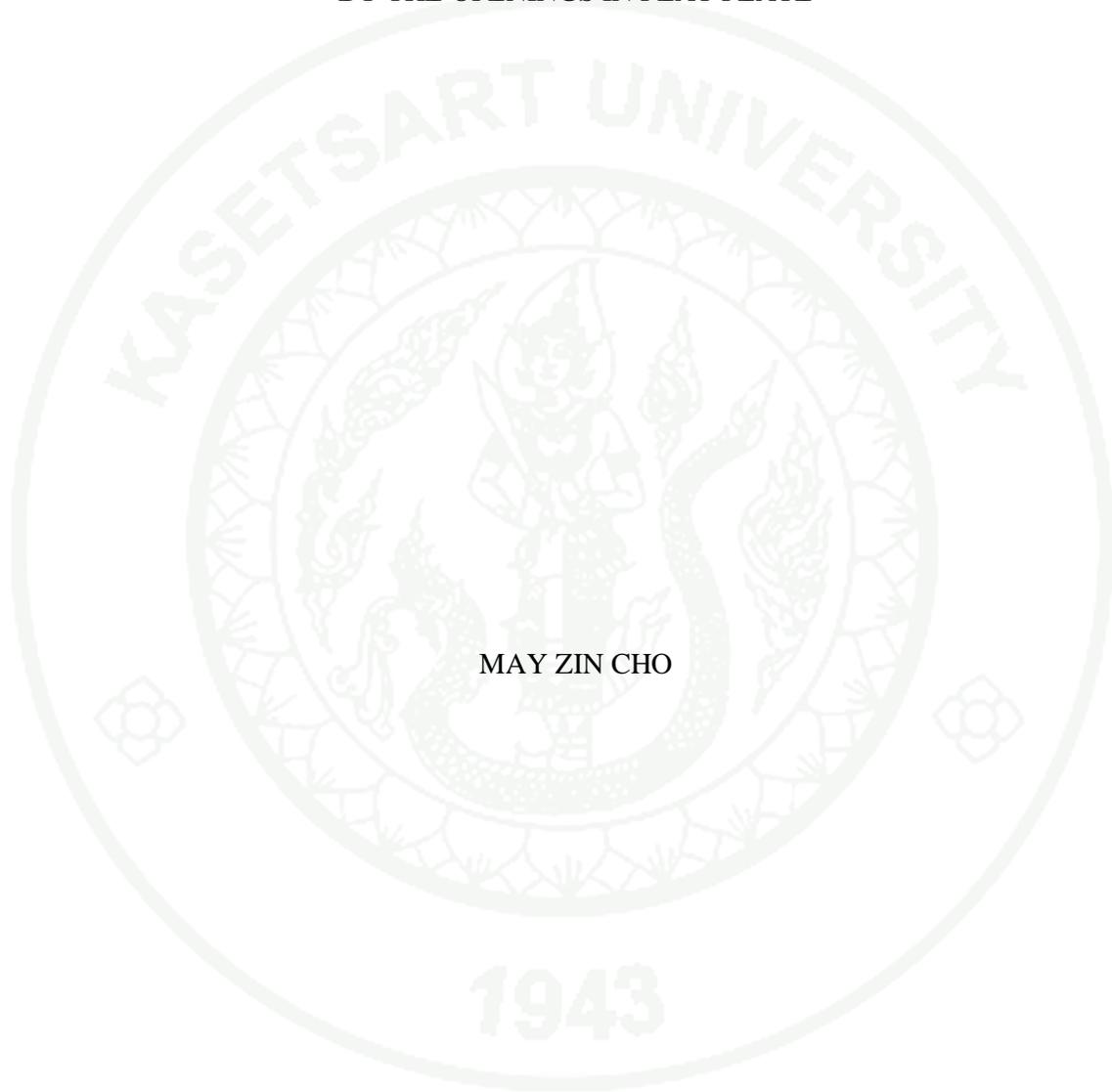
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THESIS

STUDY OF THE EFFECT ON THE SHEAR STRENGTH
BY THE OPENINGS IN FLAT PLATE



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A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
Master of Engineering (Civil Engineering)
Graduate School, Kasetsart University
2010

May Zin Cho 2010: Study of the Effect on the Shear Strength by the Openings in Flat Plate. Master of Engineering (Civil Engineering), Major Field: Civil Engineering, Department of Civil Engineering. Thesis Advisor: Associate Professor Trakool Aramraks, Ph.D. 196 pages.

This research aimed to study the effect on shear strength by the openings in flat plate. In the first step, eight numbers of square openings were used to study the effect of the locations of openings in the flat plate. In the second step, openings with various rectangular sizes located at critical locations and the effect of the sizes of the openings were studied. In the final step, the effect on shear strength by the openings was investigated and two methods of shear strengthening were studied to increase the shear strength of flat plate with the openings.

In first step, the results showed that the openings at the face of the column are the most critical for the flat plate with openings. In second step, the results showed that the critical sizes of the opening are: the opening width parallel to the face of the column larger than three-tenths of the column strip width, and the opening width perpendicular to the face of the column larger than one-tenth of the column strip width. In the final step, the result showed that shear strength provided by the concrete of the flat plate decreases with the increase of the opening sizes. Moreover, the shearhead reinforcement was found to be more effective than bar reinforcement in increasing the shear strength of the flat plate with openings. When the drop panel was used as shear strengthening, the results showed that the original slab thickness should be increased not less than 1.8 times the slab thickness around the various sizes of openings at the face of interior column, and the original slab thickness should be increased not less than 1.6 times the slab thickness around the various sizes of opening at the face of the edge column.

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ACKNOWLEDGEMENT

This research would not have been successful without the help, support and guidance rendered by many people who were directly or indirectly involved in this work. I would like to express my sincere gratitude and appreciation to my thesis advisor Associate Professor Dr. Trakool Aramraks for his invaluable guidance, continuous encouragement and kindness provided throughout the research period. My sincere appreciation is also due to Assistant Professor Dr. Kitjapat Phuvoravan and Assistant Professor Dr. Piya Chotickai for their invaluable suggestions and for serving on the thesis committee.

I would like to thank the Thailand International Cooperation Agency (TICA) for the scholarship and all the staff of the International Graduate Program in Civil Engineering (IPCE), Kasetsart University.

I would like to express my gratitude to my beloved parents for giving permission to study in abroad and their continuous encouragement. Finally, thanks are also to my younger brothers for their taking care of my beloved parents on behalf of me during my study time.

May Zin Cho

April 2010

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LIST OF ABBREVIATIONS

a	=	opening width in the direction perpendicular to the column face
ACI	=	American Concrete Institute
b	=	opening width in the direction parallel to the column face
b_0	=	perimeter of critical section
d	=	effective depth of slab
d_p	=	effective depth of drop panel
E	=	Young's modulus
EIT	=	Engineering Institute of Thailand
Eq	=	equation
FDM	=	Finite Difference Method
FEM	=	Finite Element Method
f'_c	=	concrete strength
F_{11}, F_{22}	=	membrane direct forces
F_{12}	=	membrane shear force
h_a	=	overall thickness of drop panel
kN	=	kilo Newton
kN-m	=	kilo Newton per meter
kN-m/m	=	kilo Newton meter per meter
kg/cm ²	=	kilogram per square centimeter
l	=	center to center span length
m	=	meter
M_x	=	bending moment in x -direction
M_y	=	bending moment in y -direction
M_{11}, M_{22}	=	plate bending moments
M_{12}	=	plate twisting moment
PCA	=	Portland Cement Association
Q_{max}	=	maximum shear stress per unit length

LIST OF ABBREVIATIONS (Continued)

th	=	membrane thickness
thb	=	plate-bending thickness
V_c	=	shear strength provided by concrete
V_n	=	maximum shear strength permitted with shear reinforcement
V_s	=	shear strength provided by shear reinforcement
V_u	=	required shear force
V_{13}, V_{23}	=	plate transverse shear forces
w	=	uniformly distributed load per length
w_d	=	minimum width of the drop panel beyond the perimeter of opening and the column
x	=	drop panel width along x direction axis
x_1	=	in-plane coordinate parallel to the local 1 axis
x_2	=	in-plane coordinate parallel to the local 2 axis
y	=	drop panel width along y direction axis
2D	=	Two Dimensional
3D	=	Three Dimensional
\emptyset	=	shear strength reduction factor
ν	=	Poisson's ratio
β_c	=	ratio of long side to short side of the column
β_x	=	coefficient of maximum bending moment M_x
β_y	=	coefficient of maximum bending moment M_y
β_0	=	parameter area aspect ratio
γ_x	=	coefficient of maximum shear force V_x
γ_y	=	coefficient of maximum shear force V_y
$\sigma_{11}, \sigma_{22}, \sigma_{33}$	=	direct stresses
$\sigma_{12}, \sigma_{13}, \sigma_{23}$	=	shear stresses

STUDY OF THE EFFECT ON THE SHEAR STRENGTH BY THE OPENINGS IN FLAT PLATE

INTRODUCTION

General

Flat plates are solid concrete slabs of uniform depth that transfer loads directly to the supporting columns without the aid of beams or capitals or drop panels. Flat plates have several advantages over other slab systems. The absence of beams, drops and column capitals allow the flat plates to be constructed quickly due to their simple formwork and reinforcing bar arrangements, leading to economical fast construction. The lack of the beams permits the smallest overall story height and gives the most flexibility in the arrangement of columns and partitions.

The saving in story height is advantageous to reduce the foundation load and the building weight due to lower partitions. Another benefit of flat plates is the smooth underside of the slab which allows all of the mechanical and electrical services to be mounded directly on the undersides of slabs. Based on economy of construction as well as the loading limitations described above, flat plate systems are well suited for use in multi-story and high-rise reinforced concrete hotels, apartments, hospitals, and light office spaces, and are perhaps the most commonly used slab system for these types of structures today.

Unlike ordinary reinforced concrete structures, flat plates are usually subjected to complex stress states under normal load conditions. In flat plate, shear stresses near the columns may be very high. The use of flat plate is limited by its shear capacity around the columns. Among the two kinds of shear that must be considered in the design of flat plates, punching shear is critical consideration for the flat plate design around the columns.

Usually, slab systems must include openings. These may be of substantial size, as required by stairways and elevator shafts, or they may be of smaller dimensions such as those needed to accommodate heating, plumbing, air conditioning, and ventilating risers; floor and roof drains; and access hatches. When openings are provided in the flat plate due to design requirement of the floor system, these openings may reduce the strength of flat plate because of the increase in bending moments and shear forces. According to ACI Code, if the opening is close to the column (within 10 times of slab thickness or within the column strips), then that part of the punching shear parameter included within the radial lines projecting from the opening to the centroid of the column should be considered ineffective.

Statement of Problems

The Building Code Requirements for Structural Concrete (ACI) permits the specified sizes and locations of the opening in the flat plates. However, opening sizes larger than the permitted sizes may be needed according to the architectural requirement of the floor system. In this case, the effect of these large openings on the strength of the flat plate needs to be studied. Very large openings should preferably be framed by beams or slab bands of increased depth to restore, as closely as possible, the continuity of the slab.

The importance of openings in slabs supported directly by columns (flat slabs and flat plates) depends on the location of the opening with respect to the columns. From a structural point of view, they are best located away from the columns, preferably in the area common to the slab middle strips. Unfortunately, architectural and functional considerations usually cause them to be located close to the columns. In this case, the reduction on effective shear perimeter is the major concern, because flat plate floors are usually shear-critical.

Punching shear, one major controlling factor around the columns in the flat plate, generally occurs at concentrated load or column support regions. In this case the column tends to punch through the slab, producing diagonal tensile stresses. This is

one of the most critical considerations when determining the thickness of flat plates at the column-slab intersection. Therefore, a general increase in the slab thickness is required or special reinforcement is used.

The general analysis methods for the flat plates include the direct design, equivalent frame, yield line, and strip design techniques, all of which approximate the results of classical plate theory. These methods have gained wide acceptance among engineers because of their simplicity. However, these approximate techniques have significant limitations. Direct design and equivalent frame methods are both limited to structures with very regular geometry. The application of yield lines or strip design may lead to overly conservative designs as well as to poor serviceability.

The finite element method has gained acceptance as an appropriate tool for the analysis of flat plates, especially those with highly irregular or unusual geometries where the direct design and equivalent frame techniques are not valid. In irregular slabs, the finite element method can be used to solve accurately the distribution of stress where numerous approximations and assumptions would be required if the yield line or strip design technique were applied.

In this research, the opening sizes are larger than the ACI permitted sizes in order to study their effect on the shear strength by using FEM program. Finally, the shear reinforcement and drops with various thicknesses were introduced around the openings where the applied shear stress is larger than the resisting shear strength of the flat plate.

OBJECTIVES

The main purposes of the present research are as following,

1. To study the changes of bending moment in general and shear force resultant in flat plate due to openings at different locations.
2. To study the effect of openings on the resisting shear strength of the flat plate provided by the concrete.
3. To present the shear reinforcement and drops with appropriate thickness for different sizes of openings at different locations in the flat plate.

Scope of Study

1. The flat plate models are nine square panels comprising of three by three equal width panels supported by sixteen square columns.
2. The locations of the opening are the opening in the area common to intersecting middle strips, the area common to one column strip and one middle strip, the area common to one middle-column strip and one middle strip and the area common to intersecting column strips.
3. For the column strip, the shape of the opening is rectangular with various sizes near the interior, edge and corner columns.
4. Use elastic plate theory and flat plate is homogeneous material.
5. Use SAFE Version12 to analyze the flat plates.
6. Use ACI 318-95 to calculate the shear strength of flat plates with openings.

LITERATURE REVIEW

1. Flat plate

Concrete slabs may in some cases be carried directly by columns, without the use of beams or girders. Such slabs are described as flat plates and are commonly used where spans are not large and loads not particularly heavy (Nilson, 1997). All building slabs supported on columns are referred to as flat slabs in the United Kingdom. But in North America flat slabs without drops or column heads are referred to as flat plates. The decision to use a flat plate system is often determined based on the span length and loading.

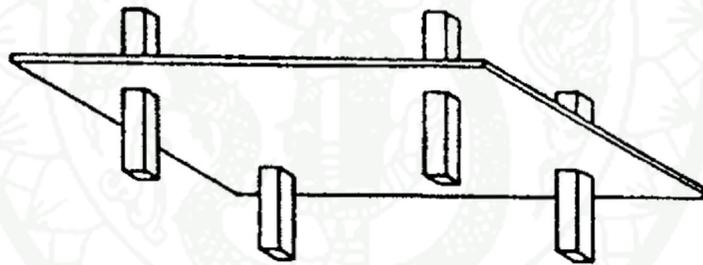


Figure 1 Flat Plate

Source: Rice (1985)

Flat plate is called two-way slab because the reinforcing bars usually form an orthogonal grid of two layers of steel. Negative moment steel is placed near the top of the plate close to the columns and crossing the column lines (imaginary lines connecting the columns), and positive moment steel is used near the bottom surface out in the middle of the plate in both directions. Positive moment steel is also needed parallel to the column lines. For some applications, it can be economically prestressed by using continuous post-tensioned tendons embedded in the slab (Shaeffer, 1992).

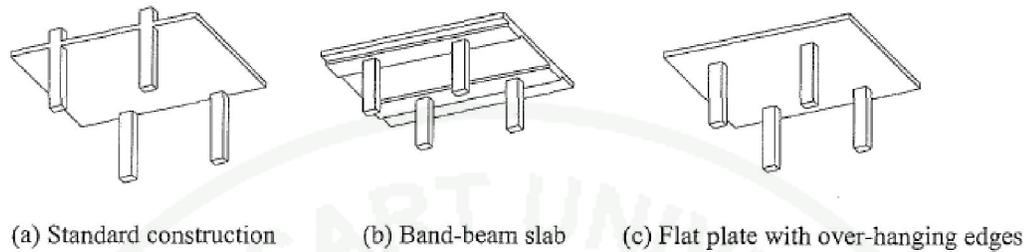


Figure 2 Flat plate categories

Source: Guan (1996)

In general, the flat plate system may be one of the three categories as illustrated in Figure 2.

(a) Standard construction where exterior columns are located at the edge of the slabs;

(b) Band-beam slabs where the portion of the slab along the column line is thickened in one direction or the other. This is coupled with a thickness reduction at the remaining portions of the slab;

(c) Flat plates with overhanging edges.

2. Openings in slabs

Slabs with small openings can usually be designed as if there were no openings, replacing the interrupted steel with bands of rebar of equivalent area on either side of the opening in each direction. Slabs with larger openings must be treated more rigorously. Opening in the vicinity of column supports should always be considered in the analysis. The distance between openings in a particular zone should not be less than three times the opening dimension in the direction considered (Andrzej, 1990). In the region between the two column-strip intersections, this

distance will be reduced to one and half times the side dimension of the opening unless the sum of the reinforcement intersected by opening exceeds 40% of total reinforcement in this zone.

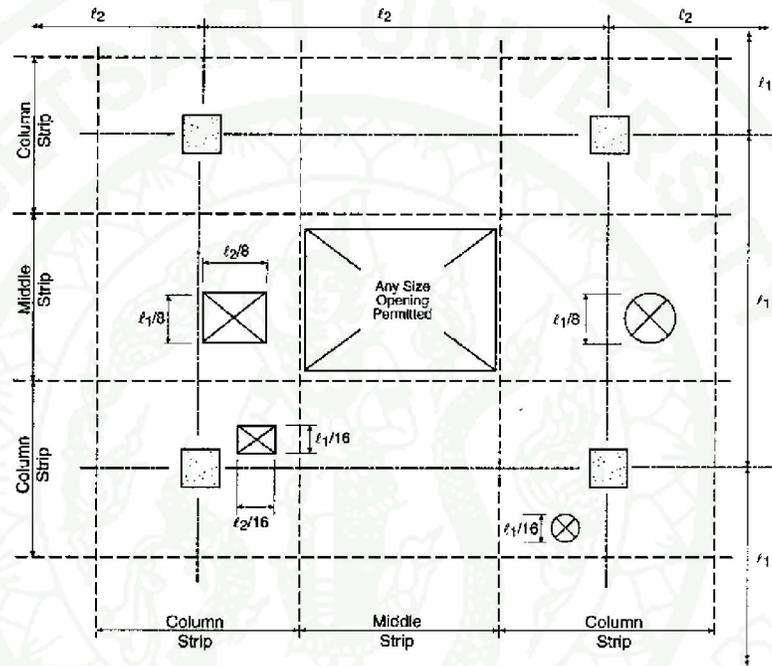


Figure 3 Opening in slab systems without beams

Source: PCA (1996)

The Building Code Requirements for Structural Concrete (ACI 318M-95) defined the criteria of opening in slab system as follows:

1. Openings of any size shall be permitted in slab systems if shown by analysis that the design strength is at least equal to the required strength considering required strength and design strength, and that all serviceability conditions, including the specified limits on deflections, are met.

2. As an alternative to special analysis as required by article 1, openings shall be permitted in slab systems without beam only in accordance with the following:

2.1 Openings of any size shall be permitted in the area common to intersecting middle strips, provided total amount of reinforcement required for the panel without the opening is maintained.

2.2 In the area common to intersecting column strips, not more than one-eighth the width of column strip in either span shall be interrupted by openings. An amount of reinforcement equivalent to that interrupted by an opening shall be added on the sides of the opening.

2.3 In the area common to one column strip and one middle strip, not more than one-quarter of the reinforcement in either strip shall be interrupted by openings. An amount of reinforcement equivalent to that interrupted by an opening shall be added on the sides of the opening.

3. Shear strength of flat plates

Design of flat plates for shear in the region of columns, concentrated loads or reactions is governed either by the wide-beam action or two-way action. For one-way slabs, in which the bending action is primarily in one direction, wide-beam action is the primary mode of behavior. For two-way slab systems, such as flat plates and flat slabs, two-way action is the primary mode of behavior and the failure mechanism changes to that of punching (PCA, 1996).

Even though the wide-beam action shear rarely controls the shear strength of two-way slab systems, the designer must ensure that shear strength for beam action is not exceeded. Tributary areas and corresponding critical sections for wide-beam action shear strength and two-way shear strength at slab and column connection are illustrated in Figure 4.

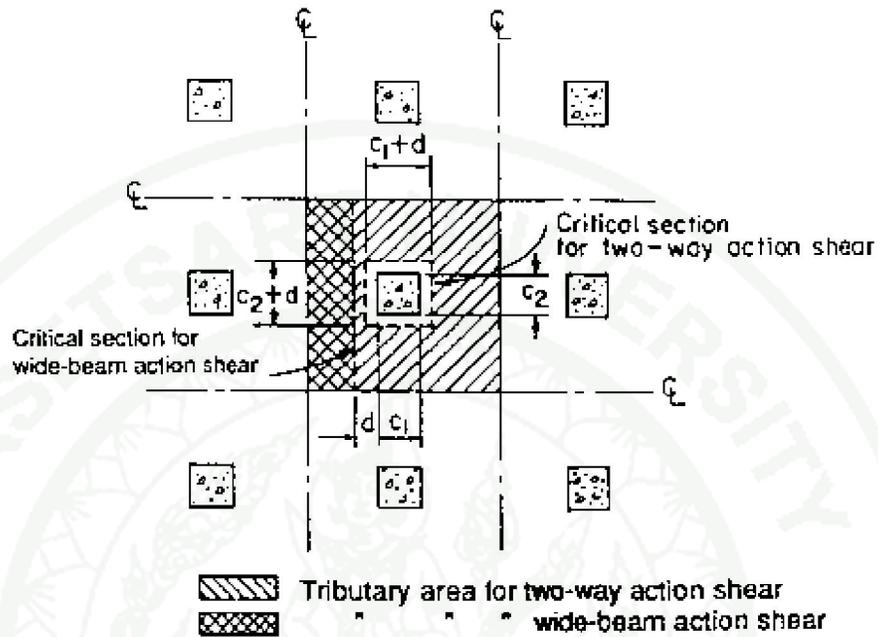


Figure 4 Tributary areas and critical sections for slab shear at a slab-column connection

Source: PCA (1996)

In punching shear failure, failure may occur with the potential diagonal crack following the surface of a truncated cone or pyramid around the column as shown in Figure 5(a). The failure surface extends from the bottom of the slab, at the support, diagonally upward to the top surface. The angle of inclination with the horizontal, Figure 5(b), depends upon the nature and amount of reinforcement in the slab. It may range between about 20 and 45 degrees. The critical section for shear is taken perpendicular to the plane of the slab and a distance $d/2$ (half of the effective depth of the slab) from the periphery of the support (Nilson, 1997).

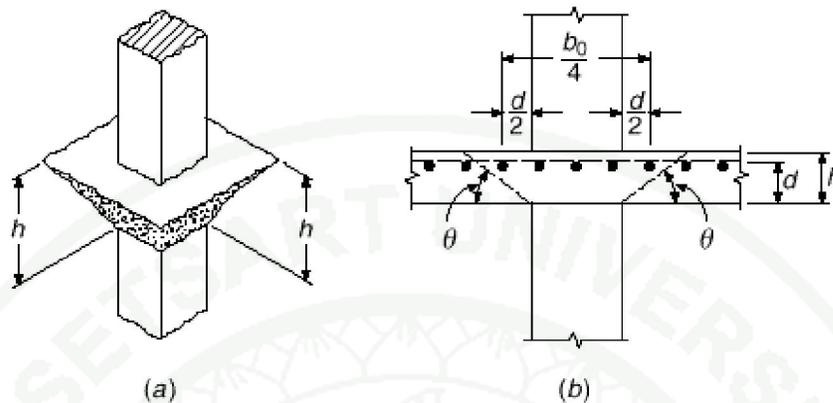


Figure 5 Failure surface defined by punching shear

Source: Nilson (1997)

Load transfer directly between a slab and a column, without intermediate load transfer through a beam, is one of the more critical design conditions for two-way slab systems without beams between column supports. Shear strength at an exterior slab-column connection (without spandrel beams) is especially critical, because the total exterior negative slab moment must be transferred directly to the column.

The ACI code specifies that the unbalanced moment at a slab-column connection must be transferred from the slab (without beams) to the column by eccentricity of shear and by flexure. The general mechanism of transfer is illustrated in Figure 6. Shear transfer is assumed to occur on a critical section at a distance $d/2$ (half of the effective depth of the slab) away from the face of the column, while the fraction of unbalanced moment transferred by flexure is resisted by a width of slab equal to the transverse column width, plus 1.5 times the thickness of the slab on each side of the column.

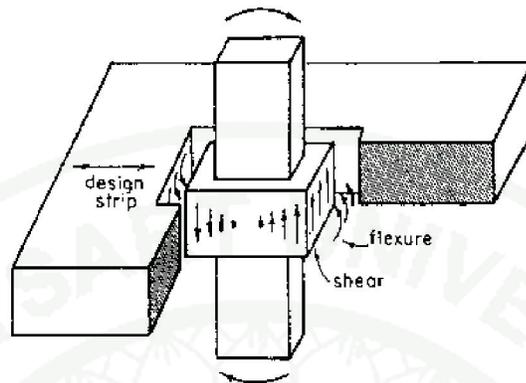


Figure 6 Direct shear and moment transfer

Source: PCA (1996)

According to ACI 318M-95, shear requirements of slabs with openings shall satisfy the following:

When openings in slabs are located at a distance less than ten times the slab thickness from a concentrated load or reaction area, or when openings in flat slabs are located within column strips, the critical slab sections for shear shall be modified as follows:

1. For slabs without shear heads, that part of the perimeter of the critical section that is enclosed by straight lines projecting from the centroid of the column, concentrated load, or reaction area and tangent to the boundaries of the openings shall be considered ineffective.
2. For slabs with shear heads, the ineffective portion of the perimeter shall be one-half of that defined in article 1.
3. The locations of the effective portion of the critical section near typical openings and free edges are shown by dash line in Figure 7 and 8.

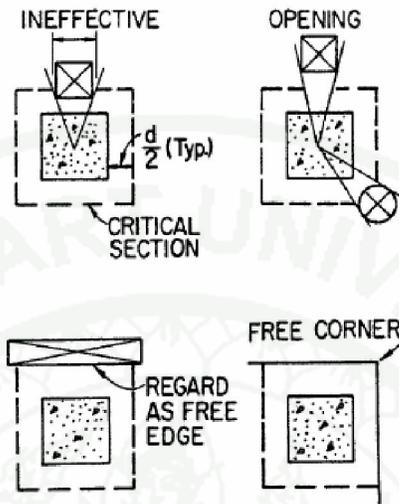
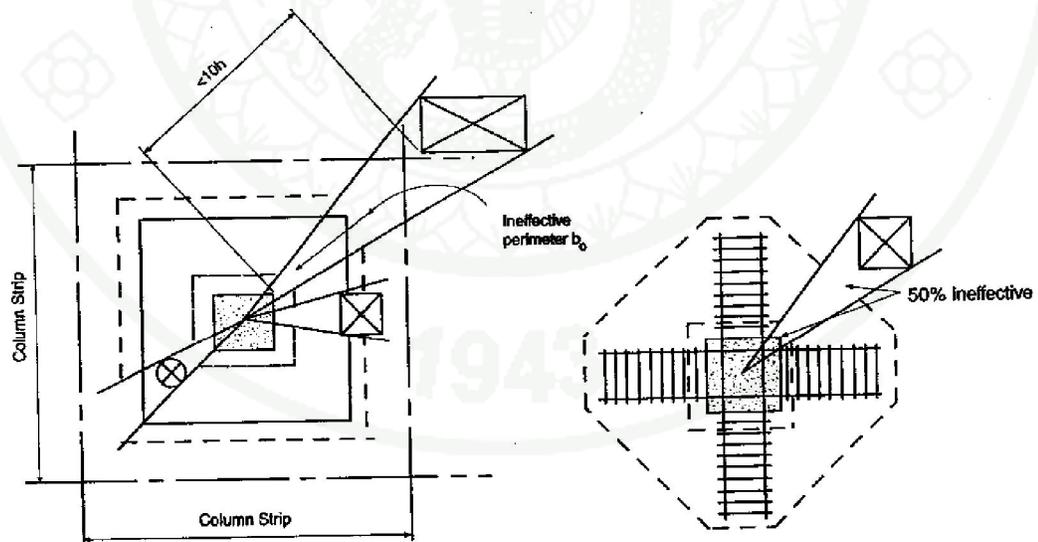


Figure 7 Critical perimeters for shear

Source: ACI 318M-95 (1995)



(a) Slab with drop panel

(b) Slab with bar reinforcement

Figure 8 Effect of slab openings on shear strength

Source: PCA (1996)

Two-way action shear strength of slabs (without shear reinforcement) is affected by the following five principal variables:

1. concrete strength
2. relationship between size of loaded area and slab thickness
3. loaded area aspect ratio (shape of loaded area)
4. perimeter area aspect ratio
5. shear-to-moment ratio at slab-column connections

These variables are taken into account in the following formulations (ACI 318M-95)

$$V_c = \left(2 + \frac{4}{\beta_c} \right) \sqrt{f'_c} b_o d \quad (1)$$

$$V_c = \left(2 + \frac{\alpha_s}{b_o/d} \right) \sqrt{f'_c} b_o d \quad (2)$$

$$V_c = 4 \sqrt{f'_c} b_o d \quad (3)$$

Equation (2) may be rewritten as

$$V_c = \left(2 + \frac{\alpha_s}{\beta_o} \right) \sqrt{f'_c} b_o d \quad (4)$$

Where, b_o = perimeter of critical section

β_c = ratio of long side to short side of the column

β_o = parameter area aspect ratio (b_o/d)

$\alpha_s = 40$ for interior column

$\alpha_s = 30$ for edge column

$\alpha_s = 20$ for corner column

The β_c variable provides a transition between two-way action shear strength ($4\sqrt{f'_c}$) and beam-action shear strength ($2\sqrt{f'_c}$) as the loaded area (support size) becomes more elongated. For a support with aspect ratio less than or equal to 2 ($\beta_c \leq 2$), equation (1) reduces to $V_c = 4\sqrt{f'_c}b_o d$. Shear strength varies as a function of β_c as shown in Figure 9.

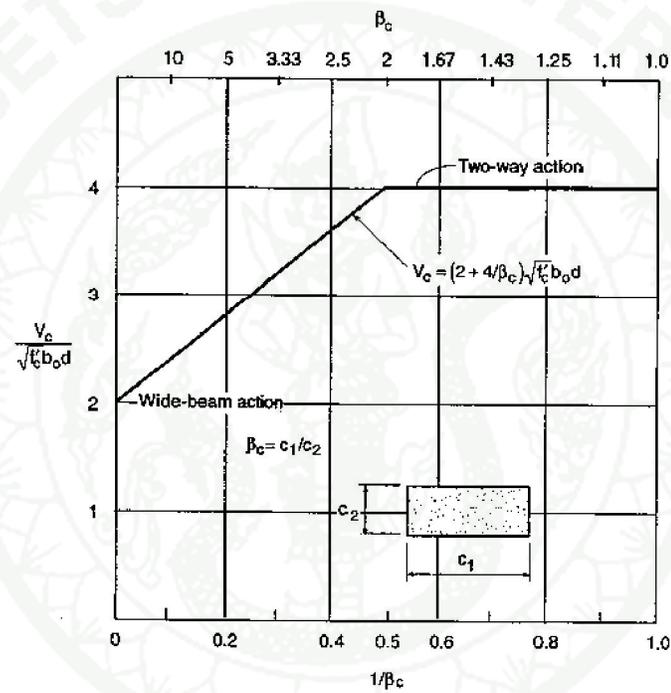


Figure 9 Shear strength of slabs without shear reinforcement (effect of loaded area aspect ratio, β_c)

Source: PCA (1996)

Equation (2) was introduced to account for a decrease in shear strength caused by increase in the perimeter area aspect ratio β_0 . Recent tests have indicated a decrease in shear strength as the ratio of the perimeter b_0 to the effective depth d increases. Shear strength variation as a function of β_0 is shown in Figure 10. Equation (2) reduces to $V_c = 4\sqrt{f'_c}b_o d$ for interior columns (4 sides effective, $\alpha_s = 40$) when $\beta_0 \leq 20$, edge columns (3 sides effective, $\alpha_s = 30$) when $\beta_0 \leq 15$, and corner

columns (2 sides effective, $\alpha_s = 20$) when $\beta_0 \leq 10$. With the adoption of equation (2), shear strength for very thin slabs or at larger and larger critical sections more distant from a loaded area or column, such as at the edges of drop panels or column capitals, may be significantly reduced due to the larger perimeter area aspect ratio β_0 .

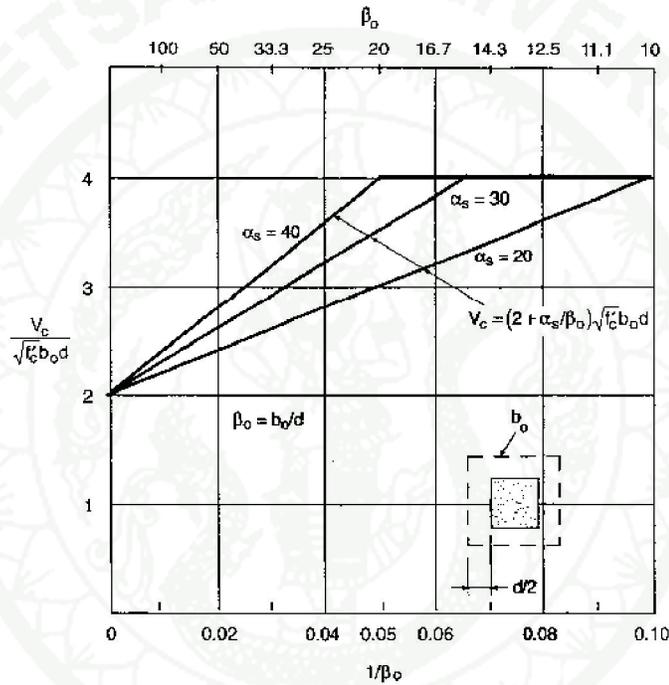


Figure 10 Shear strength of slabs without shear reinforcement (Effect of perimeter area aspect ratio β_0)

Source: PCA (1996)

Two-way action shear strength V_c is the lesser of values given by equations (1) and (2) but not greater than $V_c = 4\sqrt{f'_c} b_0 d$, where V_c is to be investigated at each of the critical sections b_0 .

The same shear strength V_c , the lesser of the values given by equations (1) and (2) but not greater than $4\sqrt{f'_c} b_0 d$, applies for transfer of moment at slab-column

connections without shear reinforcement. For moment transfer design condition, equations (1) and (2) must be expressed in terms of shear stress and maximum shear stress due to the fact direct shear and moment transfer shall not exceed ϕv_c . For usual design conditions, the governing shear stress will be $4\sqrt{f'_c}$.

$$\phi v_c = \phi \left(2 + \frac{4}{\beta_c} \right) \sqrt{f'_c} \quad (5)$$

$$\phi v_c = \phi \left(2 + \frac{\alpha_s}{\beta_0} \right) \sqrt{f'_c} \quad (6)$$

4. Increasing the shear strength of flat plates

When shear strength of slab is not adequate to transfer the factored shear force from slab to column support, shear strength can be increased by:

1. Increasing concrete strength f'_c
2. Increasing slab thickness at column support, i.e., using a drop panel
3. Providing shear reinforcement

If the drop panel is used for increasing the shear strength of the flat plate, investigation of two-way shear at critical sections b_0 more than a distance $d/2$ away from the column face is also required at edges of drop panels as shown in Figure 11(b).

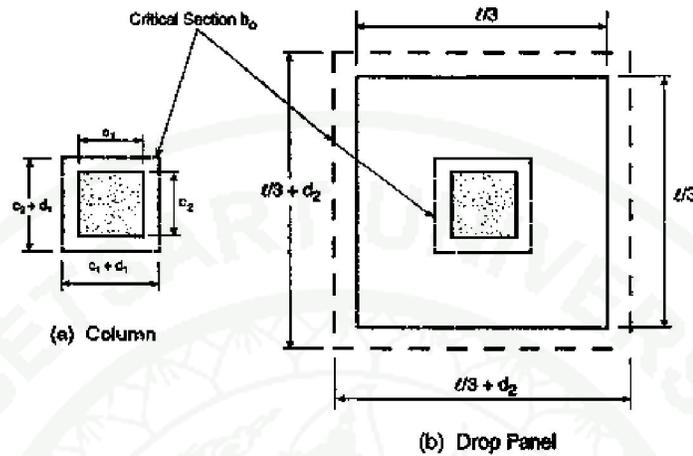


Figure 11 Critical section b_0 for investigation of two-way action shear strength

Source: PCA (1996)

When the factored shear force V_u exceeds the design shear strength ϕV_c available without shear reinforcement, special shear reinforcement can be used for flat plates. A few common types of shear reinforcement are as follows (Nilson, 1997):

The shearheads (Figure 12a) consist of standard structural steel shapes embedded in the slab and projecting beyond the column. They serve to increase the effective perimeter b_0 of the critical section for shear. The reinforcement is particularly suited for use with concrete columns. The channel frame (Figure 12c) is adapted for use with steel columns.

The bent-bar arrangement (Figure 12b) is suited for use with concrete columns. The bars are usually bent at 45 degree across the potential diagonal tension crack, and extend along the bottom of the slab a distance sufficient to develop their strength by bond. The flanged collar (Figure 12d) is designed mainly for use with lift-slab construction. It consists of a flat bottom plate with vertical stiffening ribs.

Another type of shear reinforcement (Figure 12e) is vertical stirrup, also called bar or wire reinforcement, which has been used in conjunction with supplementary horizontal bars radiating outward in two perpendicular directions from the support. ACI Code requires the slab effective depth d to be at least 6 in, but not less than 16 times the diameter of the shear reinforcement. The closed hoop stirrups should be used, with a large diameter horizontal bar at each bend point, and the stirrups must be terminated with a standard hook.

The last type is the shear stud reinforcement (Figure 12f). This consists of large-head studs welded to steel strips supported on wire chairs during construction, and the usual cover is maintained over the top of the head. Because of the positive anchorage provided by the stud and the steel strip, these devices are more effective than bent bars or integral beam reinforcement.

When bars or wires are used as shear reinforcement in slabs, the maximum shear strength V_n permitted is $6\sqrt{f'_c}b_0d$, i.e. the maximum shear strength provided by bar reinforcement is limited to $4\sqrt{f'_c}b_0d$ and shear strength provided by the concrete $V_c = 2\sqrt{f'_c}b_0d$. This can be expressed by the equation (7).

$$\phi V_n = \phi V_c + \phi V_s = \phi 6\sqrt{f'_c}b_0d \quad (7)$$

When shearheads are used as shear reinforcement in slabs, use of shearheads can increase the shear strength by $3\sqrt{f'_c}b_0d$ and the maximum shear strength V_n permitted with shearheads becomes $7\sqrt{f'_c}b_0d$ in which shear strength provided by the concrete $V_c = 4\sqrt{f'_c}b_0d$. The equation for the maximum strength with shearheads is:

$$\phi V_n = \phi V_c + \phi V_s = \phi 7\sqrt{f'_c}b_0d \quad (8)$$

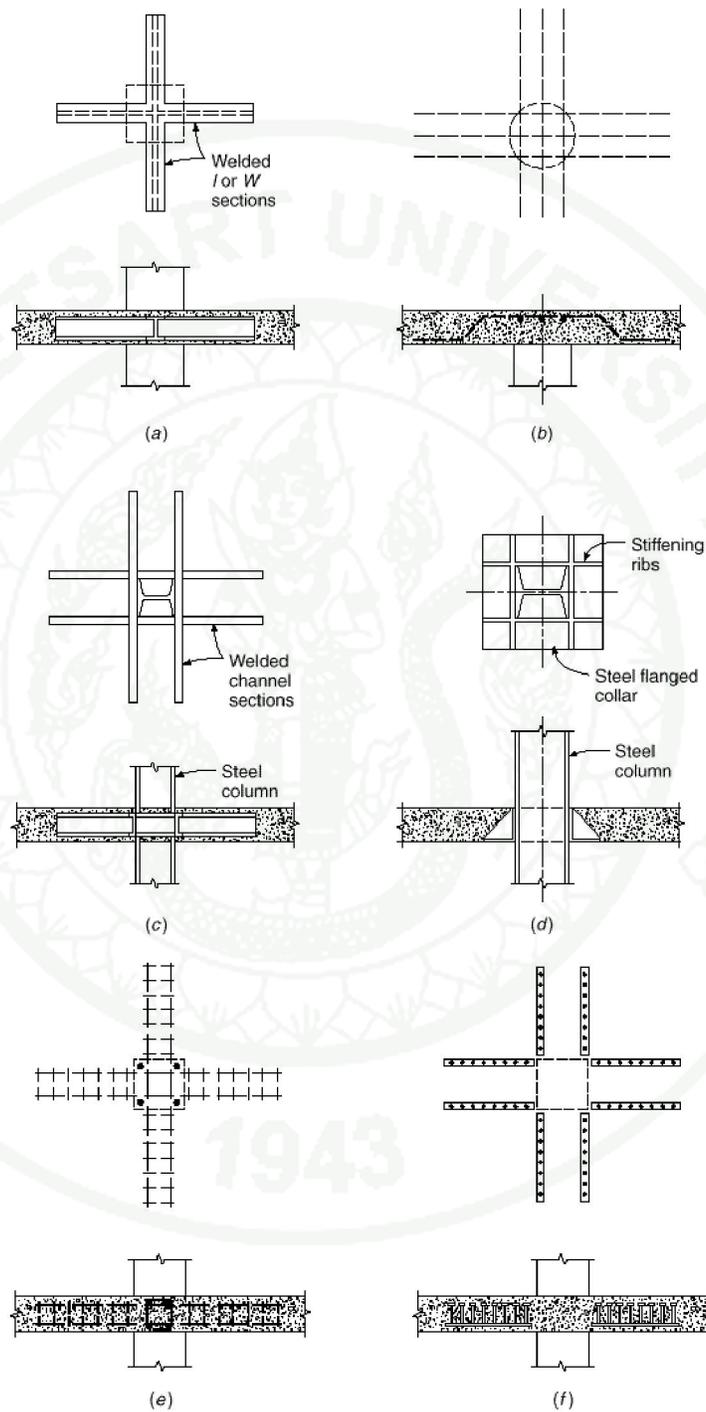


Figure 12 Shear reinforcement for flat plates

Source: Nilson (1997)

5. SAFE v12 Finite Element Formulations

Only the thick shell finite element is used in SAFE v12 as it includes shear deformation. The analytical model is a full three-dimensional model with 6 degrees of freedom at each joint.

5.1 Shell Element

The shell element is a type of area object that is used to model membrane, plate, and shell behavior in planar and three-dimensional structures. The shell material may be homogeneous or layered through the thickness. The shell element is a three- or four-node formulation that combines membrane and plate-bending behavior.

The homogeneous shell combines independent membrane and plate behavior. The membrane behavior uses an isoparametric formulation that includes translational in-plane stiffness components and a rotational stiffness component in the direction normal to the plane of the element. In-plane displacements are quadratic. The homogenous plate-bending behavior includes two-way, out-of-plane, plate rotational stiffness components and a translational stiffness component in the direction normal to the plane of the element. By default, a thin-plate (Kirchhoff) formulation is used that neglects transverse shearing deformation. Optionally, a thick plate (Mindlin/Reissner) formulation which includes the effects of transverse shearing deformation can be used. Out-of-plane displacements are cubic.

For each homogeneous shell element in the structure, pure-membrane, pure-plate, or full-shell behavior can be modeled. Structures that can be modeled with the shell element include:

1. Three-dimensional shells, such as tanks and domes
2. Plate structures, such as floor slabs
3. Membrane structures, such as shear walls

Homogeneous material properties are used for the non-layered Membrane, Plate, and Shell section types. A variable, four-to-eight-point numerical integration formulation is used for the shell stiffness. Stresses and internal forces and moments, in the element local coordinate system, are evaluated at the 2-by-2 Gauss integration points and extrapolated to the joints of the element.

Each shell element may have either of the quadrilateral or triangular shapes, as shown in Figure 13. The shell element always activates all six degrees of freedom at each of its connected joints. When the element is used as a pure plate, restraints or other supports must be provided to the degrees of freedom for in-plane translations and the rotation about the normal.

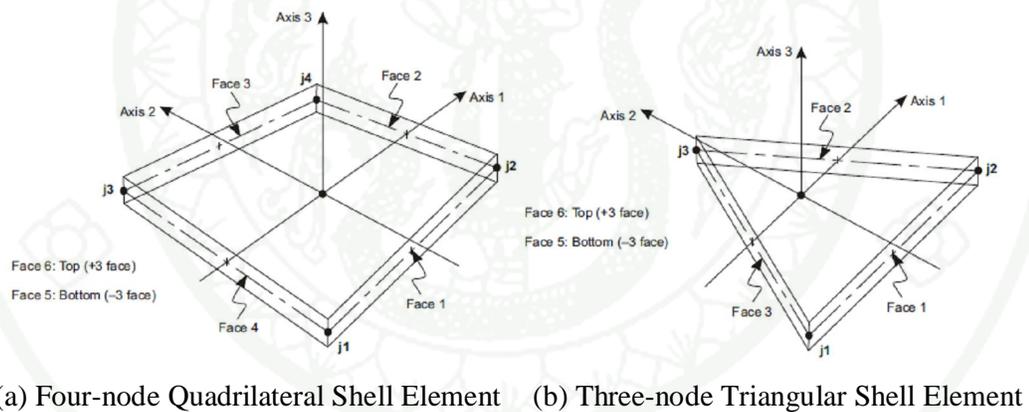


Figure 13 Area Element Joint Connectivity and Face Definitions

Source: Computer and structure (2008)

5.2 Thickness Formulation

Two thickness formulations are available, which determine whether or not transverse shearing deformations are included in the plate-bending behavior of a plate or shell element:

1. The thick-plate (Mindlin/Reissner) formulation, which includes the effects of transverse shear deformation

2. The thin-plate (Kirchhoff) formulation, which neglects transverse shearing deformation

Shearing deformations tend to be important when the thickness is greater than about one-tenth to one-fifth of the span. They can also be quite significant in the vicinity of bending-stress concentrations, such as near sudden changes in thickness or support conditions, and near holes or re-entrant corners.

Even for thin-plate bending problems where shearing deformations are truly negligible, the thick-plate formulation tends to be more accurate, although some what stiffer, than the thin-plate formulation. The thickness formulation has no effect upon membrane behavior, only upon plate-bending behavior.

5.3 Internal Force and Stress Output

The shell element internal forces (also called stress resultants) are the forces and moments that result from integrating the stresses over the element thickness. For a homogeneous shell, these internal forces are:

1. Membrane direct forces:

$$F_{11} = \int_{-th/2}^{+th/2} \sigma_{11} dx_3 \quad (9)$$

$$F_{22} = \int_{-th/2}^{+th/2} \sigma_{22} dx_3$$

2. Membrane shear force:

$$F_{12} = \int_{-th/2}^{+th/2} \sigma_{12} dx_3 \quad (10)$$

3. Plate bending moments:

$$M_{11} = - \int_{-th/2}^{+th/2} x_3 \sigma_{11} dx_3 \quad (11)$$

$$M_{22} = -\int_{-th/2}^{+th/2} x_3 \sigma_{22} dx_3$$

4. Plate twisting moment:

$$M_{12} = -\int_{-th/2}^{+th/2} x_3 \sigma_{12} dx_3 \quad (12)$$

5. Plate transverse shear forces:

$$V_{13} = \int_{-thb/2}^{+thb/2} \sigma_{13} dx_3 \quad (13)$$

$$V_{23} = \int_{-thb/2}^{+thb/2} \sigma_{23} dx_3$$

Where x_3 represents the thickness coordinate measured from the mid-surface of the element, th is the membrane thickness, and thb is the plate-bending thickness.

These stress resultants are forces and moments *per unit of in-plane length*. They are present at every point on the mid-surface of the element.

For the thick-plate (Mindlin/Reissner) formulation of the homogeneous shell, and for the layered shell, the shear stresses are computed directly from the shearing deformation. For the thin-plate homogeneous shell, shearing deformation is assumed to be zero, so the transverse shear forces are computed instead from the moments using the equilibrium equations:

$$V_{13} = -\frac{dM_{11}}{dx_1} - \frac{dM_{12}}{dx_2} \quad (14)$$

$$V_{23} = -\frac{dM_{12}}{dx_1} - \frac{dM_{22}}{dx_2}$$

Where x_1 and x_2 are in-plane coordinates parallel to the local 1 and 2 axes.

The sign conventions for the stresses and internal forces are illustrated in Figure 14. Stresses acting on a positive face are oriented in the positive direction of

the element local coordinate axes. Stresses acting on a negative face are oriented in the negative direction of the element local coordinate axes.

Positive internal forces correspond to a state of positive stress that is constant through the thickness. Positive internal moments correspond to a state of stress that varies linearly through the thickness and is positive at the bottom. Thus for a homogeneous shell:

$$\begin{aligned}
 \sigma_{11} &= \frac{F_{11}}{th} - \frac{12M_{11}}{thb^3} x_3 \\
 \sigma_{22} &= \frac{F_{22}}{th} - \frac{12M_{22}}{thb^3} x_3 \\
 \sigma_{12} &= \frac{F_{12}}{th} - \frac{12M_{12}}{thb^3} x_3 \\
 \sigma_{13} &= \frac{V_{13}}{thb} \\
 \sigma_{23} &= \frac{V_{23}}{thb} \\
 \sigma_{33} &= 0
 \end{aligned} \tag{15}$$

The force and moment resultants are reported identically for homogeneous and layered shells. Stresses are reported for homogeneous shells at the top and bottom surfaces, and are linear in between.

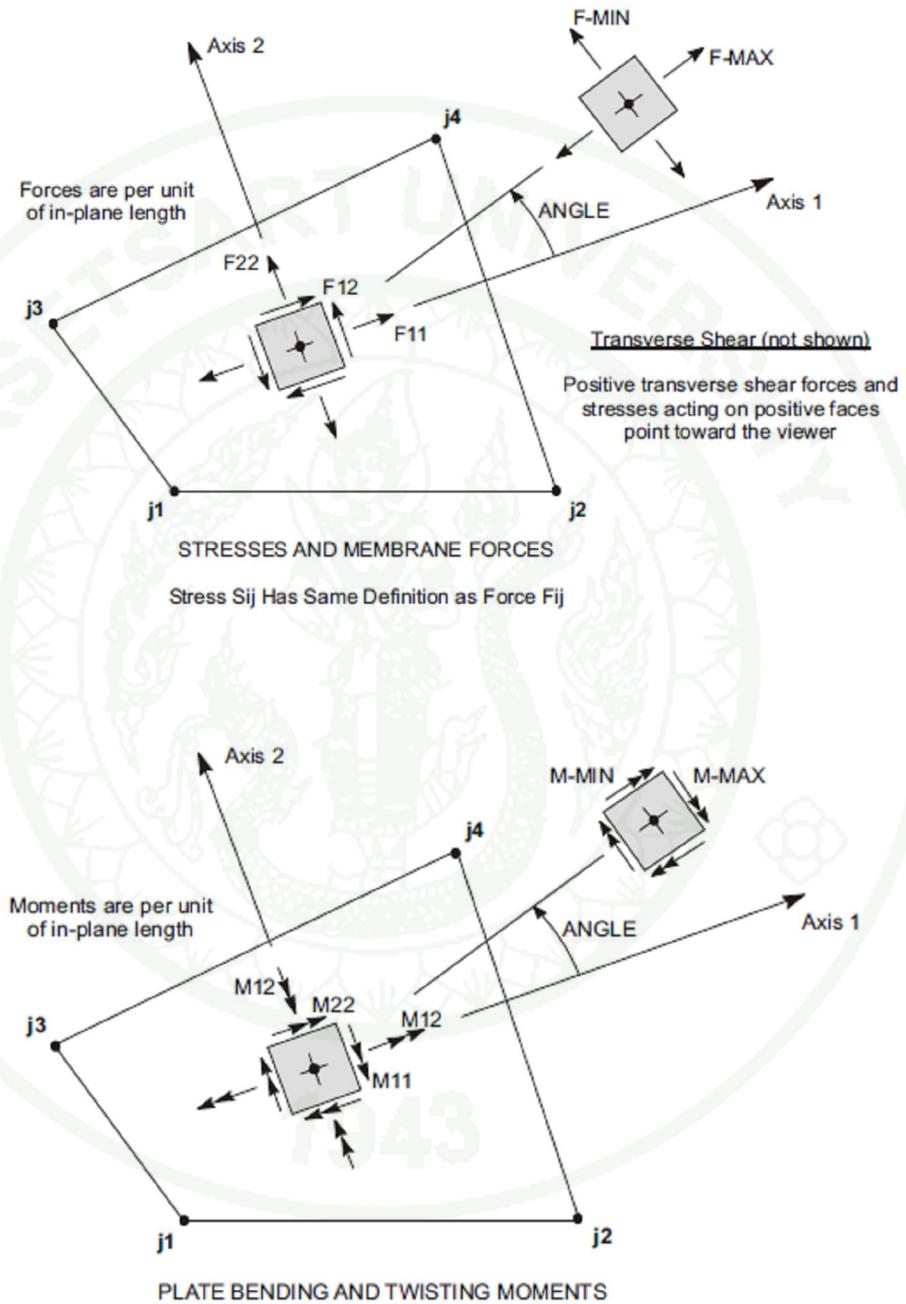


Figure 14 Shell Element Stresses and Internal Resultant Forces and Moments

Source: Computer and structure (2008)

6. Review of studies on flat plate with openings

Prawat (2000) studied the behavior of flat plates with openings of any size, varying from the size permitted by the building code and standard of ACI and EIT to the size larger than permitted size. The four locations of openings were the openings in the area common to intersecting middle strips, the area common to one column strip and one middle strip, the area common to one middle-column strip and one middle strip and the area common to intersecting column strips. The result of study indicated that the openings in the area common to the intersecting middle strips could be any size according to the code. In the area common to one column strip and one middle strip, the bending moments and shears were increased if the opening size was larger than the permitted one. For the opening in the area common to intersecting column strips, no significant changes in behavior of plate were found if the opening size was according to the code. If the opening size was larger than specified by the code, the bending moments and shears were increased by varying amount according to its size and location closing to the column.

Sukhom (2007) studied the behavior of flat plate with opening in column strip. The locations of openings in column strip were the openings at interior column, the openings at corner column and the openings at the edge column. The openings sizes are one-tenth, one-fifth, three-tenths, and two-fifths of the width of column strip. From this study, the results showed that the openings at the face of the column were more critical than the openings at the corner of column in column strip region of the flat plate. With the openings either at the interior side or the exterior side of the interior column, the sizes of opening affected the stress resultants when the openings expanded in parallel direction of the face of the column.

MATERIALS AND METHODS

Materials

1. PC-Computer with CPU speed 2.0 GHz and 1.99 GB of RAMS
2. Software SAFE v12 (2008)

Methods

1. Literature Review

Past literature related to the behavior of flat plate with openings was reviewed for the sizes and locations of openings in the flat plate to be used in this study. ACI methods for the shear strength calculation of slabs were studied to compute the shear strength provided by the concrete of the flat plates and also by the shear reinforcement of the flat plates.

2. Computer program testing

Before analyzing for this research, the software SAFE v12 was tested by comparing the analysis results with other analytical methods.

Table 1 List of models and analytical methods for computer program testing

Models	Analytical Methods
1. Flat plate without opening	Lèvy method
2. Flat plate without opening	Equivalent frame method
3. Single panel flat plate with openings	Finite difference method

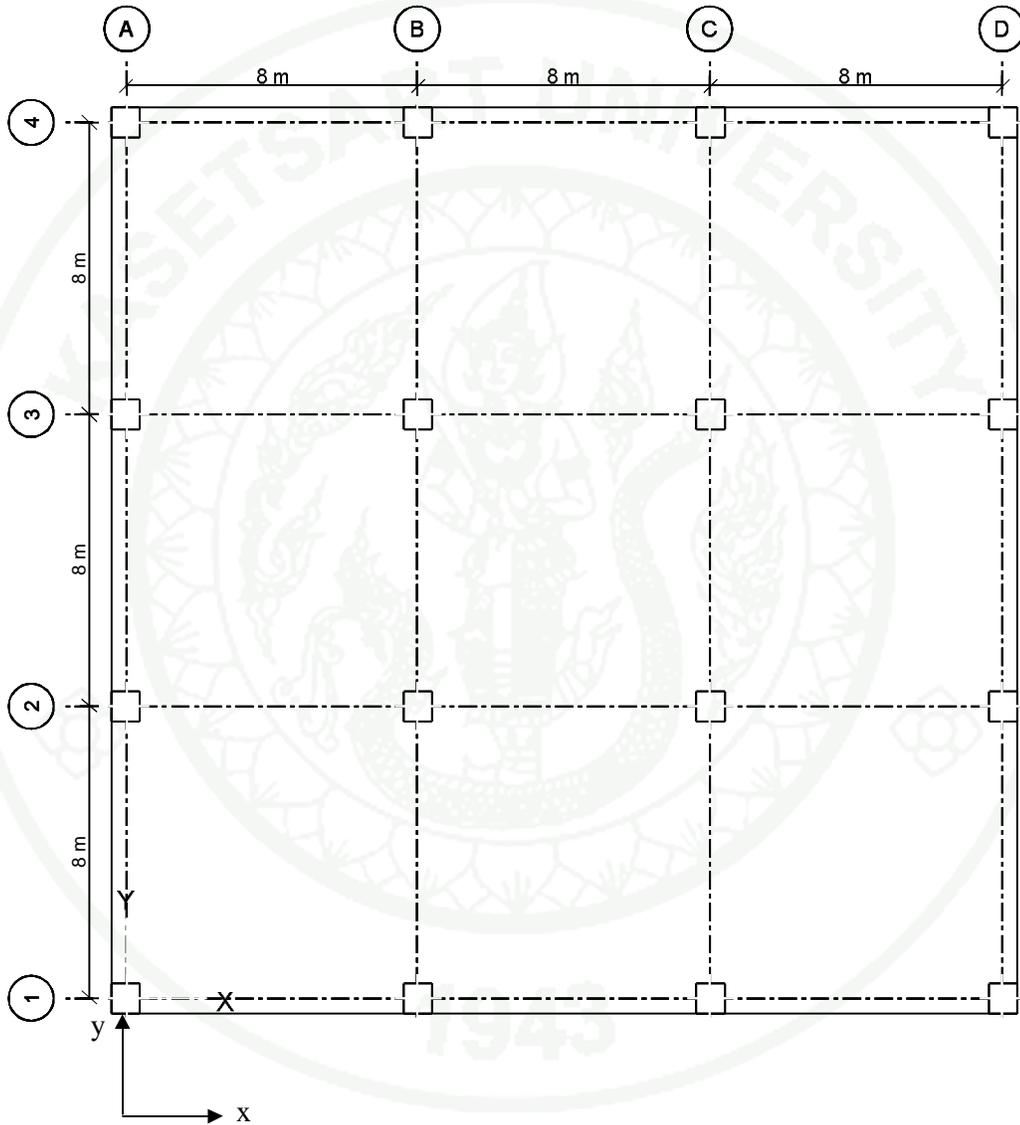


Figure 15 Plan of flat plate model (without opening)

2.1 Flat plate without openings

Flat plate model without openings shown in Figure 15 is used for comparing the software with analytical method. To compare with the values given by Lèvy method (Timoshenko, 1959), the model was analyzed for a uniform service load of 1 kN/m^2 . To compare with the Equivalent Frame Method (EFM) (ACI 318M-95), the model was analyzed for a uniform factored load of 14.6 kN/m^2 .

Table 2 Comparison of analysis resultants of flat plate model between SAFE v12 and Lèvy method

Resultant	SAFE v12	Lèvy method	% difference	location
M_x, M_y (kN-m/m)	1.8789	2.1056	-10.8	x= 12 m, y=12 m
M_x (kN-m/m)	-1.2186	-1.1648	4.6	x= 16 m, y=12 m
M_y (kN-m/m)	3.2512	2.9257	-10	x= 16 m, y=12 m
Q_{\max} (kN/m)	22.1	21.84	1.2	-

In Table 2, the positive bending moments given by Lèvy method are larger than the SAFE v12 result because the Lèvy method assumed that the reactions are uniformly distributed over the column area to calculate the bending moments. But, the least difference between the program and Lèvy method is shown for the maximum shear force of the flat plate.

Table 3 Comparison of bending moment and shear force of flat plate model between Equivalent Frame Method and SAFE v12

Method	Bending Moment (kN-m)					Shear Force (kN)		
	End Span		Interior Span			End support	Interior support	
	Exterior negative	Positive	Interior negative	Negative	Positive	Right	Left	Right
EFM	244	372	525	476	281	381	459	420
SAFE	341	332	526	483	281	389	443	417
% difference	40	-10	0.2	1.5	-	2	-3.5	-1

The comparison of the interior design strip forces is shown in Table 3. The SAFE v12 and EFM results for exterior negative strip moment show the greatest difference. This is expected because EFM simplifies a 3D structure to a 2D structure, thereby neglecting the transverse interaction between adjacent strips (SAFE verification manual, 2008). Except for this localized difference, the percentages of difference are less than 5 percent.

2.2 Flat plate with openings

Single span flat plate model with openings is shown in Figure 16. The flat plate is supported by four square columns and four square openings located at the corner of each column. The deflection and stress resultants are compared between the SAFE v12 and Finite Difference Method (FDM) as shown in Table 4.

The data for analysis of single span flat plate model are as follows:

Size of flat plate	8.0 m x 8.0 m
Thickness	0.25 m
Size of columns	0.8 m x 0.8 m
Size of openings	0.8 m x 0.8 m
E	271900 kg/cm ²
ν	0.19
Uniform load	14.6 kN/m ²

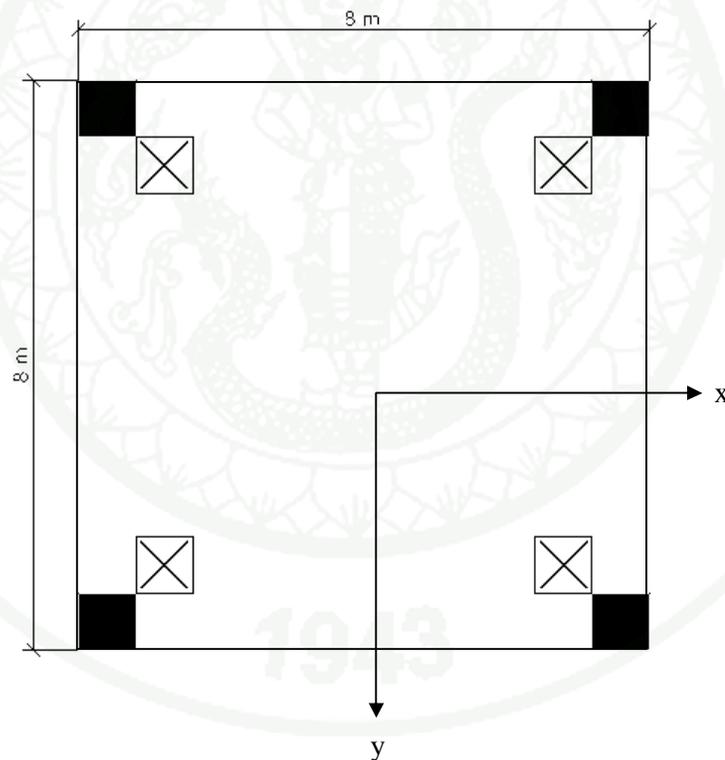


Figure 16 Plan of single span flat plate model

At the coordinate (0.8,-0.8), the shear force results difference between SAFE v12 and FDM is about 15% while all other analysis results differences as shown in Table 4 are less than 10%.

Table 4 Comparison of deflection, moment and shear of single flat plate model with openings between SAFE v12 and Finite Difference Method (FDM)

Coordinate		w		M_x		M_y		V_x		V_y	
(m)		(mm)		(kN-m/m)		(kN-m/m)		(kN/m)		(kN/m)	
x	y	SAFE	FDM	SAFE	FDM	SAFE	FDM	SAFE	FDM	SAFE	FDM
0	0	7.34	7.35	33.93	34.83	33.93	34.83	0	0	0	0
0.8	-0.8	6.83	6.82	31.23	32.15	31.24	32.15	5.34	6.33	-5.39	-6.33
1.6	0	6.42	6.38	21.78	21.26	39.11	37.67	7.69	8.44	0	0
0	-1.6	6.42	6.38	39.11	37.67	21.78	21.26	0	0	-7.69	-8.44

3. Analysis of flat plate with and without openings

After SAFE v12 was tested by comparing the analysis results with other analytical method, the analyses were continued for the flat plate with and without openings by SAFE v12. Flat plate model is comprised of three by three equal width panels supported by sixteen square columns as shown in Figure 15. All column dimensions are 0.8m x 0.8m. The center to center span length of flat plate models is 8 m in both direction (x and y axes) and the thickness is 0.25 m. Superimposed dead load of 1.5 kN/m² and service live load of 2.5 kN/m² are applied to the models as uniformly distributed load.

According to ACI 318-95, the column strip is design strips with a width on each side of a column centerline equal to one-quarter the transverse or longitudinal span, whichever is smaller and the middle strip is a design strip bounded by two column strips. When the flat plate models are divided into the middle and column strips of 4.0 m width, a total of 49 areas occur in the flat plate model as shown in Figure 17.

The properties of flat plate model used for structural analysis are as follows:

Concrete	f'_c	320 kg/cm ²
	E	271900 kg/cm ²
	v	0.19

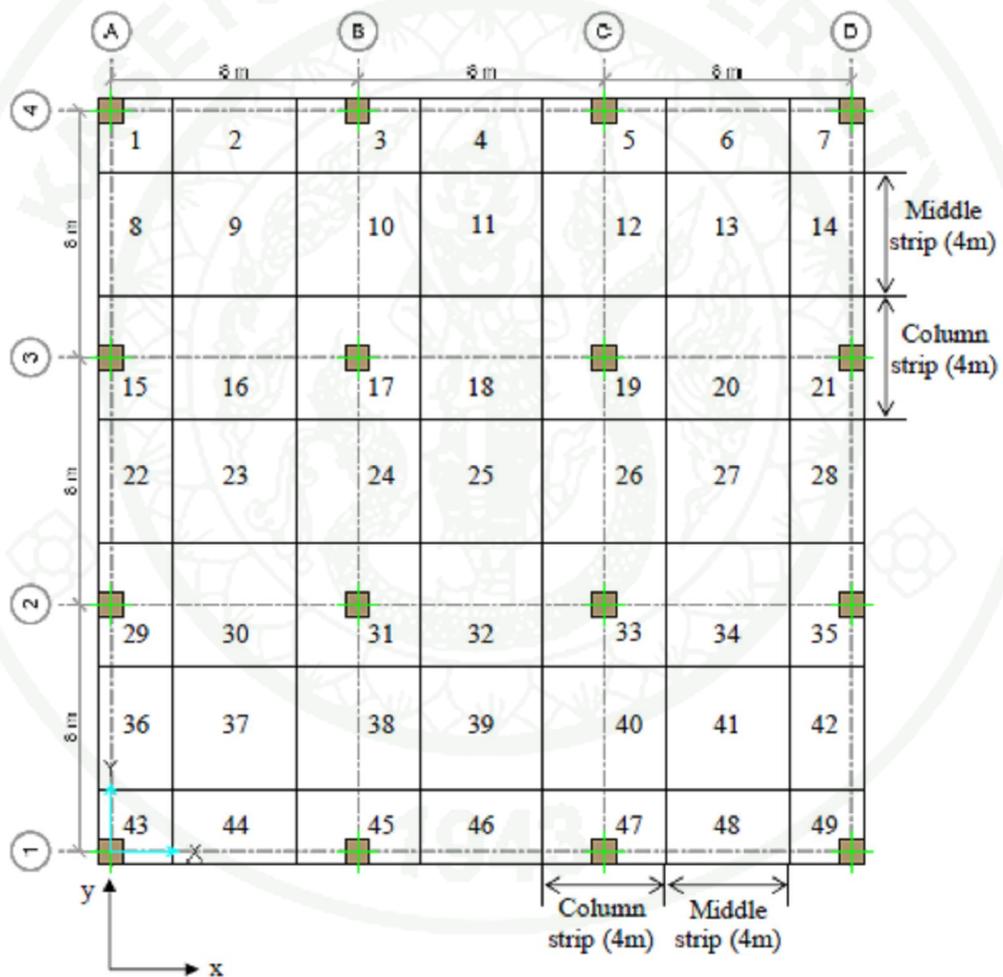


Figure 17 Plan of flat plate model (without opening) divided into the 49 areas

The effects of openings on the resultants of flat plate were investigated by the following steps:

3.1 Effect by the locations of the openings

3.2 Effect by the sizes of the openings

In the first step, the eight numbers of openings were located in individual areas (shown in Figure 18) and these openings can be categorized as shown in Table 5. The location effect of the openings in the flat plate was studied by comparing the percentage differences in the bending moment and shear force resultants between the flat plate with openings and without opening.

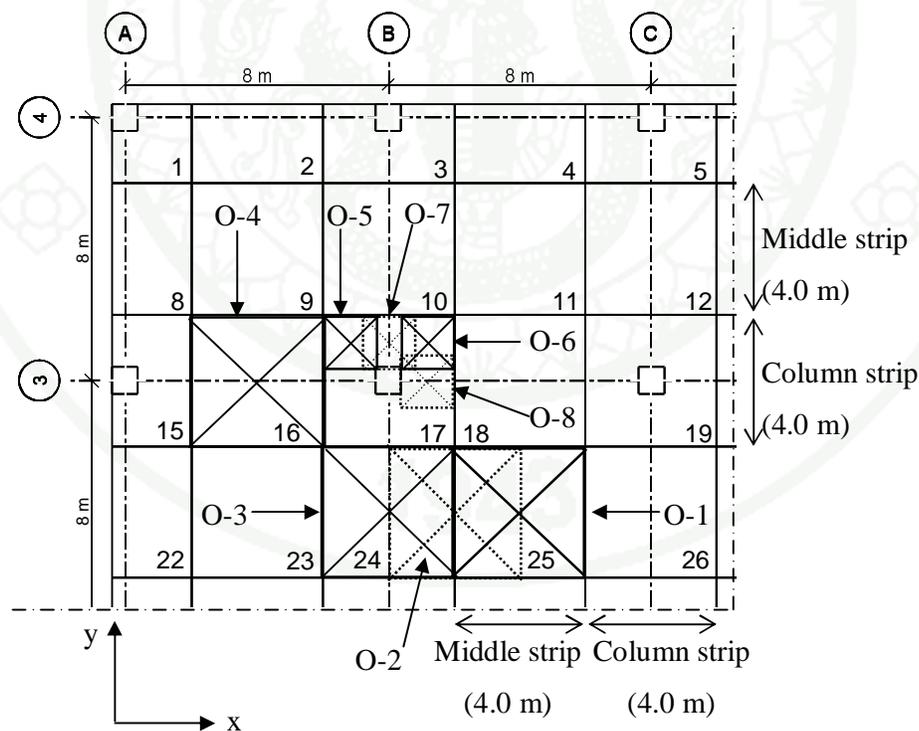


Figure 18 Locations of openings used in first step of analysis

Table 5 Categories of openings in flat plate used in first step of analysis

Designation	Location	Size (m ²)	Area No.
O-1	Middle, middle	4.0 x 4.0	25
O-2	Middle-column, middle	4.0 x 4.0	24, 25
O-3	Middle, column	4.0 x 4.0	24
O-4	Middle, column	4.0 x 4.0	16
O-5	Column, column	1.6 x 1.6	17
O-6	Column, column	1.6 x 1.6	17
O-7	Column, column	1.6 x 1.6	17
O-8	Column, column	1.6 x 1.6	17

After the first step, only the openings affecting the resultants will be investigated by varying their sizes. In the second step, a total number of four openings were located in different areas of the critical location and the effect of opening size was studied. The size of openings were varied as 0.40 m, 0.80 m, 1.20 m and 1.60 m in the direction parallel to the column face 'b' and in the direction transverse to the column face 'a' (shown in Figure 19). The bending moment and shear force resultants were compared with the flat plate without openings.

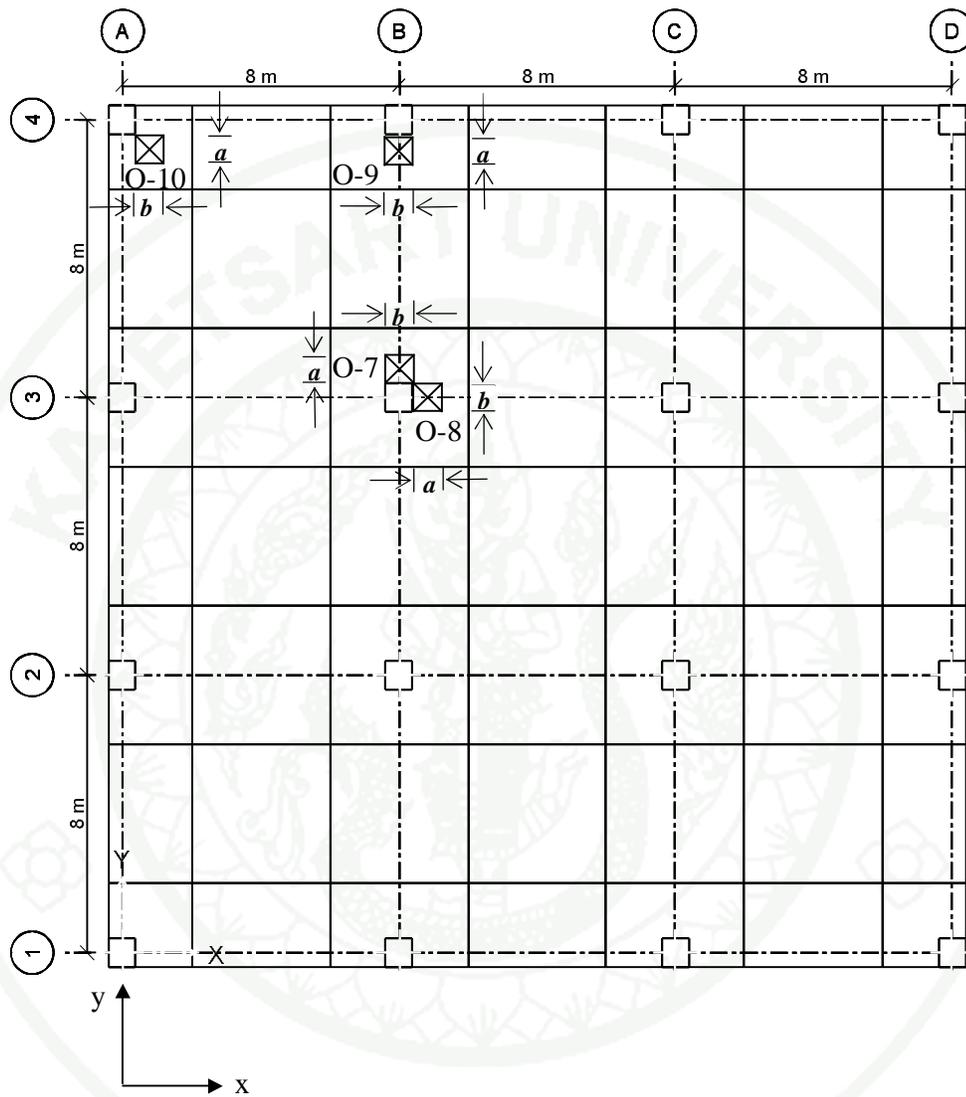


Figure 19 Locations of opening size variation used in second step of analysis

4. Effect by the openings on shear strength of the flat plate

As the final step of the study, the effect on the shear strength by the openings was studied. The resisting shear strength provided by the concrete was calculated by using the ACI formulae (Equations 1, 2, and 3). The shear forces of the flat plate under the given loading analyzed by SAFE v12 were compared with the resisting shear strength given by ACI formulae. For the openings O-7, O-8 and O-9 in which the resulting shear force is greater than the resisting shear strength, two methods were studied to increase the shear strength.

1. Increasing the shear strength by shear reinforcement

First, bar reinforcement (Figure 12e) and shearheads reinforcement (Figure 12a) were introduced without increasing the thickness of the flat plate. The maximum shear strength (ϕV_n) permitted with these shear reinforcements were calculated by using equations (7) and (8), and the ratios $V_u/\phi V_n$ were calculated for the openings which require the additional shear strength to resist the required shear force.

2. Increasing the shear strength by drop panel around opening

Next, the thickness of the flat plate was increased around the opening and the column as shown in Figure 20, i.e. providing a drop panel. Both the size and thickness of drops were varied to study their effect on the shear strength. The minimum width of the drop panel (w_d) beyond the perimeter of opening and the column is used as 0.2m for first trial and 0.4m for second trial. The overall thickness of the drop panel (h_d) is increased with an increment of 0.05m until the shear strength provided by the concrete meet the required shear force.

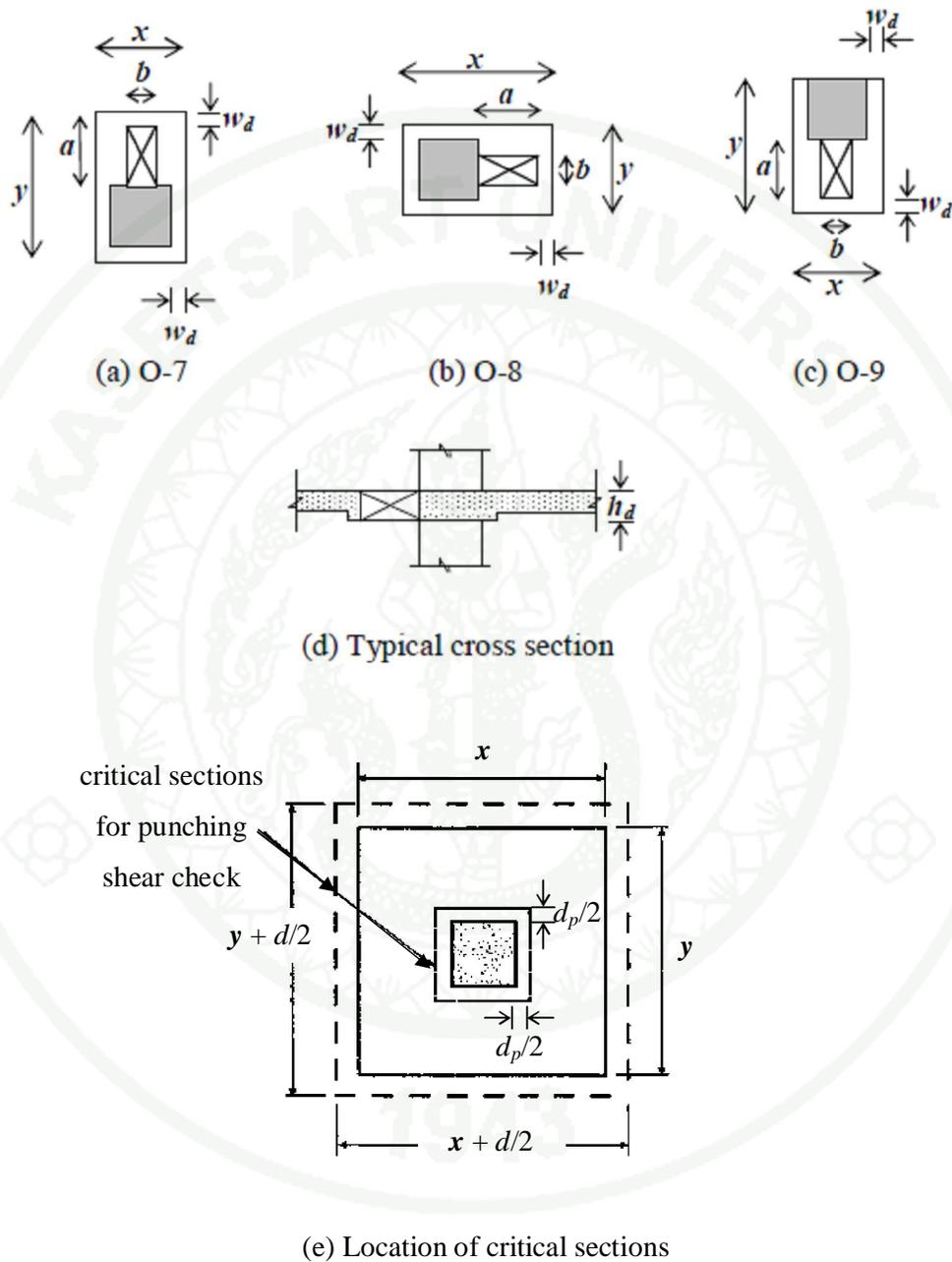


Figure 20 Drop panel details

- a = opening width in the direction perpendicular to the column face
- b = opening width in the direction parallel to the column face
- x = drop panel width along x direction axis

y = drop panel width along y direction axis

d = effective depth of slab (0.25m)

w_d = minimum width of the drop panel beyond the perimeter of opening and column

d_p = effective depth of drop panel

h_d = overall thickness of the drop panel (d_p + concrete cover 0.05m)

The shear strength provided by the concrete around the opening of the flat plate with drop panel is calculated by using equations (1), (2) and (3). For the required shear force, the flat plates with drop panels around openings O-7, O-8 and O-9 are analyzed by SAFE v12. The shear strength of the flat plate around the openings with the drop panel is investigated for two critical sections, i.e. at a distance $d_p/2$ away from the column face and at a distance $d/2$ away from edge of drop panel as shown in Figure 20.

RESULTS AND DISCUSSIONS

1. Analysis of flat plate without openings

For the flat plate without opening, the analytical results are presented in term of coefficients for the maximum bending moments and absolute maximum shear forces of the individual areas (Appendix Table B1). The maximum bending moments and absolute maximum shear forces of the flat plate without opening occurred at the areas 17, 19, 31 and 33 as shown in Table 6. The interpretation of coefficients is shown in Figure 21 and Equation 14.

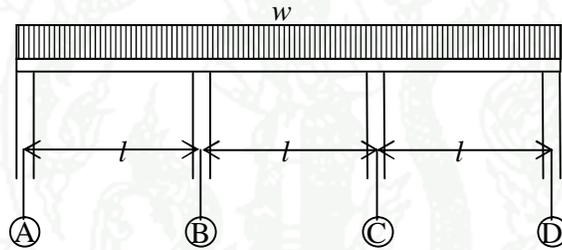


Figure 21 Interpretation of coefficients of bending moments and shear forces

$$\begin{aligned}
 M_x &= \beta_x wl^2 \\
 M_y &= \beta_y wl^2 \\
 V_x &= \gamma_x wl \\
 V_y &= \gamma_y wl
 \end{aligned}
 \tag{14}$$

Table 6 Coefficients of maximum bending moment and shear force resultants of flat plate without opening

Area No.	Coefficients			
	β_x	β_y	γ_x	γ_y
17	-0.031	-0.031	0.324	0.324
19	-0.031	-0.031	0.323	0.323
31	-0.031	-0.031	0.323	0.323
33	-0.031	-0.031	0.324	0.324

2. Analysis of flat plate with openings

The flat plate with openings was analyzed to study the effect of opening location and the effect of opening size at critical location. The analysis results are compared between the flat plate with openings and without openings.

2.1 Effect by the locations of the openings

To study the location effect of openings, a total of eight openings [O-1 to O-8] were located in the different locations in the flat plate to study the location effect of openings. The eight locations of the openings are as shown in Figure 18.

2.1.1 Opening at the area common to intersecting middle strips [O-1]

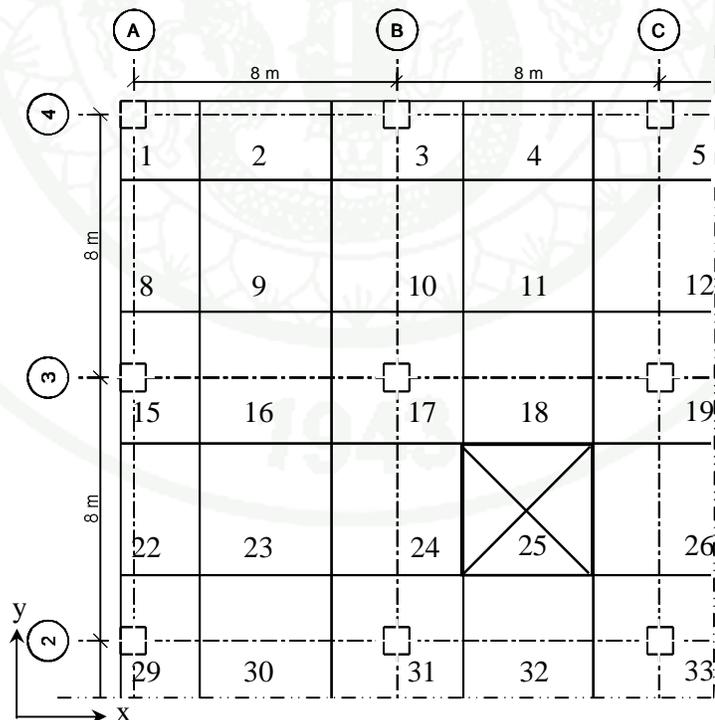


Figure 22 Flat plate model with opening at the area common to intersecting middle strips [O-1]

Table 7 Changes in percentage of maximum bending moment and shear force resultants in flat plate with opening O-1

Area No.	Resultant Coefficients				Resultant changes (%)			
	β_x	β_y	γ_x	γ_y	M_x	M_y	V_x	V_y
17	-0.031	-0.031	0.308	0.307	0	0	-5	-5
18	0.005	-0.005	0.053	0.033	-13	-15	-12	2
19	-0.031	-0.031	0.307	0.307	0	0	-5	-5
24	-0.005	0.005	0.033	0.053	-15	-13	2	-12
26	-0.005	0.005	0.033	0.053	-15	-13	2	-12
31	-0.031	-0.031	0.307	0.307	0	0	-5	-5
32	0.005	-0.005	0.053	0.033	-13	-15	-12	2
33	-0.031	-0.031	0.307	0.308	0	0	-5	-5

When the 4.0 m square size of opening O-1 is located at the area 25 which is the area common to intersecting middle strips as shown in Figure 22, the bending moments M_x and M_y increase in the areas around the exterior columns and decrease in the areas around the opening. The maximum change of bending moment is 15% decrease in the areas 24 & 26 for M_x and in areas 18 & 32 for M_y . However, the overall maximum bending moments of the flat plate do not change due to the opening O-1 as shown in Table 15 and occur in the same locations as the flat plate without opening.

Shear forces V_x and V_y also increase in the areas around the exterior columns and decrease in the areas around the opening. The maximum change of shear force is 12% decrease in areas 18 & 32 for V_x and in areas 24 & 26 for V_y . The overall maximum shear forces of the flat plate with opening O-1 occur in the same locations as the flat plate without opening but decrease about 5%.

2.1.2 Opening at the area common to one middle-column strip and one middle strip [O-2]

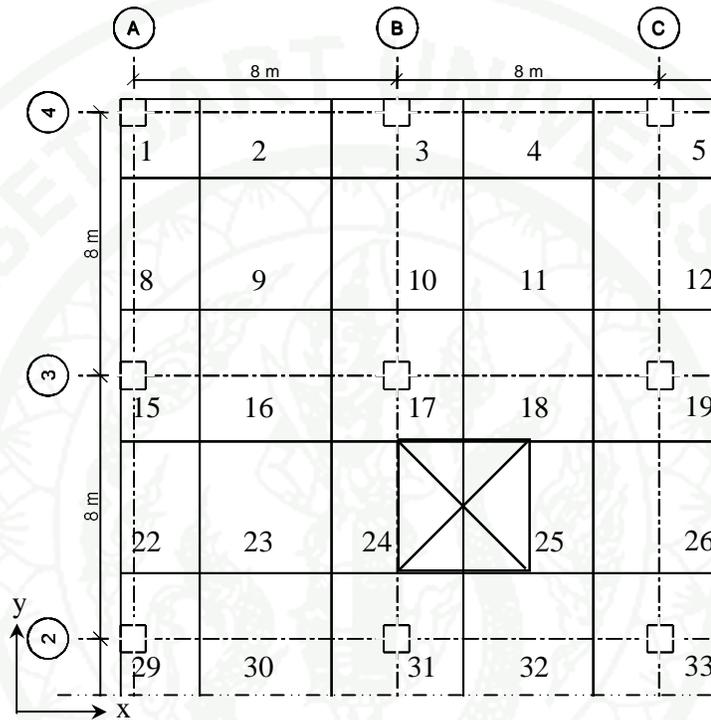


Figure 23 Flat plate model with opening at the area common to one middle-column strip and one middle strip [O-2]

When the halves of areas 24 & 25 are opened for the 4.0 m square size of opening O-2 at the area common to one middle-column strip and one middle strip as shown in Figure 23, the bending moment M_x increases in most of the areas but M_y decreases in the areas around the opening and increases in the areas around the exterior columns. The maximum changes of bending moment are 93% increase in areas 18 & 32 for M_x and 14% decrease in areas 24 & 25 for M_y . The overall maximum bending moments of the flat plate do not change due to the opening O-2 as shown in Table 15. Overall maximum M_x occurs at areas 17, 19, 31 & 33 and overall maximum M_y occurs at areas 19 & 33.

Shear forces V_x and V_y increase in the areas around some of the edge columns and decrease in most of the areas. The maximum changes of shear force in V_x and V_y are 57% increase and 83% increase respectively in area 24. The overall maximum shear forces of the flat plate with opening O-2 occur at areas 19 & 33 but decrease about 2%.

Table 8 Changes in percentage of maximum bending moment and shear force resultants in flat plate with opening O-2

Area No.	Resultant Coefficients				Resultant changes (%)			
	β_x	β_y	γ_x	γ_y	M_x	M_y	V_x	V_y
17	-0.031	-0.031	0.297	0.299	0	-2	-8	-8
18	0.011	-0.006	0.057	0.033	93	-5	-6	4
19	-0.031	-0.031	0.318	0.318	0	0	-2	-2
24	-0.006	0.005	0.050	0.110	-2	-14	57	83
25	0.005	0.004	0.021	0.036	20	-14	-17	38
31	-0.031	-0.031	0.296	0.299	0	-2	-8	-8
32	0.011	-0.006	0.057	0.033	93	-5	-6	4
33	-0.031	-0.031	0.319	0.318	0	0	-2	-2

2.1.3 Openings at the area common to one column strip and one middle strip [O-3 and O-4]

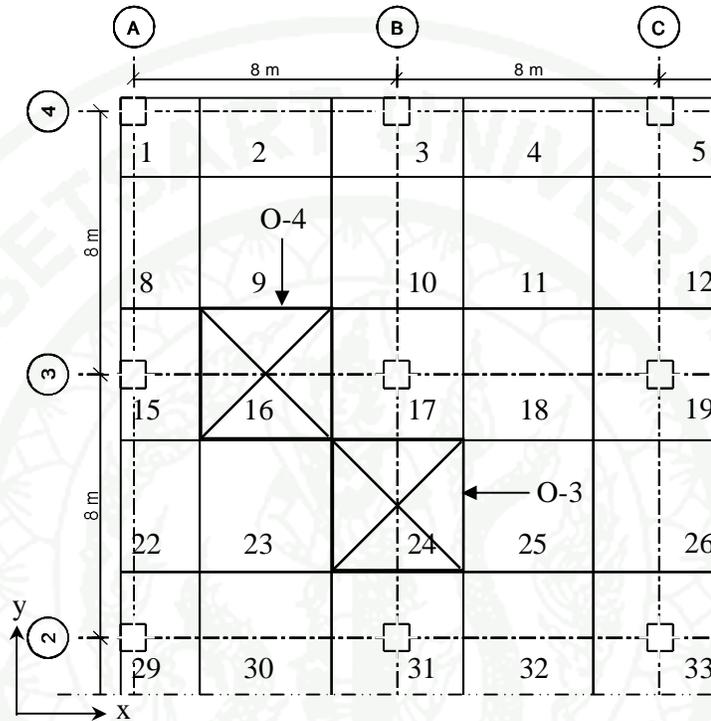


Figure 24 Flat plate model with openings at the area common to one column strip and one middle strip [O-3 and O-4]

Table 9 Changes in percentage of maximum bending moment and shear force resultants in flat plate with opening O-3

Area No.	Resultant Coefficients				Resultant changes (%)			
	β_x	β_y	γ_x	γ_y	M_x	M_y	V_x	V_y
17	-0.031	-0.031	0.289	0.298	0	-1	-11	-8
19	-0.031	-0.031	0.324	0.324	0	0	0	0
23	0.006	0.005	0.071	0.115	3	11	145	341
25	0.005	0.005	0.064	0.106	4	6	150	309
31	-0.031	-0.031	0.288	0.298	0	-1	-11	-8
33	-0.031	-0.031	0.324	0.324	0	0	0	0

When the 4.0 m square size of opening O-3 is located at area 24, which is the area common to one column strip and one middle strip as shown in Figure 24, the bending moment M_x increases in some of the areas. Also, M_y increases in areas around the columns close to the opening but decreases in the areas adjacent to the opening except in areas 23 & 25. The maximum changes of bending moment are 4% increase in area 25 for M_x and 11% increase in area 23 for M_y .

Shear forces V_x and V_y increase in the areas around the opening. The maximum changes of shear force are 150% increase in area 25 for V_x and 341% increase in area 23 for V_y . The overall maximum bending moments and shear forces of the flat plate do not change due to the opening O-3 as shown in Table 15. Overall maximum M_x occurs at the same locations as the flat plate without opening and overall maximum of M_y , V_x and V_y occur at areas 19 & 33.

Table 10 Changes in percentage of maximum bending moment and shear force resultants in flat plate with opening O-4

Area No.	Resultant Coefficients				Resultant changes (%)			
	β_x	β_y	γ_x	γ_y	M_x	M_y	V_x	V_y
9	0.006	0.006	0.124	0.075	13	3	330	160
15	-0.022	-0.025	0.167	0.169	-25	-9	-28	-20
17	-0.028	-0.030	0.291	0.286	-9	-4	-10	-11
19	-0.031	-0.031	0.324	0.324	0	0	0	0
23	0.006	0.005	0.116	0.070	9	4	301	166
31	-0.031	-0.031	0.324	0.324	0	0	0	0
33	-0.031	-0.031	0.324	0.324	0	0	0	0

When the 4.0 m square size of opening O-4 is located at area 16 which is the area common to one column strip and one middle strip as shown in Figure 24, the changes in bending moment and shear force occur in the areas adjacent

to the opening. The maximum changes of bending moment in M_x and M_y are 25% decrease and 9% decrease respectively in area 15.

The maximum changes of shear force are 330% increase in area 9 for V_x and 166% increase in area 23 for V_y . However the overall maximum bending moments and shear forces of the flat plate do not change due to the opening O-4 as shown in Table 15 and occur at areas 19, 31 & 33.

2.1.4 Openings at the area common to intersecting column strips [O-5, O-6, O-7 and O-8]

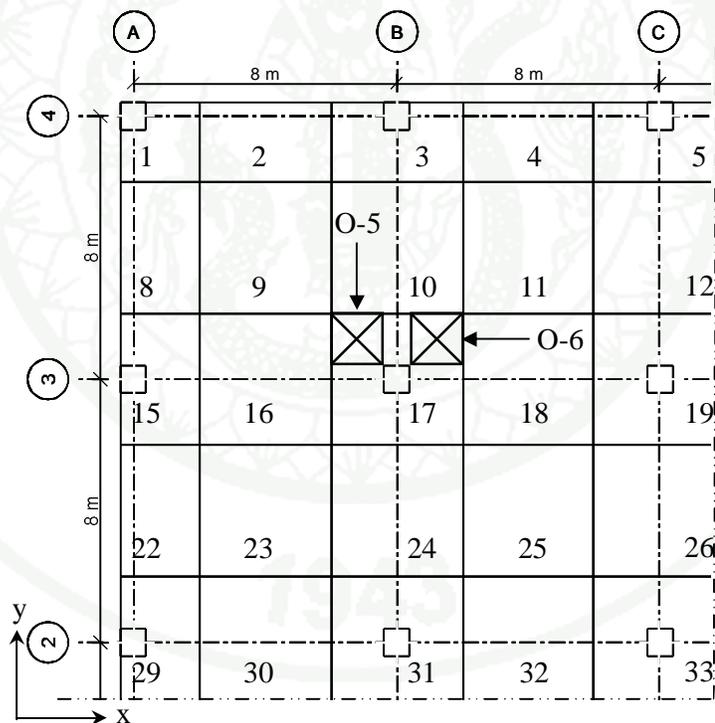


Figure 25 Flat plate model with openings at the area common to intersecting column strips [O-5 and O-6]

Table 11 Changes in percentage of maximum bending moment and shear force resultants in flat plate with opening O-5

Area No.	Resultant Coefficients				Resultant changes (%)			
	β_x	β_y	γ_x	γ_y	M_x	M_y	V_x	V_y
10	-0.015	0.008	0.164	0.110	151	23	413	71
16	0.008	-0.015	0.110	0.164	23	151	71	411
17	-0.036	-0.036	0.318	0.318	16	16	-2	-2
19	-0.031	-0.031	0.324	0.324	0	0	0	0
31	-0.031	-0.031	0.324	0.324	0	0	0	0
33	-0.031	-0.031	0.323	0.324	0	0	0	0

When the 1.6 m square size of opening O-5 is located at the left corner of the column in area 17 which is the area common to intersecting column strips as shown in Figure 25, bending moments and shear forces increase in the areas around the opening. The maximum changes of bending moment in M_x and M_y are 151% increase at area 10 and 16 respectively. The overall maximum bending moments of the flat plate with opening O-5 occur only at area 17 and increase about 16% more than the flat plate without opening.

The maximum changes of shear forces are 413% increase in the area 10 for V_x and 411% increase in the area 16 for V_y . However the overall maximum shear forces of the flat plate do not change due to opening O-5 as shown in Table 15 and occur at areas 19, 31 & 33.

Table 12 Changes in percentage of maximum bending moment and shear force resultants in flat plate with opening O-6

Area No.	Resultant Coefficients				Resultant changes (%)			
	β_x	β_y	γ_x	γ_y	M_x	M_y	V_x	V_y
10	-0.015	0.008	0.161	0.108	139	19	404	69
17	-0.034	-0.037	0.325	0.317	7	19	0	-2
18	0.008	-0.015	0.102	0.154	31	150	70	381
19	-0.031	-0.031	0.326	0.327	0	1	1	1
31	-0.031	-0.031	0.324	0.324	0	0	0	0
33	-0.031	-0.031	0.324	0.324	0	0	0	0

When the 1.6 m square size of opening O-6 is located at the right corner of the column in area 17 as shown in Figure 25, the bending moments and shear forces increase in the areas around the opening. The maximum changes of bending moment are 139% increase at area 10 for M_x and 150% increase at area 18 for M_y . Due to the effect of opening O-6, the overall maximum values of the bending moments M_x and M_y of the flat plate increase about 7% and 19% respectively and occur only at area 17.

The maximum changes of shear force are 404% increase in the area 10 for V_x and 381% increase in area 18 for V_y . The overall maximum shear forces of the flat plate increase about 1% as shown in Table 15 and occur only at area 19.

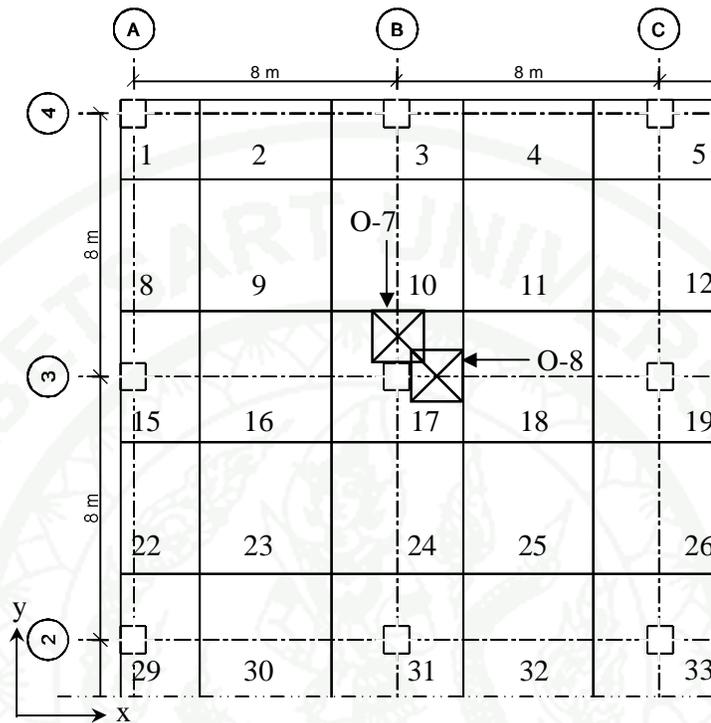


Figure 26 Flat plate model with openings at the area common to intersecting column strips [O-7 and O-8]

Table 13 Changes in percentage of maximum bending moment and shear force resultants in flat plate with opening O-7

Area No.	Resultant Coefficients				Resultant changes (%)			
	β_x	β_y	γ_x	γ_y	M_x	M_y	V_x	V_y
10	-0.012	0.007	0.073	0.058	94	11	127	-9
16	0.007	-0.007	0.073	0.053	6	19	14	64
17	-0.050	-0.032	0.567	0.425	60	3	75	31
18	0.006	-0.007	0.068	0.051	8	19	13	59
19	-0.031	-0.032	0.327	0.329	0	1	1	2
31	-0.031	-0.031	0.323	0.323	0	-1	0	0
33	-0.031	-0.031	0.323	0.323	0	-1	0	0

When the 1.6 m square size of opening O-7 is located along the x direction face of the column in area 17 as shown in Figure 26, the bending moments and shear forces increase in the areas around the opening. The maximum changes of bending moment are 94% increase in the area 10 for M_x and 19% increase in areas 16 & 18 for M_y . Due to the effect of opening O-7, the overall maximum values of the bending moments M_x and M_y of the flat plate increase about 60% and 3% respectively and occur at area 17.

The maximum changes of shear force are 127% increase in area 10 for V_x and 64% increase in the area 16 for V_y . The overall maximum values of the shear forces V_x and V_y of the flat plate increase about 75% and 31% respectively as shown in Table 15 and occur only at the area 17 where the opening is located.

Table 14 Changes in percentage of maximum bending moment and shear force resultants in flat plate with opening O-8

Area No.	Resultant Coefficients				Resultant changes (%)			
	β_x	β_y	γ_x	γ_y	M_x	M_y	V_x	V_y
10	-0.007	0.007	0.050	0.073	16	6	55	14
17	-0.030	-0.047	0.416	0.560	-3	51	29	73
18	0.007	-0.011	0.065	0.067	12	95	9	110
19	-0.031	-0.031	0.330	0.332	1	1	2	3
24	-0.007	0.006	0.047	0.068	16	7	48	13
31	-0.031	-0.031	0.326	0.326	-1	0	1	1
33	-0.031	-0.031	0.324	0.324	1	0	0	0

When the 1.6 m square size of opening O-8 is located along the y direction face of the column in area 17 as shown in Figure 26, the bending moments and shear forces increase in the areas around the opening. The maximum changes of bending moment are 16% increase in areas 10 & 24 for M_x and 95% increase in area 18 for M_y . Due to the effect of opening O-8, the overall maximum value of the

bending moment M_y of the flat plate increases about 51% and occurs only at area 17. But the overall maximum value of the bending moment M_x of the flat plate increases only 1% and occurs at area 19 & 33.

The maximum changes of shear force are 55% increase in area 10 for V_x and 110% increase in area 18 for V_y . The overall maximum values of the shear forces V_x and V_y of the flat plate increase about 29% and 73% respectively as shown in Table 15 and occur only at area 17.

2.1.5 Comparison of the effect by the various locations of openings on the overall maximum resultants

Generally, the bending moments and shear forces of the flat plate increase in the areas around the openings. The overall maximum bending moments and shear forces increase due to the openings which are located at the area common to intersecting column strips (Table 15). By comparing the effect by the locations of the openings on the overall maximum bending moments and shear forces of the flat plate, the openings at the face of the column in the area common to intersecting column strips are the most critical for the flat plate with openings as shown in Figure 27.

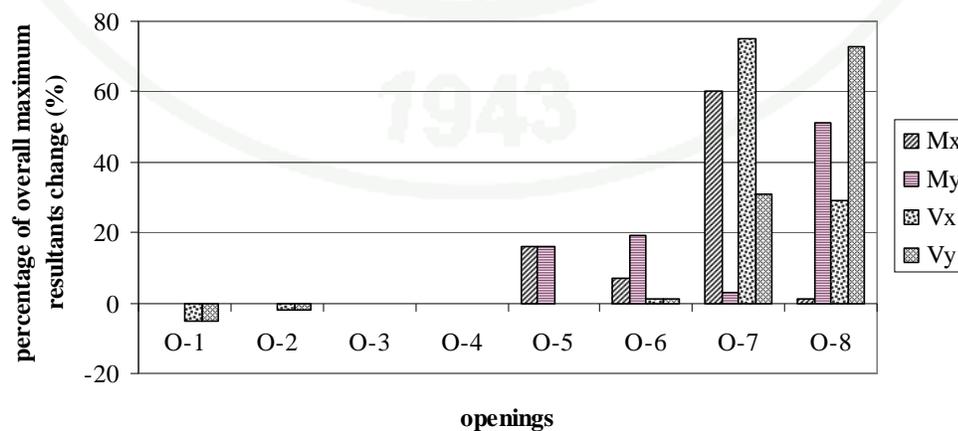


Figure 27 Comparison of the effect by the locations of the openings on the overall maximum bending moments and shear forces

Table 15 Change in percentage of the overall maximum bending moment and shear force resultants between the flat plates with and without openings

Flat plate type	Coefficient				Resultant changes (%)			
	β_x	β_y	γ_x	γ_y	M_x	M_y	V_x	V_y
without opening	-0.031	-0.031	0.324	0.324	-	-	-	-
with opening O-1	-0.031	-0.031	0.308	0.308	0	0	-5	-5
with opening O-2	-0.031	-0.031	0.319	0.318	0	0	-2	-2
with opening O-3	-0.031	-0.031	0.324	0.324	0	0	0	0
with opening O-4	-0.031	-0.031	0.324	0.324	0	0	0	0
with opening O-5	-0.036	-0.036	0.324	0.324	16	16	0	0
with opening O-6	-0.034	-0.037	0.326	0.327	7	19	1	1
with opening O-7	-0.050	-0.032	0.567	0.425	60	3	75	31
with opening O-8	-0.031	-0.047	0.416	0.560	1	51	29	73

2.2 Effect by the sizes of the openings

After the analysis of the flat plate with openings at the different locations, a total of four openings at the areas common to intersection column strip are selected to study the effect by the sizes of the openings. In addition to the openings O-7 and O-8, which are already used in the first step of analysis, the openings O-9 and O-10 located respectively at the face of the edge column and at the corner of the corner column are also selected (Figure 19). The opening dimensions are varied as one-tenth, one-fifth, three-tenth, and two-fifth of the width of the column strip, in the two direction of the plane of the flat plate.

2.2.1 Effect by the opening size at the exterior face of the interior column [O-7]

The location of the opening at the exterior face of the interior column is shown in Figure 28. The dimension a is the width of opening in perpendicular direction of the face of column and the dimension b is the width of opening in parallel direction of the face of column. The size of the openings (a and b) are varied as 0.40 m, 0.80 m, 1.20 m and 1.60 m.

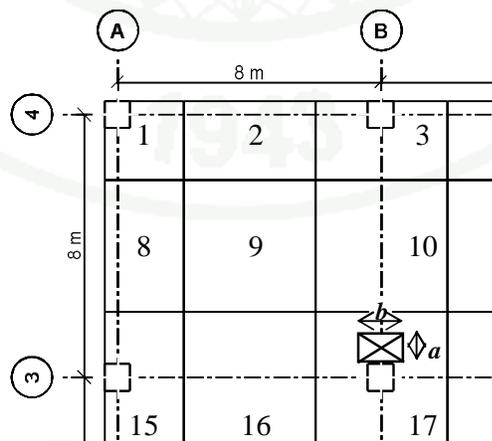


Figure 28 Flat plate model with opening at the exterior face of interior column [O-7]

The effect of the various sizes of opening [O-7] on the changes of maximum bending moments and shear forces of the flat plate in the individual areas are shown in appendix Table D3. Generally, the bending moments and shear forces increase at the area 11, 17 and 18 but decrease in the area 9 and 10. At the area 23, 24 and 25, bending moment M_x and shear force V_x increase. When the opening width a is equal to 1.6 m, the maximum changes in M_x and V_x occur at the area 10.

Table 16 Changes in percentage of overall maximum bending moments and shear forces in flat plate with various sizes of opening O-7

Size of opening ($a \times b$) (m x m)	Resultant changes (%)			
	M_x	M_y	V_x	V_y
0.4 x 0.4	8	15	8	68
0.4 x 0.8	30	30	27	92
0.4 x 1.2	70	41	116	65
0.4 x 1.6	67	23	89	50
0.8 x 0.4	11	11	8	62
0.8 x 0.8	35	13	25	82
0.8 x 1.2	74	27	109	55
0.8 x 1.6	63	12	82	40
1.2 x 0.4	13	8	7	59
1.2 x 0.8	37	5	24	78
1.2 x 1.2	76	19	104	50
1.2 x 1.6	61	7	78	35
1.6 x 0.4	15	6	7	57
1.6 x 0.8	39	-2	23	75
1.6 x 1.2	76	14	101	47
1.6 x 1.6	59	3	74	31

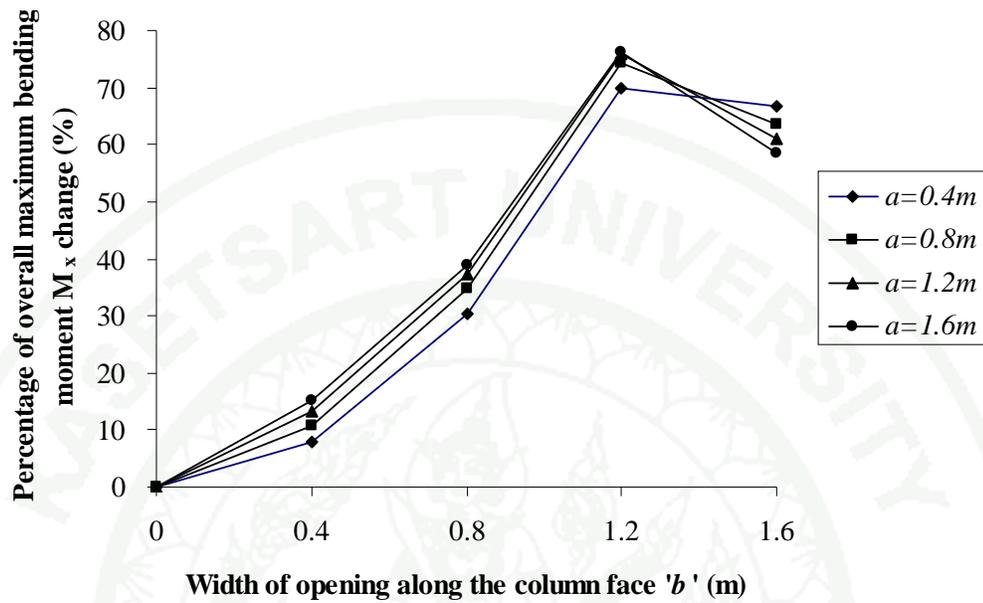


Figure 29 Percentage of overall maximum M_x changes of the flat plate due to the various sizes of opening O-7

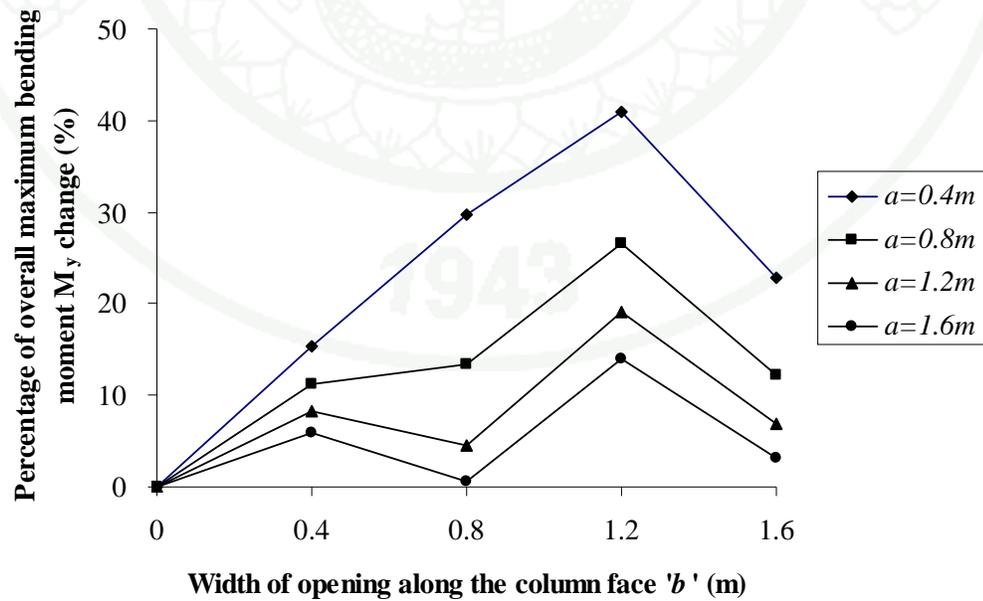


Figure 30 Percentage of overall maximum M_y changes of the flat plate due to the various sizes of opening O-7

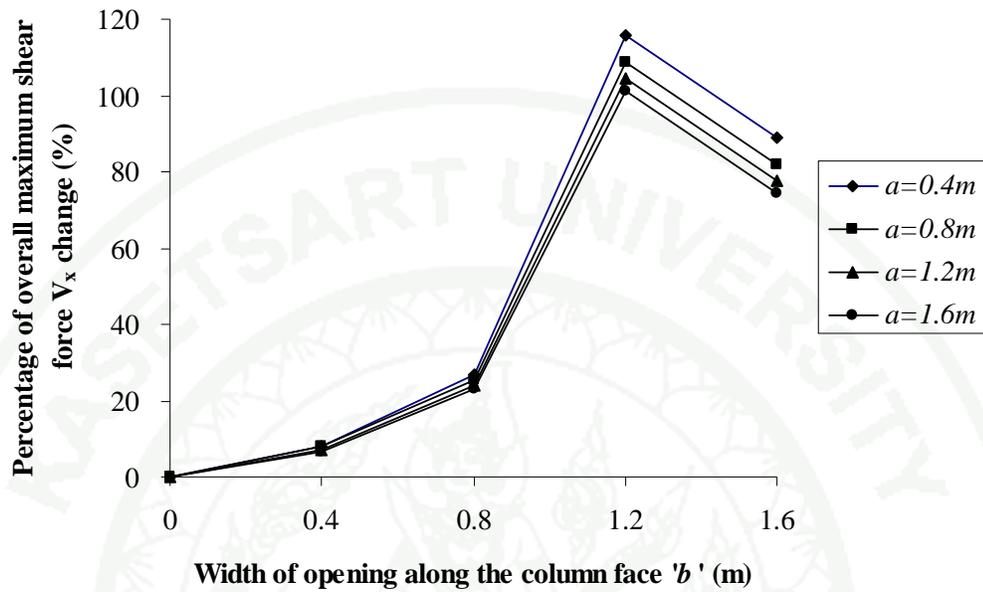


Figure 31 Percentage of overall maximum V_x changes of the flat plate due to the various sizes of opening O-7

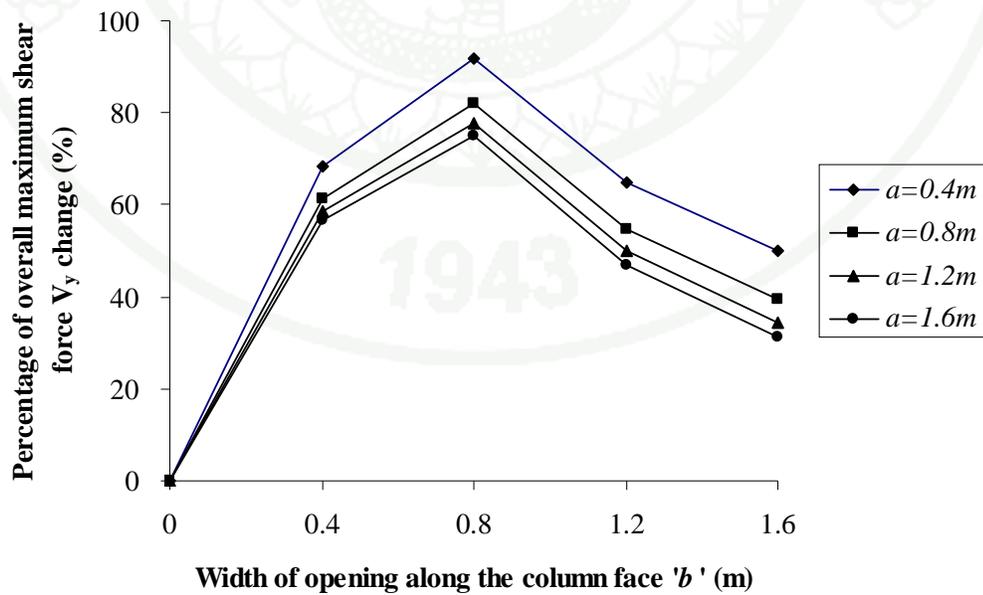


Figure 32 Percentage of overall maximum V_y changes of the flat plate due to the various sizes of opening O-7

The changes in overall maximum bending moment and shear forces of the flat plate due to various size of the opening at the exterior face of interior column are shown in Table 16 and the size effect on overall maximum resultants M_x , M_y , V_x and V_y can be compared by Figure 29 to 32.

In Table 16, the maximum percentage increments are 76% in M_x for the opening sizes 1.2 m x 1.2 m and 1.6 m x 1.2 m, 41% in M_y for the opening size 0.4 m x 1.2 m, 116% in V_x for the opening size 0.4 m x 1.2 m and 92% in V_y for the opening size 0.4 m x 0.8 m.

When the opening width a and b increases, the overall maximum M_x increases but it decreases when the width b equals 1.6 m as shown in Figure 29. The overall maximum M_x occurs at the area 17 for all sizes of the opening.

For the 0.4 m and 0.8 m length of opening width a , the overall maximum M_y increases when the opening width b increases up to 1.2 m and then it decreases as shown in Figure 30. But, the overall maximum M_y increases and decreases alternately for the 1.2 m and 1.6 m length of opening width a when width b increases. Generally, the overall maximum M_y occurs at the area 17 but it occurs at area 19 when the opening size is $a = 1.6$ m and $b = 1.2$ m.

The percentage of overall maximum V_x change increases gradually when the opening width b increases up to 0.8 m but it increases rapidly over 100% when opening width b is equal to 1.2 m and then decreases when the width b equals 1.6 m as shown in Figure 31.

The overall maximum V_y decreases when the opening width a increases as shown in Figure 32. But it increases when the opening width b increases up to 0.8 m and then decreases. Overall maximum V_x and V_y occur at the area 17 for all sizes of the opening.

2.2.2 Effect by the opening size at the interior face of the interior column [O-8]

The dimension of the opening O-8 is shown in Figure 33 represented by a and b . The dimension a is the width of opening in perpendicular direction of the face of column. The dimension b is the width of opening in parallel direction of the face of column. The size of the openings (a and b) are varied as 0.40 m, 0.80 m, 1.20 m and 1.60 m.

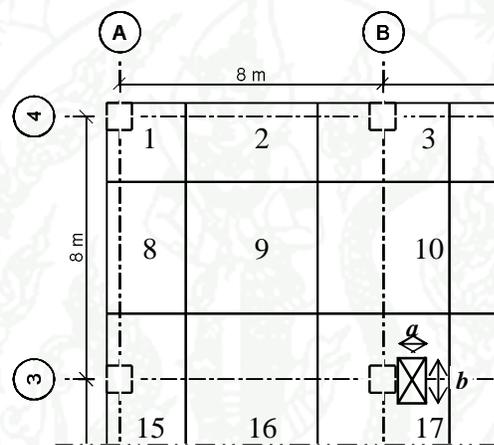


Figure 33 Flat plate model with opening at the interior face of interior column [O-8]

Due to the opening at the interior face of interior column, the changes of maximum bending moments and shear forces of the flat plate in the individual areas are shown in appendix Table D4. Generally, the bending moments and shear forces increase at the areas 10, 11, 17, 18, 24, and 25 which are the areas around the opening. Maximum changes in M_y and V_y occur at the area 18 when the width of the opening perpendicular to the column a is equal to 1.6 m.

Table 17 Changes in percentage of overall maximum bending moments and shear forces in flat plate with various sizes of opening O-8

Size of opening ($a \times b$) (m x m)	Resultant changes (%)			
	M_x	M_y	V_x	V_y
0.4 x 0.4	6	3	66	8
0.4 x 0.8	19	24	88	26
0.4 x 1.2	30	62	62	113
0.4 x 1.6	14	57	47	87
0.8 x 0.4	2	6	59	8
0.8 x 0.8	3	28	79	25
0.8 x 1.2	16	65	52	107
0.8 x 1.6	3	54	37	80
1.2 x 0.4	0	8	56	7
1.2 x 0.8	0.4	30	74	23
1.2 x 1.2	9	67	47	102
1.2 x 1.6	1	51	32	76
1.6 x 0.4	0.2	10	54	7
1.6 x 0.8	0.4	32	72	22
1.6 x 1.2	4	67	44	99
1.6 x 1.6	1	49	28	72

The changes in overall maximum bending moment and shear forces of the flat plate due to various size of the opening at the interior face of interior column is shown in Table 17 and the size effect on overall maximum resultants M_x , M_y , V_x and V_y can be compared by Figure 34 to 37.

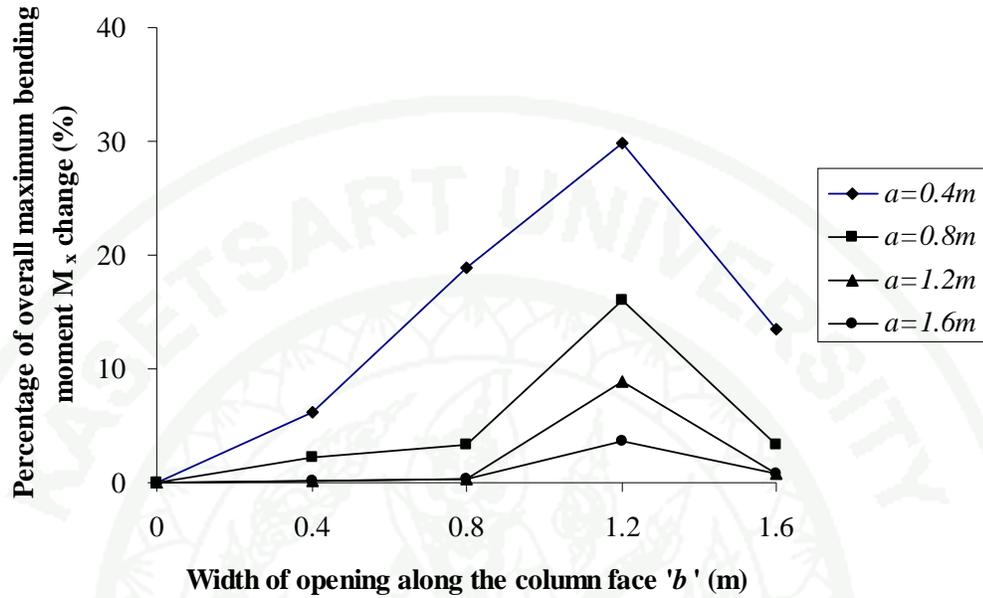


Figure 34 Percentage of overall maximum M_x changes of the flat plate due to the various sizes of opening O-8

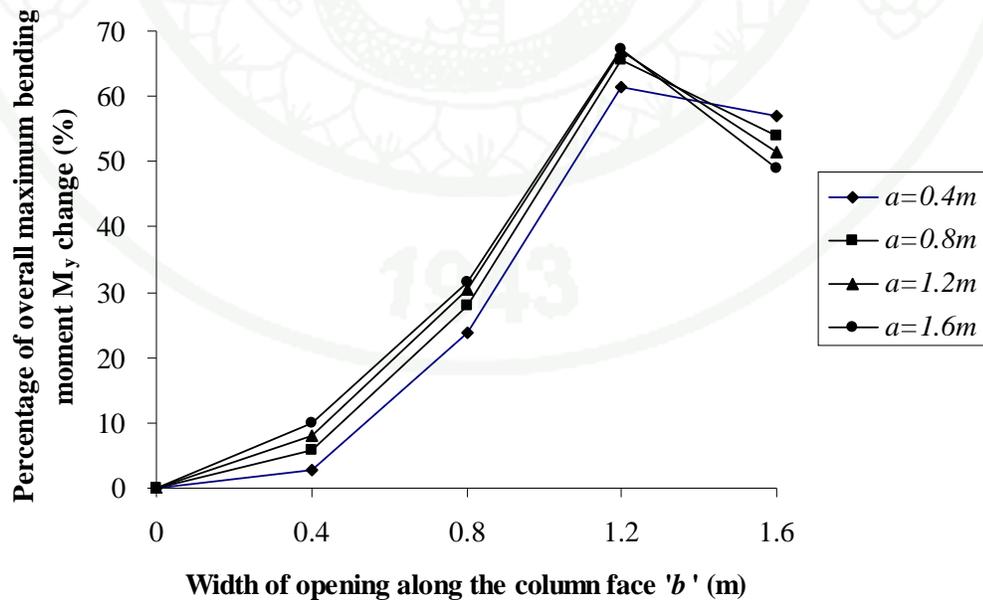


Figure 35 Percentage of overall maximum M_y changes of the flat plate due to the various sizes of opening O-8

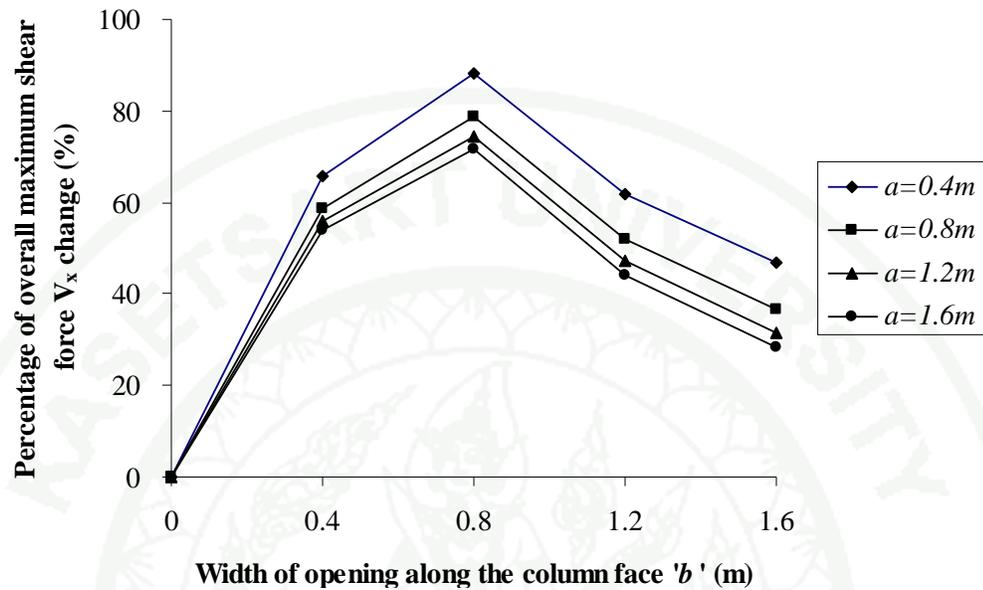


Figure 36 Percentage of overall maximum V_x changes of the flat plate due to the various sizes of opening O-8

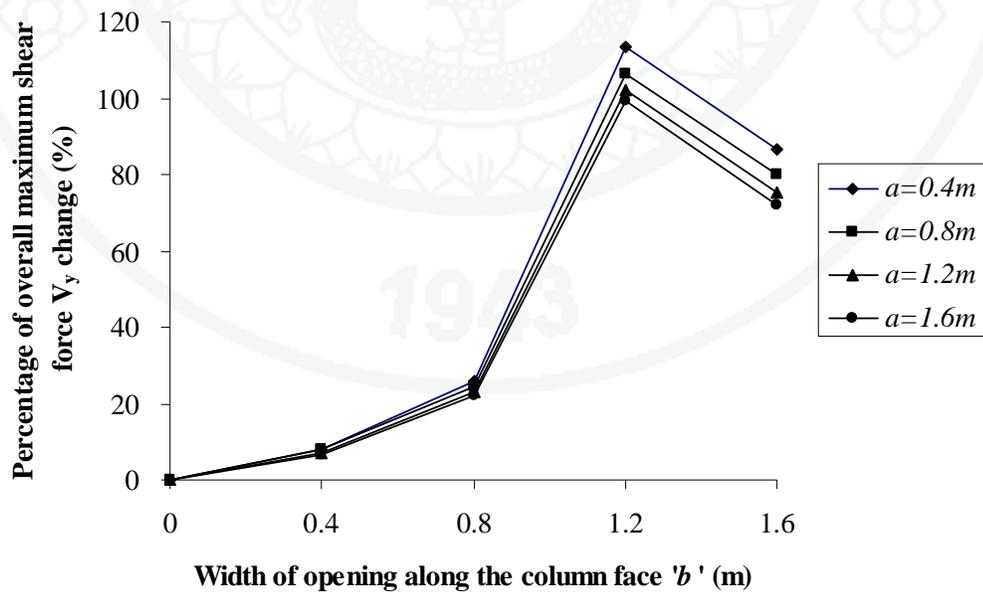


Figure 37 Percentage of overall maximum V_y changes of the flat plate due to the various sizes of opening O-8

In Table 17, the maximum percentage increments are 30% in M_x for the opening size 0.4 m x 1.2 m, 67% in M_y for the opening sizes 1.2 m x 1.2 m and 1.6 m x 1.2 m, 88% in V_x for the opening size 0.4 m x 0.8 m and 113% in V_y for the opening size 0.4 m x 1.2 m.

When the opening width a increases, the overall maximum M_x decreases as shown in Figure 34. The overall maximum M_x increases when the opening width b increases up to 1.2 m and then it decreases. Generally, overall maximum M_x occurs at the area 17 but it occurs at areas 19, 31, and 33 when the opening width a is equal to 1.2 m and 1.6 m with any length of b except 1.2 m.

The overall maximum M_y increases when the opening width a and b increase up to 1.2 m and then it decreases as shown in Figure 35. Overall maximum M_y occurs at the area 17 for all sizes of the opening.

The overall maximum V_x decreases gradually when the opening width a increases as shown in Figure 36. But it increases when the opening width b increases up to 0.8 m and then it decreases.

The percentage of overall maximum V_y change increases from about 10% to about 25% when the opening width b increases from 0.4 m to 0.8 m but it increases rapidly over 100% when opening width b is equal to 1.2 m and then decreases as shown in Figure 37. Overall maximum V_x and V_y occur at the area 17 for all sizes of the opening.

2.2.3 Effect by the opening size at the face of the edge column [O-9]

The third opening is located at the face of the edge column in the area 3 which is the area common to intersecting column strips. The dimension of the opening at the face of the edge column is shown in Figure 38. The dimension a is the width of opening in perpendicular direction of the face of column. The dimension b is the width of opening in parallel direction of the face of column. The size of the openings (a and b) are varied as 0.40 m, 0.80 m, 1.20 m and 1.60 m.

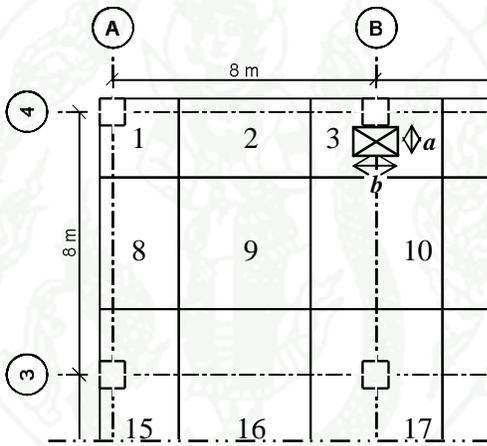


Figure 38 Flat plate model with opening at the face of edge column [O-9]

The effect of the opening, at the face of edge column, on the changes of maximum bending moments and shear forces of the flat plate in the individual areas are shown in appendix Table D5. The bending moments and shear forces increase at the areas 2, 3, 4, 9, 10, and 11. When the width a equals 1.6 m, percentage changes increase at the area 10. Generally, the maximum percentage changes occur especially at the area 3 due to all sizes of the opening.

Table 18 Changes in percentage of overall maximum bending moments and shear forces in flat plate with various sizes of opening O-9

Size of opening ($a \times b$) (m x m)	Resultant changes (%)			
	M_x	M_y	V_x	V_y
0.4 x 0.4	1	7	0	24
0.4 x 0.8	18	23	1	47
0.4 x 1.2	54	32	57	33
0.4 x 1.6	58	12	49	29
0.8 x 0.4	1	4	1	18
0.8 x 0.8	23	9	1	39
0.8 x 1.2	60	20	50	24
0.8 x 1.6	57	9	42	19
1.2 x 0.4	1	2	1	15
1.2 x 0.8	26	4	1	35
1.2 x 1.2	62	14	46	19
1.2 x 1.6	55	9	37	14
1.6 x 0.4	3	2	1	13
1.6 x 0.8	27	4	1	32
1.6 x 1.2	64	9	42	16
1.6 x 1.6	54	8	33	10

The changes in overall maximum bending moment and shear forces of the flat plate due to various sizes of the opening at the face of edge column is shown in Table 18 and the size effect on overall maximum resultants M_x , M_y , V_x and V_y can be compared by Figure 39 to 42.

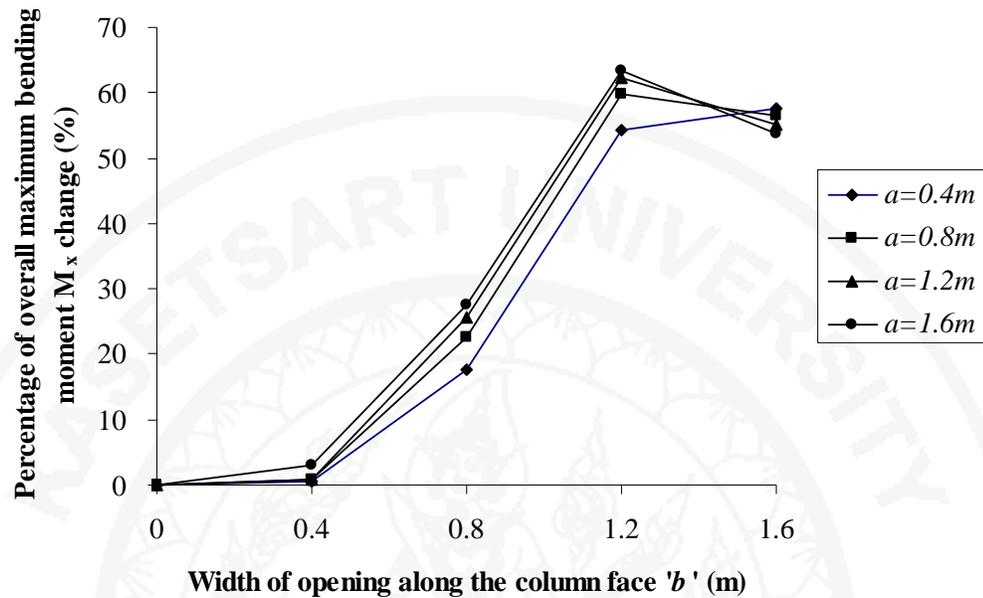


Figure 39 Percentage of overall maximum M_x changes of the flat plate due to the various sizes of opening O-9

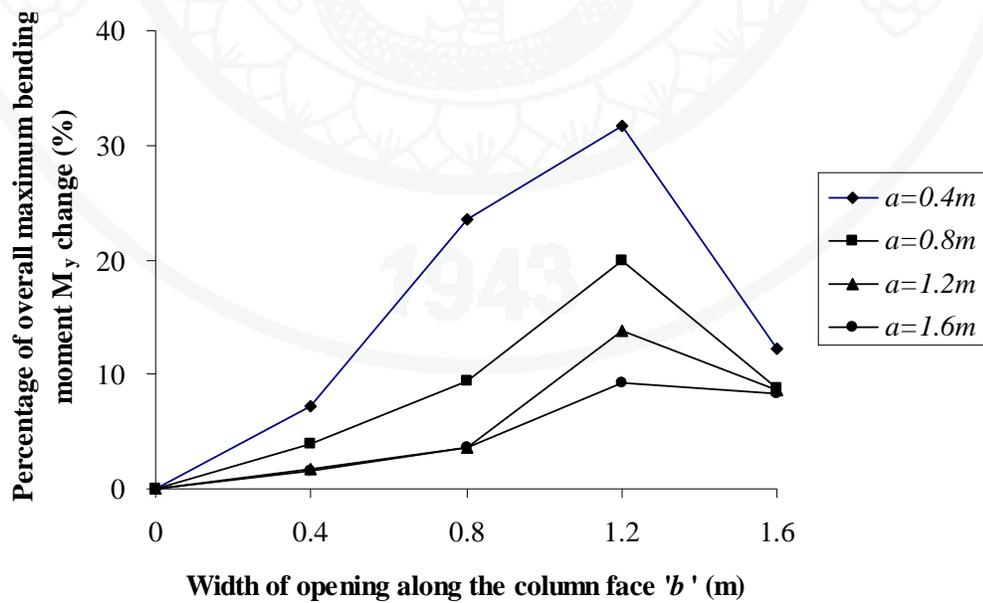


Figure 40 Percentage of overall maximum M_y changes of the flat plate due to the various sizes of opening O-9

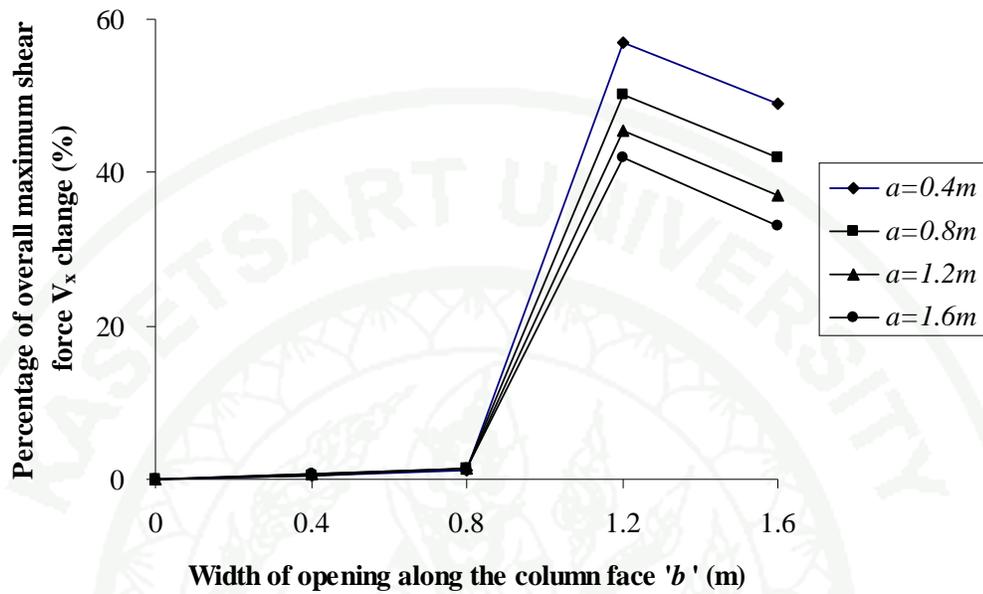


Figure 41 Percentage of overall maximum V_x changes of the flat plate due to the various sizes of opening O-9

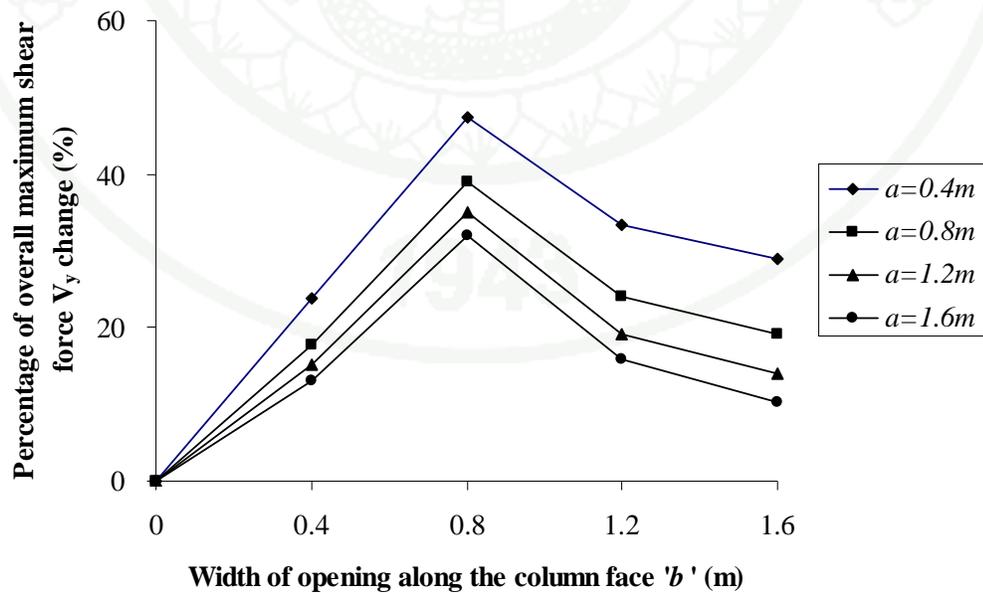


Figure 42 Percentage of overall maximum V_y changes of the flat plate due to the various sizes of opening O-9

In Table 18, the maximum percentage increments are 64% in M_x for the opening size 1.6 m x 1.2 m, 32% in M_y for the opening size 0.4 m x 1.2 m, 57% in V_x for the opening size 0.4 m x 1.2 m and 47% in V_y for the opening size 0.4 m x 0.8 m.

When the opening width a and b increases, the overall maximum M_x increases but it decreases when width b equals 1.6 m as shown in Figure 39. Generally, overall maximum M_x occurs at the area 3 but it occurs at area 17 when the opening width b is equal to 0.4 m.

The overall maximum M_y decreases when the opening width a increases but it increases when increasing width b up to 1.2 m and then decreases (Figure 40). Overall maximum M_y occurs either at the areas 3 or 17 for all sizes of the opening.

The change of overall maximum V_x remains constant when the opening width a increases up to 0.8 m as shown in Table 18. But it decreases when the opening width a increases over 0.8 m. The overall maximum V_x increases rapidly about 50% when width b equals 1.2 m (Figure 41). Generally, overall maximum V_x occurs at the area 17 but it occurs at the area 3 when width b increases over 0.8 m.

The percentage of overall maximum V_y change decreases when opening width a increases and it becomes maximum when opening width b is equal to 0.8 m (Figure 42). Overall maximum V_y occurs at the area 3 for all sizes of the opening.

2.2.4 Effect by the opening size at the corner of the corner column [O-10]

Finally, the opening [O-10] is located at the corner of the corner column as shown in Figure 43. The dimension a is the width of opening along the y direction axis. The dimension b is the width of opening along the x direction axis. The size of the openings (a and b) are varied as 0.40 m, 0.80 m, 1.20 m and 1.60 m.

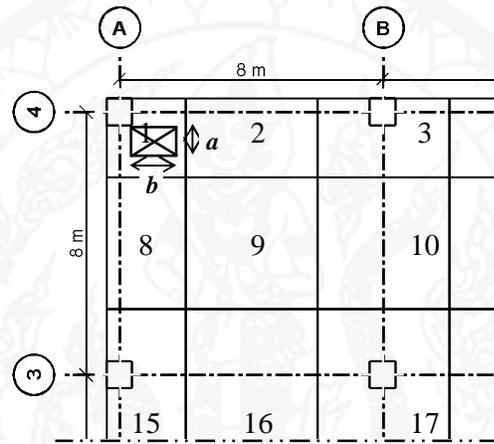


Figure 43 Flat plate model with opening at the corner of corner column [O-10]

The effect of the opening, at the corner of corner column, on the changes of maximum bending moments and shear forces of the flat plate in the individual areas are shown in appendix Table D6. Generally, the bending moments and shear forces increase at the area 1, 2, 3, 8, and 15. At the area 2, the bending moments and shear forces greatly increase when the width of opening b is equal to 1.6 m. When opening width a is equal to 1.6 m, the resultant changes increase greatly at the area 8.

Table 19 Changes in percentage of overall maximum bending moments and shear forces in flat plate with various sizes of opening O-10

Size of opening ($a \times b$) (m x m)	Resultant changes (%)			
	M_x	M_y	V_x	V_y
0.4 x 0.4	0.5	0.5	0.1	0.1
0.4 x 0.8	0.7	4	0.2	0.1
0.4 x 1.2	0.7	9	0.2	0.1
0.4 x 1.6	0.8	13	0.2	0.1
0.8 x 0.4	4	0.7	0.2	0.1
0.8 x 0.8	0.8	0.8	0.2	0.1
0.8 x 1.2	0.8	0.8	0.2	0.1
0.8 x 1.6	0.7	0.7	0.2	0.1
1.2 x 0.4	9	0.7	0.2	0.1
1.2 x 0.8	0.8	0.8	0.2	0.1
1.2 x 1.2	0.7	0.7	0.2	0.1
1.2 x 1.6	0.6	0.6	0.1	0.1
1.6 x 0.4	13	0.8	0.2	0.1
1.6 x 0.8	0.7	0.7	0.2	0.1
1.6 x 1.2	0.6	0.6	0.1	0.1
1.6 x 1.6	0.5	0.5	0.0	0.0

Although the localized resultant changes of the flat plate is very high due to the opening at the corner of the corner column, overall maximum resultants changes of the flat plate are negligible, as shown in Table 19. The size effect on overall maximum resultants M_x , M_y , V_x and V_y can be compared by Figure 44 to 47.

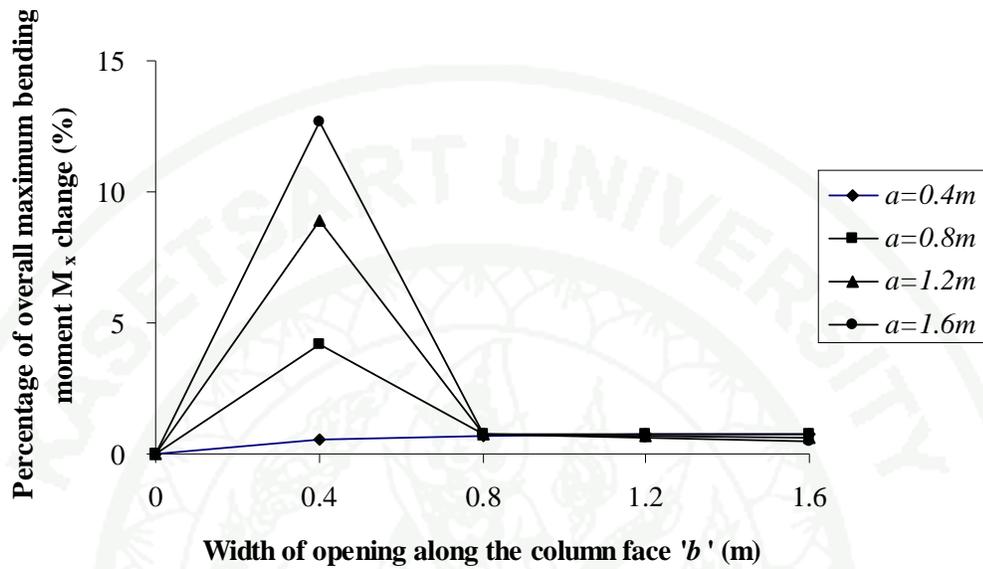


Figure 44 Percentage of overall maximum M_x changes of the flat plate due to the various sizes of opening O-10

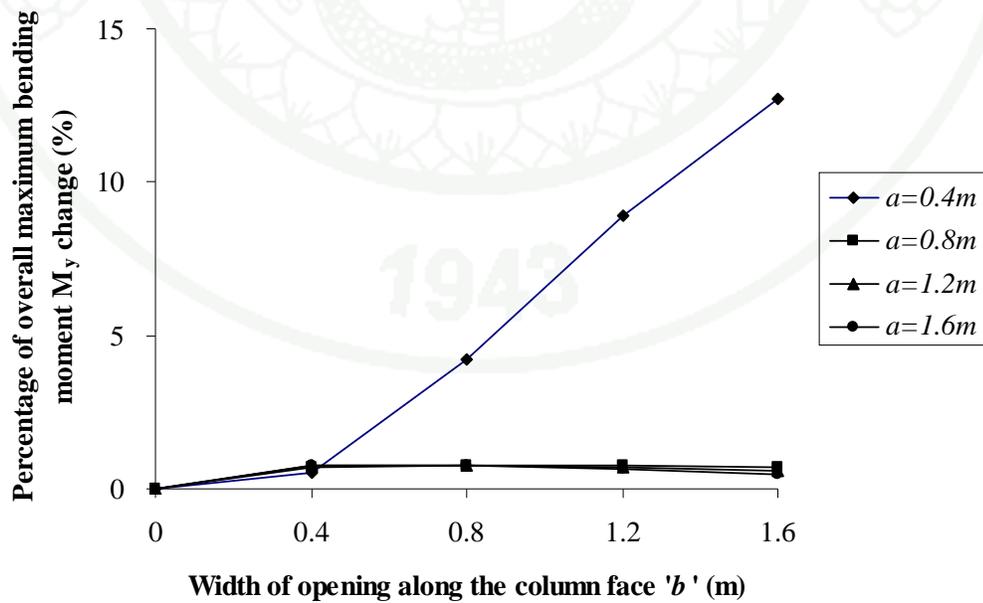


Figure 45 Percentage of overall maximum M_y changes of the flat plate due to the various sizes of opening O-10

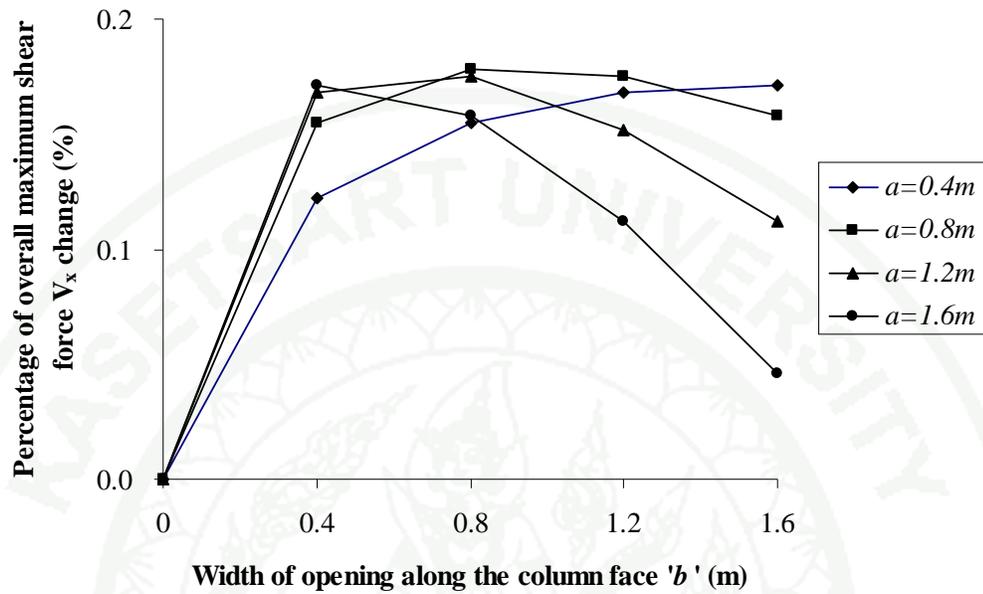


Figure 46 Percentage of overall maximum V_x changes of the flat plate due to the various sizes of opening O-10

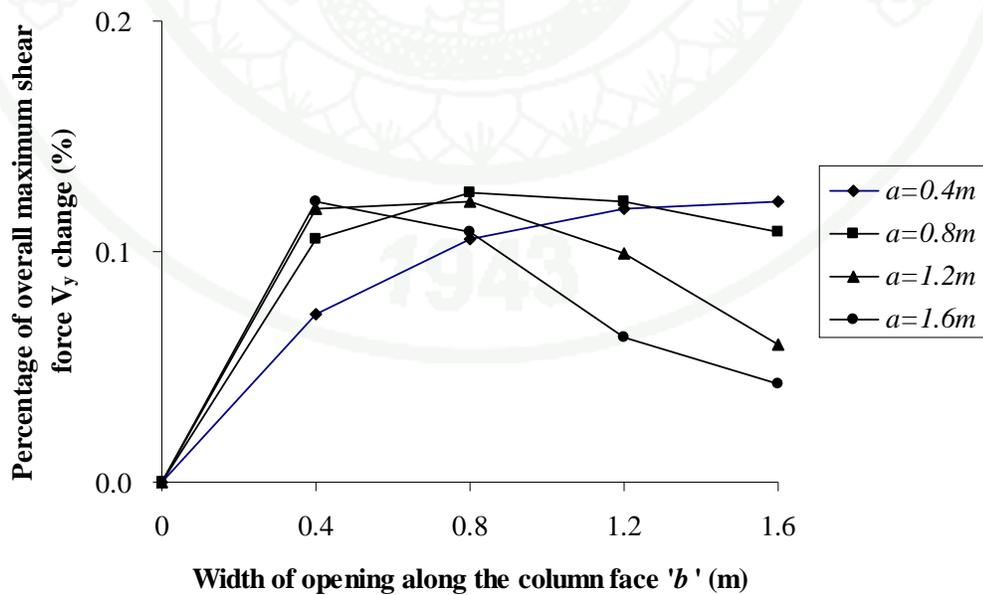


Figure 47 Percentage of overall maximum V_y changes of the flat plate due to the various sizes of opening O-10

In Table 19, the maximum percentage increments are 13% in M_x for the opening size 1.6 m x 0.4 m, 13% in M_y for the opening size 0.4 m x 1.6 m.

The overall maximum M_x increases when width a increases and width b equals 0.4 m as shown in Figure 44. The overall maximum M_y increases when width b increases and width a equals 0.4 m as shown in Figure 45. For the other size of opening, the overall maximum M_x and M_y changes are negligible. Generally, overall maximum M_x and M_y occurs at the area 17. But, when opening width b is equal to 0.4 m, overall maximum M_x occurs at the area 1 and when opening width a is equal to 0.4 m, overall maximum M_y occurs at the area 1.

The changes of overall maximum V_x and V_y are negligible and below 0.2 % as shown in Figure 46 and 47. Overall maximum V_x and V_y occur at the area 17 for all sizes of the opening.

2.2.5 Comparison of the effect by the various sizes of openings on overall maximum resultants

By comparing the effect by the various sizes the four openings at the areas common to intersecting column strips, the opening at the corner of the corner column [O-10] has the least effect on the resultant changes and any size of the opening O-10 is not critical for the flat plate with opening in that location.

For the other three openings [O-7, O-8 and O-9], the least overall maximum resultants generally occur when the opening width $b = 0.4$ m and the opening width $a = 1.6$ m. But the peak overall maximum bending moments occur when the opening width $b = 1.2$ m and the peak overall maximum shear forces occur when the opening width $a = 0.4$ m as shown in Table 20. Therefore, the critical size effecting the shear force resultant is $a = 0.4$ m and the critical size effecting the bending moment resultant is $b = 1.2$ m for the openings at areas common to the intersecting column strips around the interior and edge columns of the flat plate.

Table 20 Comparison of the effect by the various sizes of openings on overall maximum resultants

Openings	Least effect size $a \times b$ (m x m)				Peak effect size $a \times b$ (m x m)			
	M_x	M_y	V_x	V_y	M_x	M_y	V_x	V_y
O-7	0.4x0.4	1.6x0.8	1.6x0.4	1.6x1.6	1.6x1.2	0.4x1.2	0.4x1.2	0.4x0.8
O-8	1.2x0.4	0.4x0.4	1.6x1.6	1.6x0.4	0.4x1.2	1.6x1.2	0.4x0.8	0.4x1.2
O-9	0.4x0.4	1.6x0.4	0.4x0.4	1.6x1.6	1.6x1.2	0.4x1.2	0.4x1.2	0.4x0.8
O-10	1.6x1.6	1.6x1.6	1.6x1.6	1.6x1.6	1.6x0.4	0.4x1.6	0.8x0.8	0.8x0.8

3. Effect by the openings on shear strength of the flat plate

According to the analysis results of the flat plate with various sizes of openings at the area common to intersecting column strips, it is evident that overall maximum shear force usually occurs at the area around the column where the opening is located. Therefore, that region is considered as the critical location for the punching shear check and the openings O-7, O-8, O-9 and O-10 were studied for their effect on the shear strength. The shear force which is the maximum of overall maximum V_x and V_y , is taken as the required shear force (V_u) as shown in Table 21.

At first, the ratio of required shear force (V_u) to the shear strength provided by the concrete (ϕV_c) are calculated. If the demand-capacity ratios ($V_u/\phi V_c$) are greater than 1, it means that the shear strength of the flat plate with the openings needs to be increased for excessive shear forces. The shear strength of the flat plate provided by the concrete (ϕV_c) are calculated according to the ACI method using the equations (1), (2) and (3). As shown in Table 22, the shear strength provided by the concrete decreases with increasing the opening sizes, especially when the opening width b is increased.

The effect of the various sizes of openings O-7, O-8, O-9 and O-10 on the shear strength of the flat plate without shear strengthening can be compared by the Figures 48 to 51. Except for the opening at the corner of the corner column [O-10], the demand-capacity ratios are greater than 1 for all of the openings as shown in Table 23. Thus, the shear strength provided by the concrete is not sufficient to carry the shear force due to loading for the openings at the interior and exterior face of interior column and the opening at the face of edge column, i.e. O-7, O-8 and O-9.

For the openings O-7, O-8 and O-9 which require the additional shear strength to resist the required shear force, two methods of shear strengthening were studied. First, the bar reinforcement and shearheads reinforcement were introduced without increasing the thickness of the flat plate. Next, the thickness of the flat plate was increased around the opening and the column, i.e. providing a drop panel.

Table 21 Required shear force (V_u) used in punching shear check for the openings without drop panels

Opening size $a \times b$ (m x m)	V_u (kN/m)			
	O-7	O-8	O-9	O-10
without	303	303	216	155
0.4 x 0.4	511	503	375	209
0.4 x 0.8	581	570	447	243
0.4 x 1.2	654	647	476	264
0.4 x 1.6	573	566	452	280
0.8 x 0.4	490	482	357	243
0.8 x 0.8	552	542	422	207
0.8 x 1.2	633	627	455	226
0.8 x 1.6	552	545	430	241
1.2 x 0.4	481	473	349	264
1.2 x 0.8	540	529	409	226
1.2 x 1.2	620	614	442	191
1.2 x 1.6	539	532	416	204
1.6 x 0.4	475	467	343	280
1.6 x 0.8	531	521	401	241
1.6 x 1.2	611	604	431	204
1.6 x 1.6	529	522	404	170

Table 22 Shear strength provided by the concrete (ϕV_c) for the flat plate without opening and with various sizes of openings

Opening size (m)		Opening type	Critical section b_0 (m)	ϕV_c (kN)			Used ϕV_c (kN)
a	b			Eq-1	Eq-2	Eq-3	
-	-	O-7, O-8	4	1933	1288	1264	1264
-	-	O-9	2.8	1353	934	885	885
-	-	O-10	1.8	870	612	569	569
any	0.4	O-7, O-8	3.5	1691	1208	1106	1106
any	0.8	O-7, O-8	3	1449	1127	948	948
any	1.2	O-7, O-8	2.67	1288	1074	843	843
any	1.6	O-7, O-8	2.5	1208	1047	790	790
any	0.4	O-9	2.3	1111	854	727	727
any	0.8	O-9	1.8	870	773	569	569
any	1.2	O-9	1.47	709	719	464	464
any	1.6	O-9	1.3	628	692	411	411
0.4	0.4	O-10	1.3	628	531	411	411
0.4	0.8	O-10	1.22	588	518	385	385
0.4	1.2	O-10	1.18	568	511	371	371
0.4	1.6	O-10	1.15	556	507	364	364
0.8	0.4	O-10	1.22	588	518	385	385
0.8	0.8	O-10	1.13	548	505	358	358
0.8	1.2	O-10	1.09	527	498	345	345
0.8	1.6	O-10	1.07	515	494	337	337
1.2	0.4	O-10	1.18	568	511	371	371
1.2	0.8	O-10	1.10	527	498	345	345
1.2	1.2	O-10	1.05	507	491	332	332
1.2	1.6	O-10	1.03	495	487	324	324
1.6	0.4	O-10	1.15	556	507	364	364
1.6	0.8	O-10	1.07	515	494	337	337
1.6	1.2	O-10	1.03	495	487	324	324
1.6	1.6	O-10	1	483	483	316	316

Table 23 Ratio of shear force requirement (V_u) and shear strength provided by concrete (ϕV_c) for various sizes of openings O-7, O-8, O-9 and O-10

Opening size $a \times b$ (m x m)	$V_u/\phi V_c$			
	O-7	O-8	O-9	O-10
0 x 0	0.96	0.96	0.68	0.49
0.4 x 0.4	1.62	1.59	1.19	0.66
0.4 x 0.8	1.84	1.80	1.42	0.77
0.4 x 1.2	2.07	2.05	1.51	0.84
0.4 x 1.6	1.81	1.79	1.43	0.88
0.8 x 0.4	1.55	1.52	1.13	0.77
0.8 x 0.8	1.75	1.71	1.33	0.66
0.8 x 1.2	2.00	1.98	1.44	0.72
0.8 x 1.6	1.75	1.73	1.36	0.76
1.2 x 0.4	1.52	1.50	1.10	0.84
1.2 x 0.8	1.71	1.67	1.29	0.72
1.2 x 1.2	1.96	1.94	1.40	0.60
1.2 x 1.6	1.70	1.68	1.31	0.64
1.6 x 0.4	1.50	1.48	1.09	0.88
1.6 x 0.8	1.68	1.65	1.27	0.76
1.6 x 1.2	1.93	1.91	1.36	0.64
1.6 x 1.6	1.67	1.65	1.28	0.54

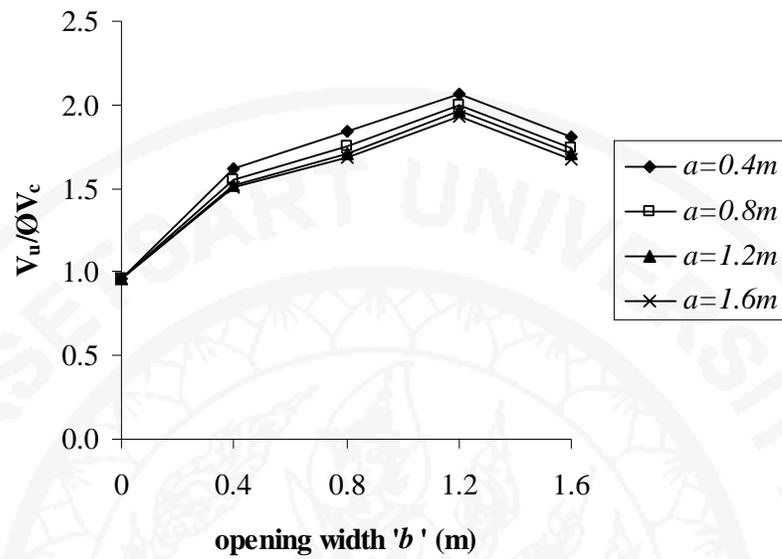


Figure 48 Ratio of shear force requirement and shear strength provided by concrete for various sizes of opening at the exterior face of interior column [O-7]

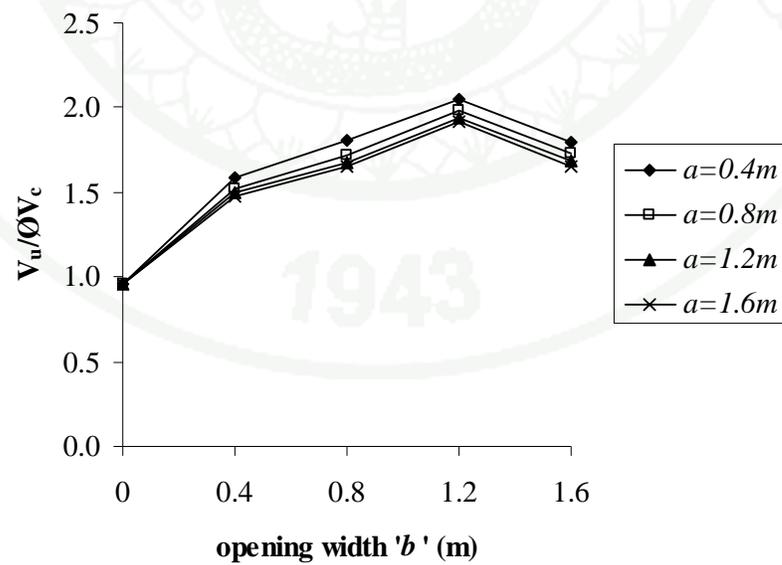


Figure 49 Ratio of shear force requirement and shear strength provided by concrete for various sizes of opening at the interior face of interior column [O-8]

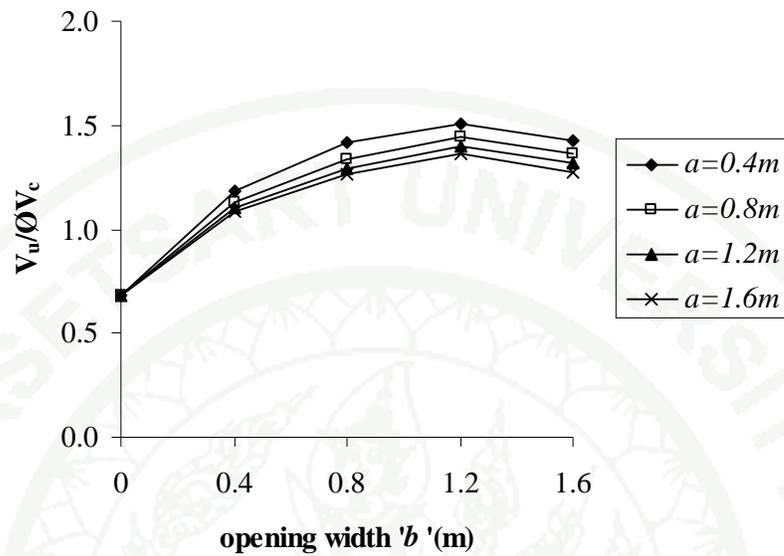


Figure 50 Ratio of shear force requirement and shear strength provided by concrete for various sizes of opening at the face of edge column [O-9]

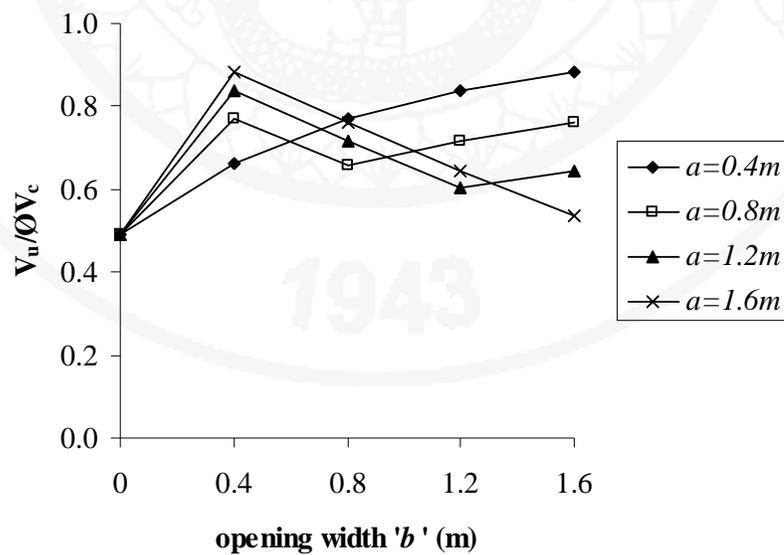


Figure 51 Ratio of shear force requirement and shear strength provided by concrete for various sizes of opening at the corner of corner column [O-10]

3.1 Increasing the shear strength by shear reinforcement

When the shear reinforcements are introduced for the increment of shear strength, the maximum shear strength (ϕV_n) permitted with these shear reinforcements are calculated by using equations (7) and (8). If the ratio of the shear force requirement to the available maximum shear strength ($V_u/\phi V_n$) is not greater than 1, either the bar or shearheads reinforcement can be used for the strengthening of the flat plate with openings.

Table 24 Maximum shear strength (ϕV_n) permitted with bar and shearheads reinforcement for the for various sizes of openings O-7, O-8, and O-9

Opening size (m)		Opening type	Critical section b_0 (m)	ϕV_n (kN)	
a	b			Bar reinforcement	Shearheads reinforcement
any	0.4	O-7, O-8	3.75	1778	2080
any	0.8	O-7, O-8	3.5	1660	1941
any	1.2	O-7, O-8	2.733	1296	1516
any	1.6	O-7, O-8	2.65	1257	1470
any	0.4	O-9	2.55	1209	1414
any	0.8	O-9	2.3	1091	1276
any	1.2	O-9	1.533	727	851
any	1.6	O-9	1.45	688	804

Table 25 Ratio of shear force requirement (V_u) and Maximum shear strength (ϕV_n) permitted with bar reinforcement and shearheads reinforcement for various sizes of openings O-7, O-8 and O-9

Opening size $a \times b$ (m x m)	$V_u/\phi V_n$					
	bar reinforcement			shearheads reinforcement		
	O-7	O-8	O-9	O-7	O-8	O-9
0 x 0	0.64	0.64	0.46	0.55	0.55	0.39
0.4 x 0.4	1.08	1.06	0.79	0.92	0.91	0.68
0.4 x 0.8	1.23	1.20	0.94	1.05	1.03	0.81
0.4 x 1.2	1.38	1.36	1.00	1.18	1.17	0.86
0.4 x 1.6	1.21	1.19	0.95	1.03	1.02	0.81
0.8 x 0.4	1.03	1.02	0.75	0.88	0.87	0.64
0.8 x 0.8	1.16	1.14	0.89	1.00	0.98	0.76
0.8 x 1.2	1.34	1.32	0.96	1.14	1.13	0.82
0.8 x 1.6	1.16	1.15	0.91	1.00	0.98	0.78
1.2 x 0.4	1.01	1.00	0.74	0.87	0.85	0.63
1.2 x 0.8	1.14	1.12	0.86	0.97	0.95	0.74
1.2 x 1.2	1.31	1.29	0.93	1.12	1.11	0.80
1.2 x 1.6	1.14	1.12	0.88	0.97	0.96	0.75
1.6 x 0.4	1.00	0.98	0.72	0.86	0.84	0.62
1.6 x 0.8	1.12	1.10	0.85	0.96	0.94	0.72
1.6 x 1.2	1.29	1.27	0.91	1.10	1.09	0.78
1.6 x 1.6	1.12	1.10	0.85	0.95	0.94	0.73

The ratios of the shear force requirement to the available maximum shear strength ($V_u/\phi V_n$) with bar reinforcement and shearheads reinforcement are shown in Table 25 for the openings O-7, O-8 and O-9.

With the bar reinforcement, the ratios ($V_u/\phi V_n$) are greater than 1 for various sizes of openings O-7 and O-8 except for the 1.2m x 0.4m and 1.6m x 0.4m sizes of the opening O-8. But the ratios ($V_u/\phi V_n$) are less than 1 for the various sizes of the opening O-9, except when the size of O-9 is 0.4m x 1.2m. Therefore, bar reinforcement cannot provide the required shear strength for almost all of the various sizes of openings O-7 and O-8. For almost all sizes of opening at the face of edge column [O-9], the bar reinforcement can be used to increase the shear strength enough to resist the required shear force.

With the shearheads reinforcement, the ratios ($V_u/\phi V_n$) are generally less than 1 for almost all sizes of the openings O-7, O-8 and O-9. By comparing the ratios ($V_u/\phi V_n$), the shearheads reinforcement is more effective than bar reinforcement to increase the shear strength of the flat plate with openings. But, for the openings at the interior and exterior face of interior column [O-7 and O-8], the ratios ($V_u/\phi V_n$) are greater than 1 when b is equal to 1.2m with any length of a and when a is equal to 0.4m with $b=0.8m, 1.2m$ and $1.6m$. Therefore, the shearheads cannot provide adequate shear strength for these sizes of openings O-7 and O-8.

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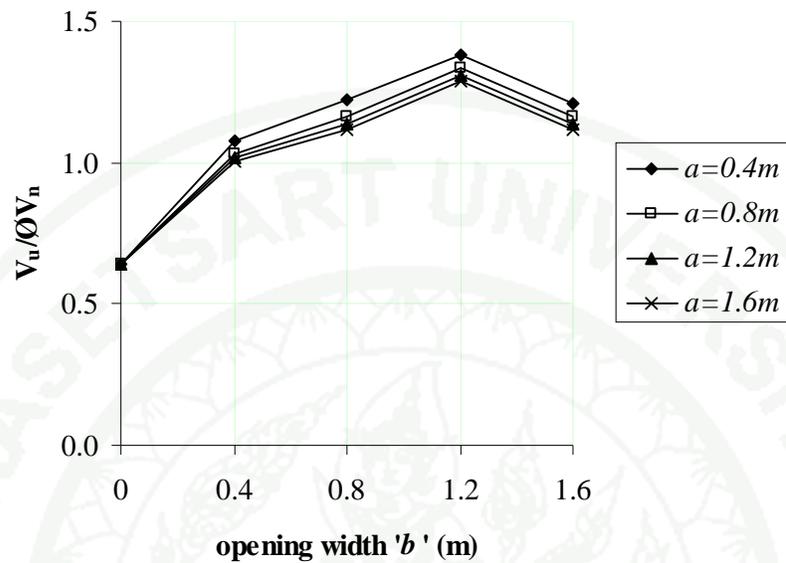


Figure 52 Ratio of shear force requirement and shear strength provided by bar reinforcement for the various sizes of opening O-7

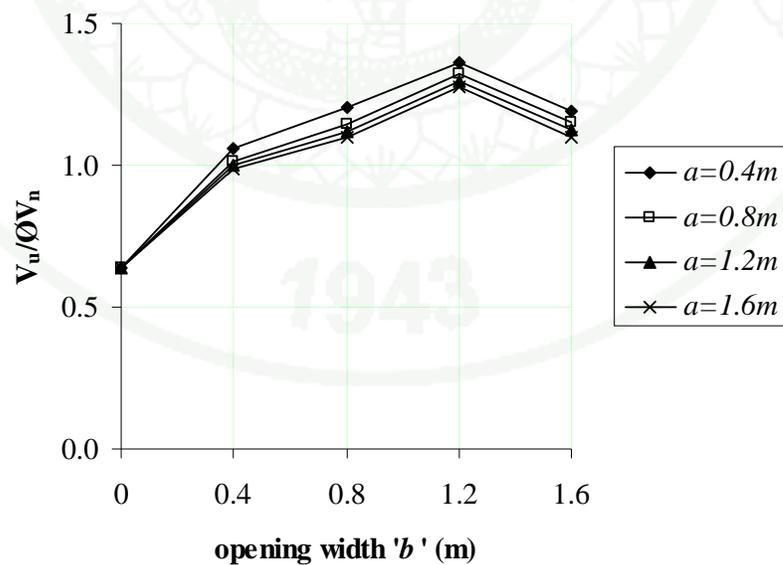


Figure 53 Ratio of shear force requirement and shear strength provided by bar reinforcement for the various sizes of opening O-8

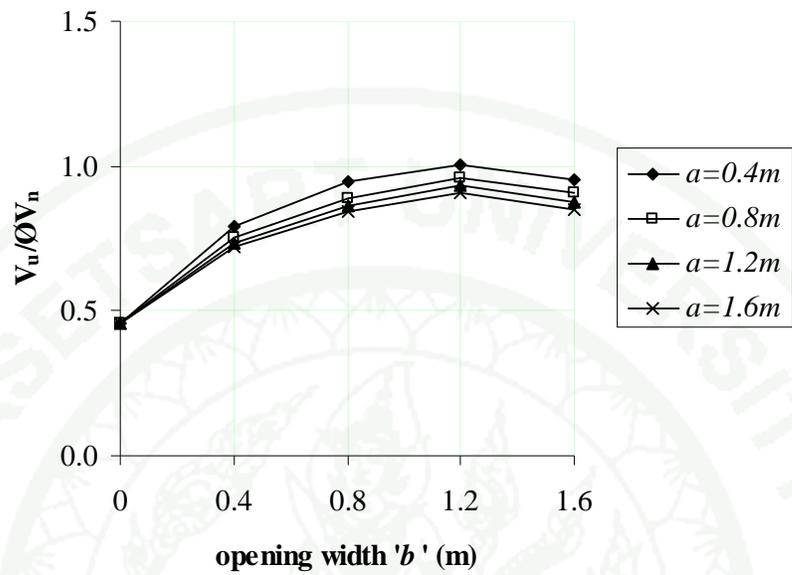


Figure 54 Ratio of shear force requirement and shear strength provided by bar reinforcement for the various sizes of opening O-9

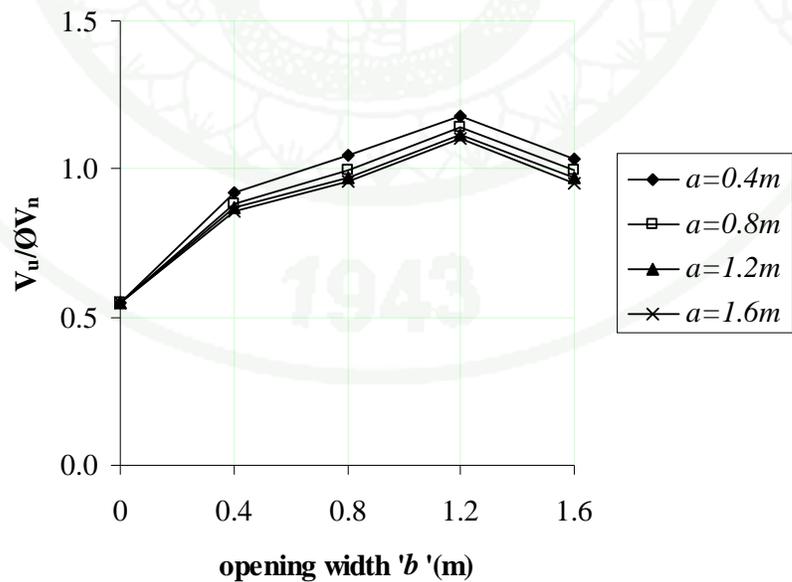


Figure 55 Ratio of shear force requirement and shear strength provided by shear heads for the various sizes of opening O-7

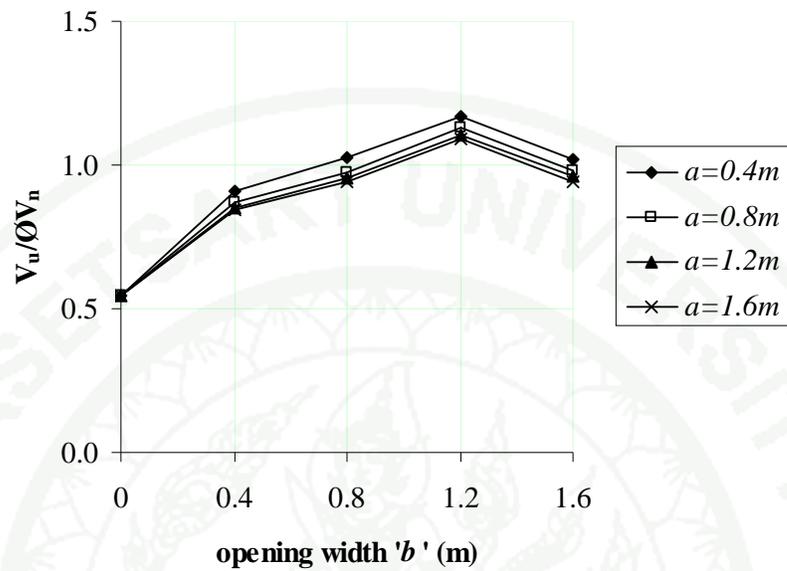


Figure 56 Ratio of shear force requirement and shear strength provided by shear heads for the opening for the various sizes of opening O-8

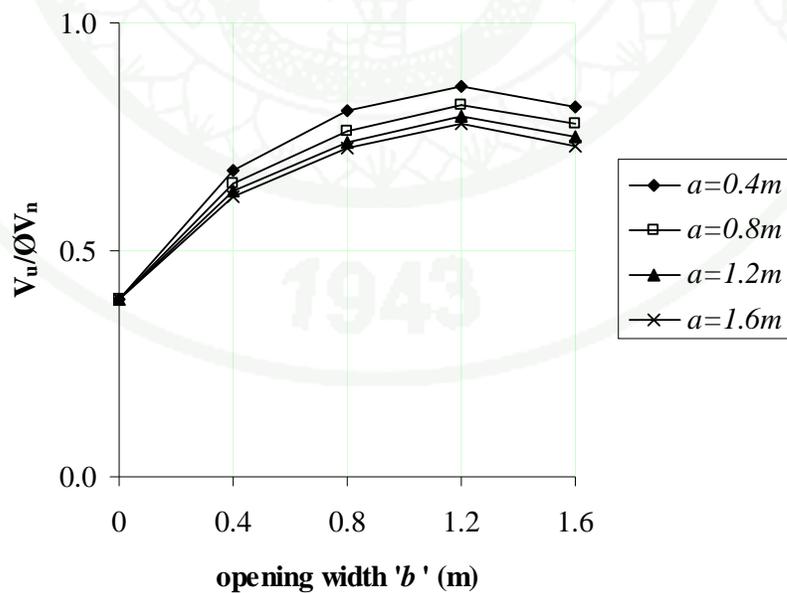


Figure 57 Ratio of shear force requirement and shear strength provided by shearheads for the various sizes of opening O-9

3.2 Increasing the shear strength by drop panel around opening

When the drop panels are introduced to resist the required shear force, the openings O-7, O-8 and O-9 are studied as shown in Figure 58. The drop panel width (w_d) is used as 0.2m for first trial and 0.4m for second trial. The overall thickness of the drop panel (h_d) is increased from 0.25m, which is the thickness of the flat plate without drop panel, with an increment of 0.05m until the shear strength of the flat plate with drop panel provided by the concrete around the opening (ϕV_c) meet the required shear force (V_u).

The flat plates with drop panels are analyzed by SAFE v12 and the shear force which is the maximum of V_x and V_y around the opening is taken as the required shear force (V_u). The shear strength provided by the concrete around the opening of the flat plate with drop panel (ϕV_c) is calculated by using ACI formulae: equations (1), (2) and (3). The ratios $V_u/\phi V_c$ are checked at the two critical sections for the punching shear. (Appendix Table C3 to C5)

First, provide the drop panel with the width w_d of 0.2m around the perimeter of the opening and the column, and the overall thickness of the drop (h_d) is increased from 0.25m up to 0.45m. The ratios $V_u/\phi V_c$ can be reduced to be less than 1 for all sizes of the opening at the exterior face of the interior column [O-7] except for the openings with the width $b=1.2$ m as shown in Figure 59. For the opening at the interior face of the interior column [O-8], the ratios $V_u/\phi V_c$ cannot be reduced to be less than 1 for all opening sizes except when the opening sizes ($a \times b$) are 0.4m x 1.6m, 1.6m x 1.2m and 1.6m x 1.6m as shown in Figure 60. The drop panel with the width (w_d) of 0.2m can provide adequate shear strength for all sizes of the opening at the face of the edge column [O-9] as shown in Figure 61.

For the opening size which the 0.2m drop width (w_d) cannot provide the adequate shear strength, the width w_d is increased to be 0.4m and overall thickness of the drop (h_d) is also increased from 0.45m until the shear strength provided by the concrete (ϕV_c) meets the required shear force (V_u). Generally, when the overall

thickness of the drop reaches 1.8 times the original slab thickness (i.e., $h_d=0.45$ m), the adequate shear strength can be provided by the drop panel for almost all sizes of openings O-7 and O-8. But $h_d=0.4$ m (1.6 times the original slab thickness) is generally adequate for the opening O-9 as shown in Table 26. The final designation of the drop panels for the various sizes of the openings O-7, O-8 and O-9 are shown in Table 27 to 29.

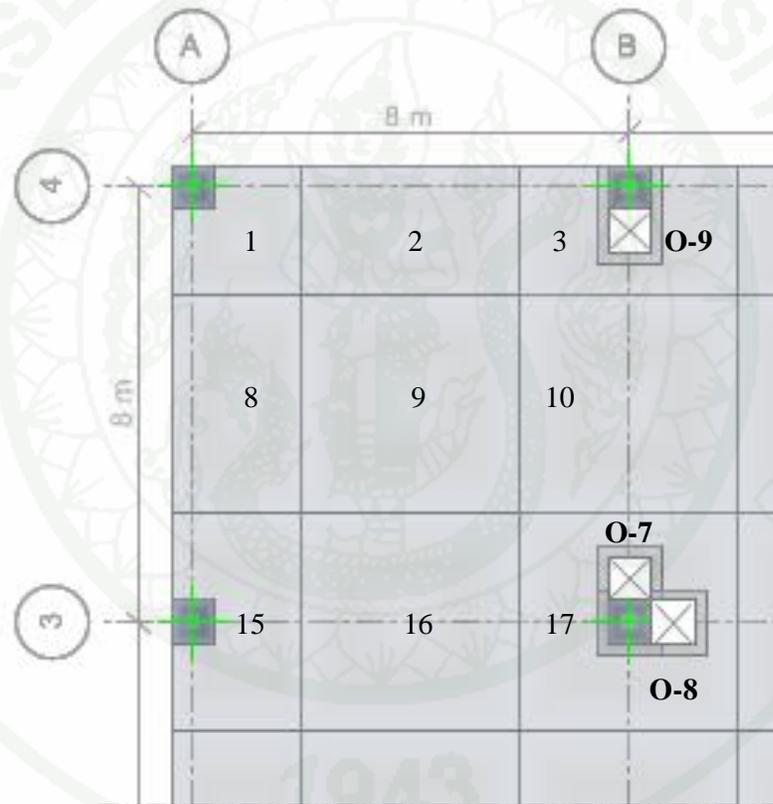


Figure 58 Location of the openings with typical drop panel

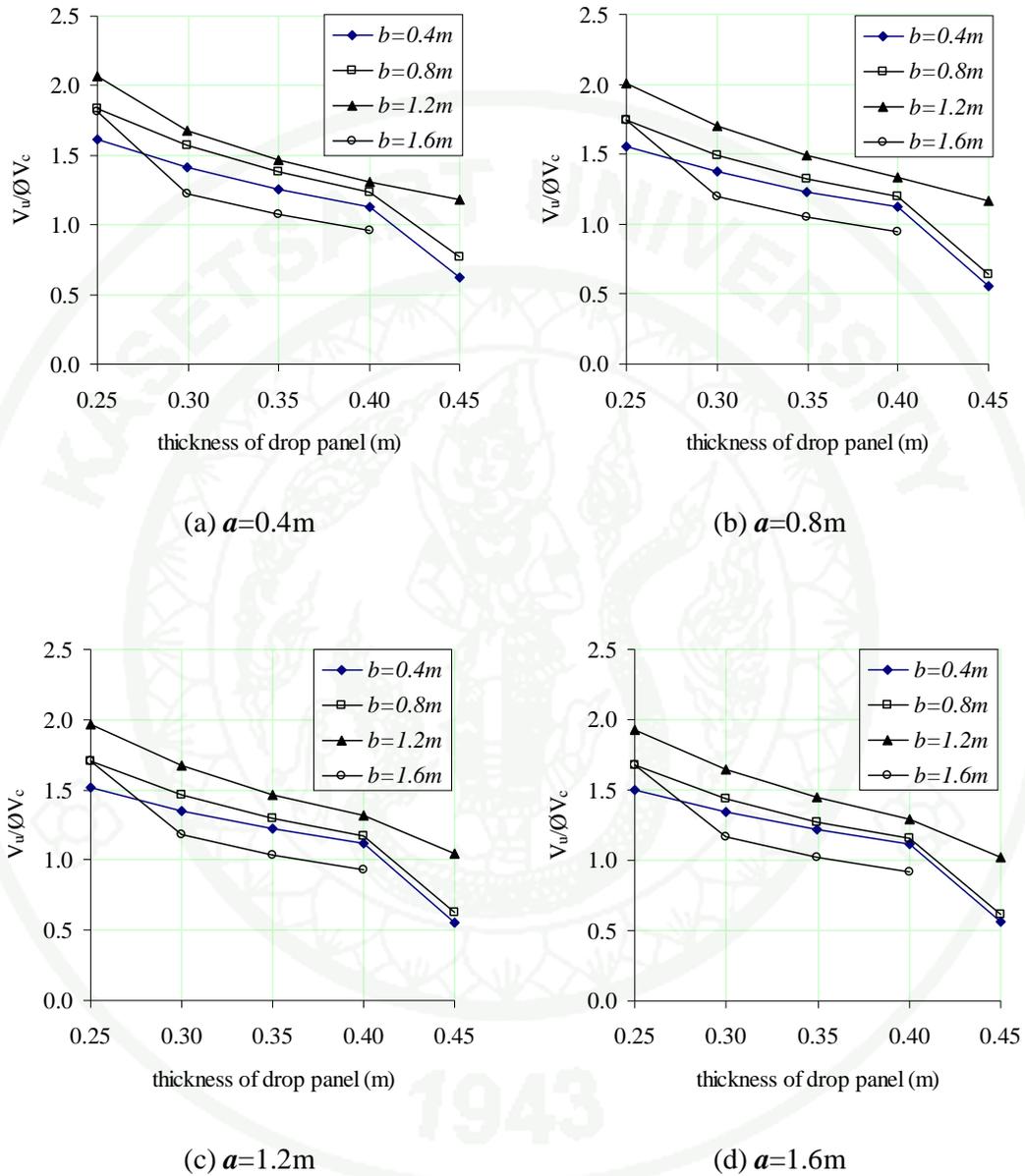


Figure 59 Ratio (at $d_p/2$ away from the column face) of shear force requirement and shear strength provided by concrete of the flat plate with drop panel $w_d = 0.2m$ around the opening at the exterior face of interior column [O-7]

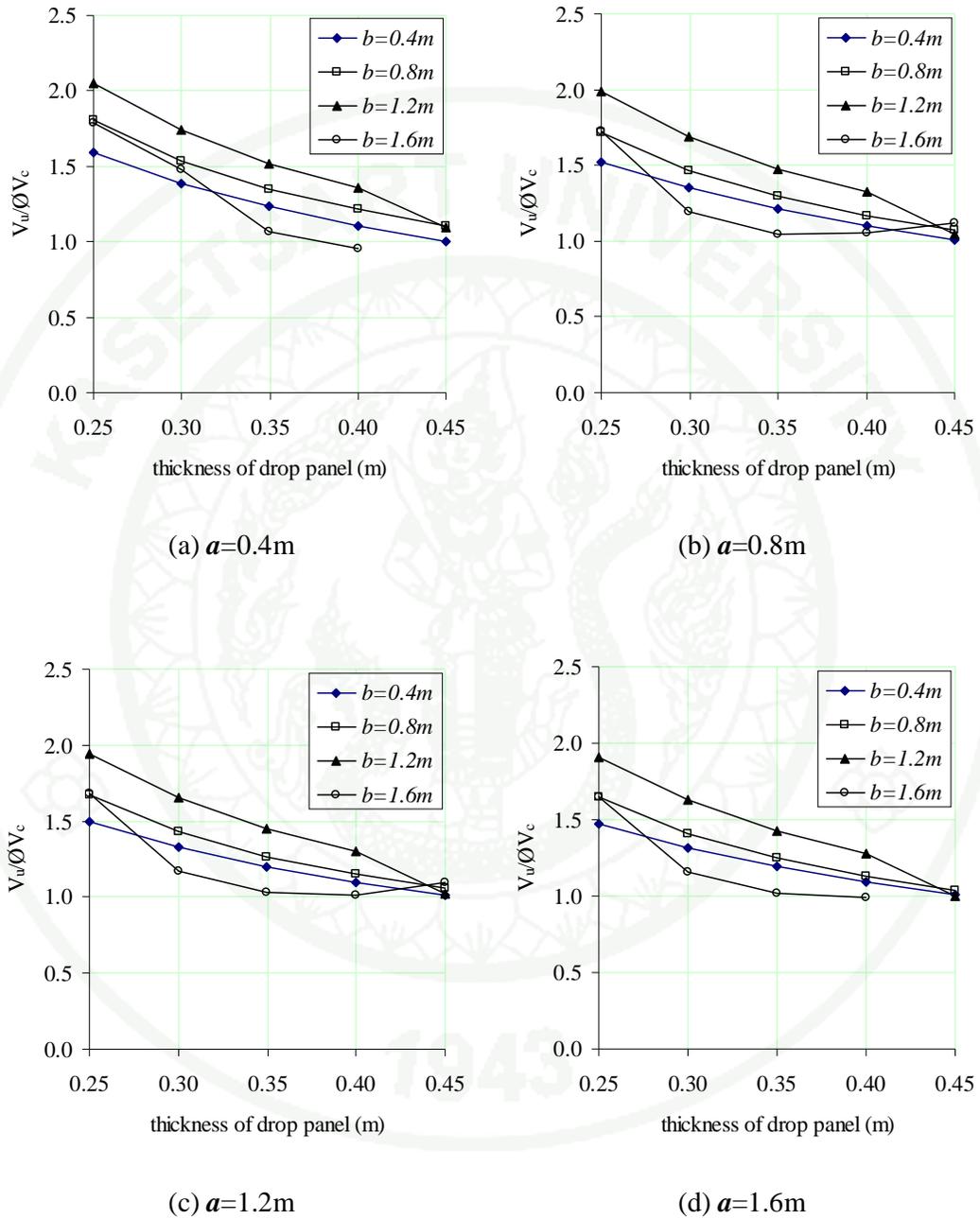


Figure 60 Ratio (at $d_p/2$ away from the column face) of shear force requirement and shear strength provided by concrete of the flat plate with drop panel $w_d = 0.2m$ around the opening at the interior face of interior column [O-8]

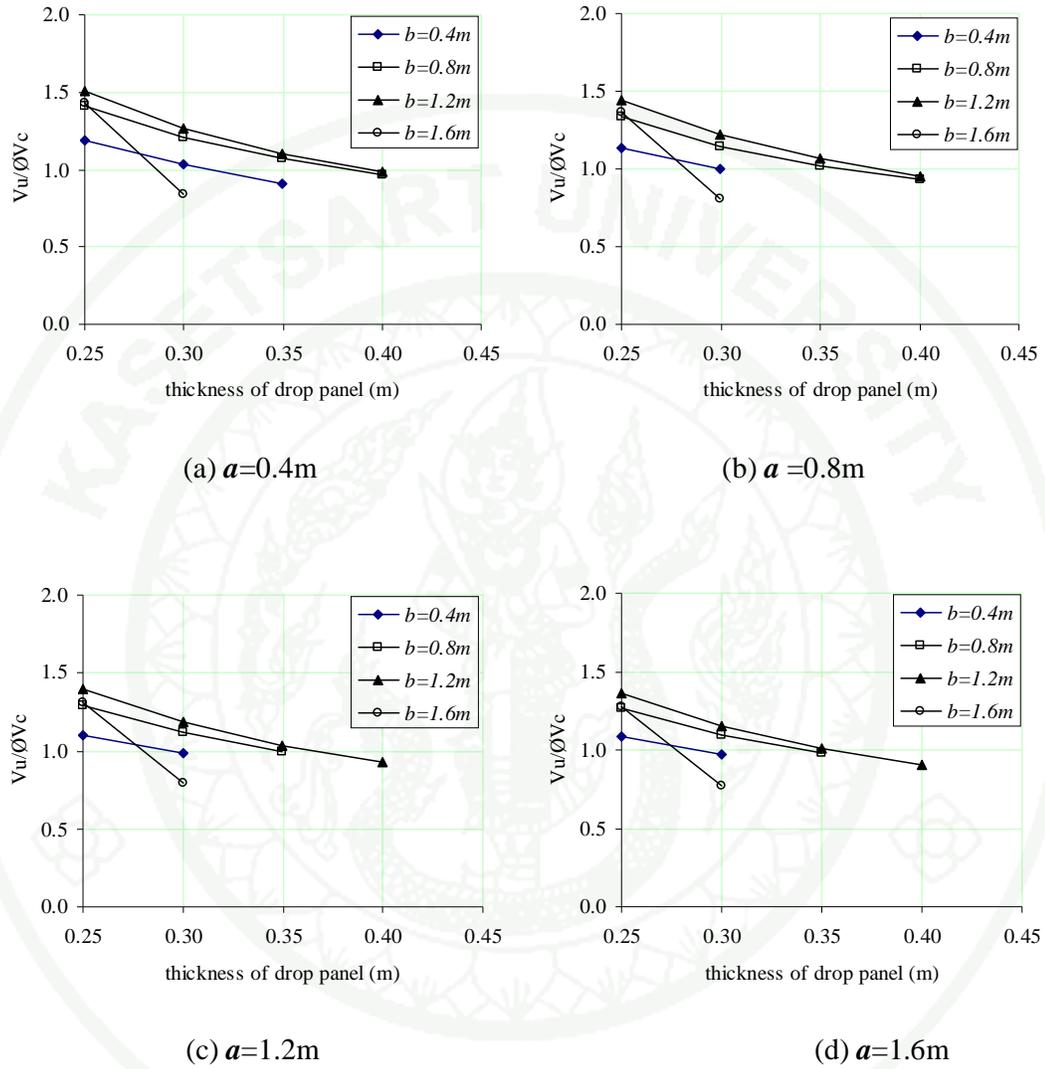


Figure 61 Ratio (at $d_p/2$ away from the column face) of shear force requirement and shear strength provided by concrete of the flat plate with drop panel $w_d = 0.2m$ around the opening at the face of edge column [O-9]

Table 26 Minimum acceptable drop thickness and opening size, which gives $V_u/\phi V_c$ less than 1

Openings	Opening size $a \times b$ (m x m)						
	h_d for $w_d = 0.2$ m				h_d for $w_d = 0.4$ m		
	0.30 m	0.35 m	0.40 m	0.45 m	0.45 m	0.50 m	0.55 m
O-7	-	-	0.4x1.6	0.4x0.4	0.4x1.2	-	1.2x1.2
O-7	-	-	0.8x0.8	0.4x0.8	0.8x1.2	-	-
O-7	-	-	0.8x1.6	0.8x0.4	1.6x1.2	-	-
O-7	-	-	1.2x1.6	1.2x0.4	-	-	-
O-7	-	-	1.6x1.6	1.2x0.8	-	-	-
O-7	-	-	-	1.6x0.4	-	-	-
O-7	-	-	-	1.6x0.8	-	-	-
O-8	-	-	0.4x1.6	1.6x1.2	0.4x0.4	0.4x0.8	0.8x1.6
O-8	-	-	1.6x1.6	-	0.8x0.4	0.4x1.2	1.2x1.6
O-8	-	-	-	-	0.8x0.8	-	-
O-8	-	-	-	-	0.8x1.2	-	-
O-8	-	-	-	-	1.2x0.4	-	-
O-8	-	-	-	-	1.2x0.8	-	-
O-8	-	-	-	-	1.2x1.2	-	-
O-8	-	-	-	-	1.6x0.4	-	-
O-8	-	-	-	-	1.6x0.8	-	-
O-9	0.4x1.6	0.4x0.4	0.4x0.8	-	-	-	-
O-9	0.8x0.4	1.2x0.8	0.4x1.2	-	-	-	-
O-9	0.8x1.6	1.6x0.8	0.8x0.8	-	-	-	-
O-9	1.2x0.4	-	0.8x1.2	-	-	-	-
O-9	1.2x1.6	-	1.2x1.2	-	-	-	-
O-9	1.6x0.4	-	1.6x1.2	-	-	-	-
O-9	1.6x1.6	-	-	-	-	-	-

Table 27 Recommended size of drop panels for the various size of openings at the exterior face of interior column [O-7]

Opening size $a \times b$ (m x m)	Drop size $x \times y$ (m x m)	h_d (m)	w_d (m)	$V_u/\phi V_c$ (at $d_p/2$ from column face)	$V_u/\phi V_c$ (at $d/2$ from drop edge)
0.4 x 0.4	1.2 x 1.6	0.45	0.2	0.62	0.73
0.4 x 0.8	1.2 x 1.6	0.45	0.2	0.77	0.68
0.4 x 1.2	2.0 x 2.0	0.45	0.4	0.59	0.60
0.4 x 1.6	2.0 x 1.6	0.40	0.2	0.96	0.68
0.8 x 0.4	1.2 x 2.0	0.45	0.2	0.55	0.73
0.8 x 0.8	1.2 x 2.0	0.45	0.2	0.64	0.68
0.8 x 1.2	2.0 x 2.4	0.45	0.4	0.99	0.60
0.8 x 1.6	2.0 x 2.0	0.40	0.2	0.94	0.68
1.2 x 0.4	1.2 x 2.4	0.45	0.2	0.55	0.74
1.2 x 0.8	1.2 x 2.4	0.45	0.2	0.62	0.68
1.2 x 1.2	2.0 x 2.8	0.55	0.4	0.48	0.59
1.2 x 1.6	2.0 x 2.4	0.40	0.2	0.93	0.67
1.6 x 0.4	1.2 x 2.8	0.45	0.2	0.56	0.73
1.6 x 0.8	1.2 x 2.8	0.45	0.2	0.61	0.68
1.6 x 1.2	2.0 x 3.2	0.45	0.4	0.96	0.60
1.6 x 1.6	2.0 x 2.8	0.40	0.2	0.92	0.66

Table 28 Recommended size of drop panels for the various size of openings at the interior face of interior column [O-8]

Opening size $a \times b$ (m x m)	Drop size $x \times y$ (m x m)	h_d (m)	w_d (m)	$V_u/\phi V_c$ (at $d_p/2$ from column face)	$V_u/\phi V_c$ (at $d/2$ from drop edge)
0.4 x 0.4	2.0 x 1.6	0.45	0.4	1.00	0.65
0.4 x 0.8	2.0 x 1.6	0.5	0.4	0.62	0.60
0.4 x 1.2	2.0 x 2.0	0.5	0.4	0.62	0.60
0.4 x 1.6	1.6 x 2.0	0.40	0.2	0.95	0.67
0.8 x 0.4	2.4 x 1.6	0.45	0.4	1.00	0.65
0.8 x 0.8	2.4 x 1.6	0.45	0.4	1.00	0.61
0.8 x 1.2	2.4 x 2.0	0.45	0.4	0.97	0.84
0.8 x 1.6	2.4 x 2.4	0.55	0.4	0.97	0.56
1.2 x 0.4	2.8 x 1.6	0.45	0.4	1.00	0.65
1.2 x 0.8	2.8 x 1.6	0.45	0.4	0.99	0.61
1.2 x 1.2	2.8 x 2.0	0.45	0.4	0.95	0.59
1.2 x 1.6	2.8 x 2.4	0.55	0.4	0.96	0.56
1.6 x 0.4	3.2 x 1.6	0.45	0.4	1.00	0.65
1.6 x 0.8	3.2 x 1.6	0.45	0.4	0.98	0.61
1.6 x 1.2	2.8 x 1.6	0.45	0.2	1.00	0.70
1.6 x 1.6	2.8 x 2.0	0.40	0.2	0.99	0.65

Table 29 Recommended size of drop panels for the various size of openings at the face of edge column [O-9]

Opening size $a \times b$ (m x m)	Drop size $x \times y$ (m x m)	h_d (m)	w_d (m)	$V_u/\phi V_c$ (at $d_p/2$ from column face)	$V_u/\phi V_c$ (at $d/2$ from drop edge)
0.4 x 0.4	1.2 x 1.4	0.35	0.2	0.91	0.36
0.4 x 0.8	1.2 x 1.4	0.40	0.2	0.97	0.45
0.4 x 1.2	1.6 x 1.4	0.40	0.2	0.98	0.58
0.4 x 1.6	2.0 x 1.4	0.30	0.2	0.84	0.56
0.8 x 0.4	1.2 x 1.8	0.30	0.2	1.00	0.39
0.8 x 0.8	1.2 x 1.8	0.40	0.2	0.93	0.46
0.8 x 1.2	1.6 x 1.8	0.40	0.2	0.95	0.57
0.8 x 1.6	2.0 x 1.8	0.30	0.2	0.81	0.56
1.2 x 0.4	1.2 x 2.2	0.30	0.2	0.98	0.39
1.2 x 0.8	1.2 x 2.2	0.35	0.2	1.00	0.45
1.2 x 1.2	1.6 x 2.2	0.40	0.2	0.93	0.56
1.2 x 1.6	2.0 x 2.2	0.30	0.2	0.79	0.55
1.6 x 0.4	1.2 x 2.6	0.30	0.2	0.97	0.38
1.6 x 0.8	1.2 x 2.6	0.35	0.2	0.98	0.44
1.6 x 1.2	1.6 x 2.6	0.40	0.2	0.91	0.55
1.6 x 1.6	2.0 x 2.6	0.30	0.2	0.77	0.53

CONCLUSION AND RECOMMENDATIONS

Conclusion

The following can be concluded from this study:

1. Almost all of the openings which are larger than the ACI permitted size have significant effects on the bending moment and shear force resultants of the flat plate.
2. The bending moments and shear forces decrease in almost all of the regions of the flat plate when the opening is located at the area common to intersecting middle strips. Therefore, the effect of this opening can be ignored and the opening can be permitted at this location according to the ACI standard.
3. When the openings are located at the area common to one middle-column strip and one middle strip or the area common to one column strip and one middle strip, the bending moments and shear forces increase in some regions of the flat plate. But the overall maximum bending moments and shear forces of the flat plate do not increase due to the effect of these openings.
4. When the openings are located at the area common to intersecting column strips, not only the localized bending moments and shear forces at the various areas of the flat plate but also the overall maximum bending moments and shear forces of the flat plate increase. The effect on the overall maximum shear force resultant changes is significant when the openings are located at the face of the column.
5. Among the openings at the area common to intersecting column strips, any size of the opening at the corner of the corner column has the least effect on the bending moment and shear force changes. The various sizes of the openings at the face of the interior and edge columns have significant effects on the resultant changes.

6. Comparing the analysis results of the various sizes of the openings at the face of the interior and edge column, the peak overall maximum bending moment and shear force changes occur when b (opening width parallel to the column face) is equal to 1.2 m and a (opening width perpendicular to the column face) is equal to 0.4 m.

7. The shear strength provided by the concrete of the flat plate without shear reinforcement decreases when increasing the opening sizes, especially when the opening width b is increased.

8. By comparing the ratios of the shear force requirement to the available maximum shear strength provided by the shear reinforcement ($V_u/\phi V_n$), the shearheads reinforcement is more effective than bar reinforcement to increase the shear strength of the flat plate with openings.

9. The bar and shearheads reinforcement cannot provide adequate shear strength for the openings at the interior and exterior faces of the interior column when width b of the opening is equal to 1.2 m and width a of the opening is equal to 0.4 m.

10. If the drop panels are provided around the opening, the adequate shear strength can be provided by the drop panels for various sizes of openings at the interior and exterior faces of interior column when the overall thickness of the drop (h_d) is not less than 1.8 times the original slab thickness around the various sizes of openings. The drop with a thickness of 1.6 times the original slab thickness is generally adequate for the opening at the face of the edge column.

Recommendations

The following recommendations are made for further study:

1. Since only rectangular shape of the opening with various sizes was used to study the opening effect on shear strength, further investigation should be carried out for circular shape of opening with various diameters.
2. In this study, each individual opening was located at the face of the column for each case of study. Several openings at the face of the column in different areas should be located at the same time and their effect on the shear strength of the flat plate with several openings should be studied for further study.
3. Further study should be carried out for the other types of shear reinforcements rather than the bar reinforcement and shearheads reinforcement which were used in this study.
4. Further study of shear strengthening should be done by using beam framing around the openings.

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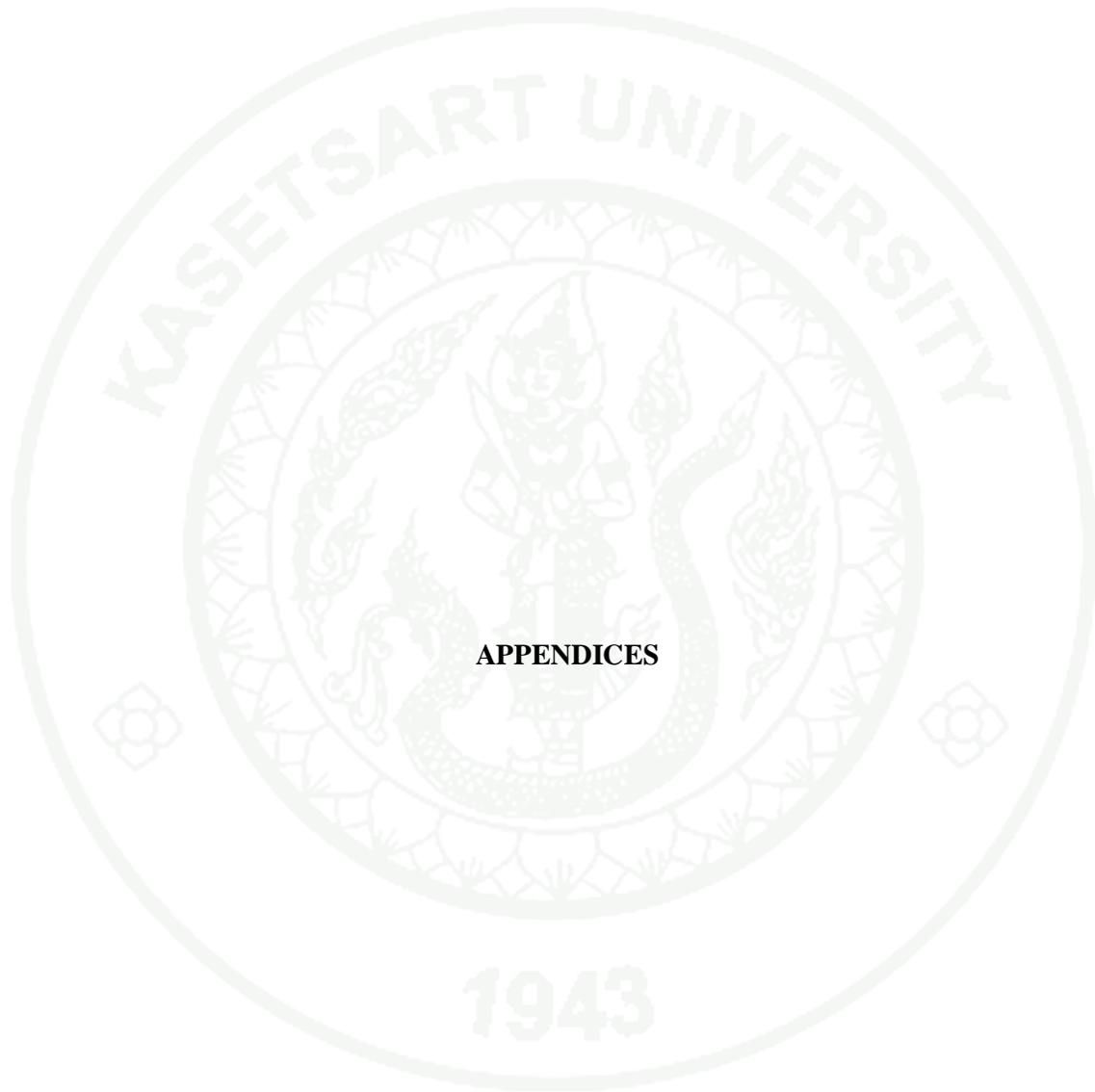
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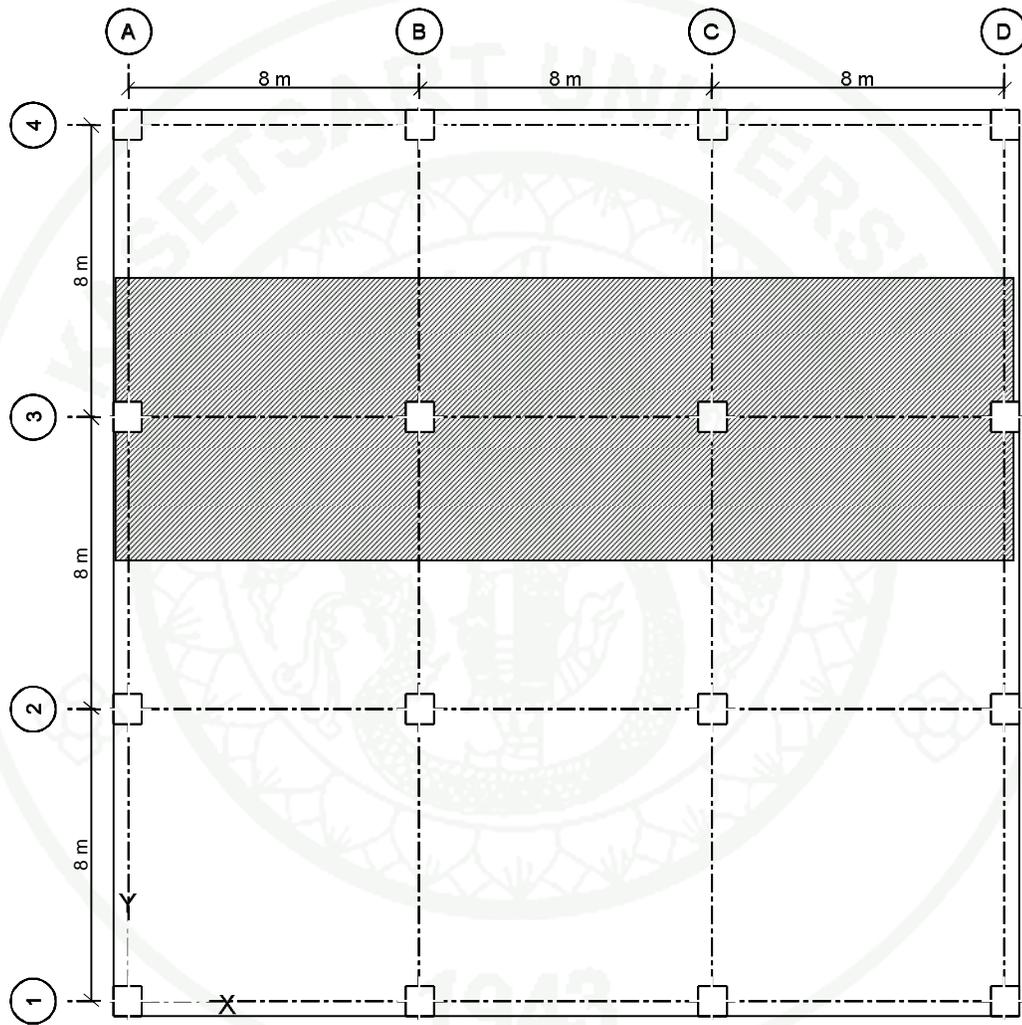
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APPENDICES



Appendix A
Computer program testing

1. Analysis of flat plate without opening by Equivalent Frame Method (EFM)**Appendix Figure A1** Plan of flat plate model

Story height	=	3 m
Column dimension	=	0.8 m x 0.8 m
Service live load	=	2.5 kN/m ²
Superimposed dead load	=	1.5 kN/m ²
Concrete f'_c	=	320 kg/cm ²
E	=	271900 kg/cm ²
v	=	0.19

1. Preliminary design for slab thickness h

(a) Control of deflection

$$h = \frac{l_n}{30} = \frac{(8.0 - 0.8)}{30} = 0.24 \text{ m}$$

Use $h = 0.25 \text{ m}$

(b) Shear strength of slab

Use average effective depth $d = 0.2 \text{ m}$ (cover = 0.05m)

Total factored load = $1.4 \times (\text{self wt.} + 1.5) + 1.7 \times 2.5 = 14.6 \text{ kN/m}^2$

Wide beam action:

$$V_u = 14.6 \times 3.4 \times 1.0 = 49.64 \text{ kN}$$

$$V_c = 0.53\sqrt{f'_c}b_wd$$

$$\phi V_c = 0.85 \times 0.53 \times \sqrt{320} \times 100 \times 20 = 16118 \text{ kg} = 158 \text{ kN}$$

$$V_u < \phi V_c$$

Two-way action:

$$V_u = 14.6 \times (8.0^2 - 1.0^2) = 919.8 \text{ kN}$$

$$V_c = 1.06\sqrt{f'_c}b_wd$$

$$\phi V_c = 0.85 \times 1.06 \times \sqrt{320} \times 400 \times 20 = 128940 \text{ kg} = 1264 \text{ kN}$$

$$V_u < \phi V_c$$

2. Frame members of equivalent frame:

(a) Slab-beams, K_{sb}

$$\frac{c_{N1}}{l_1} = \frac{0.8}{8} = 0.1$$

$$\frac{c_{N2}}{l_2} = \frac{0.8}{8} = 0.1$$

By interpolation, $k_{NF} = k_{FN} = 4.18$

$$I_s = \frac{l_2 h^3}{12} = \frac{8.0 \times 0.25^3}{12} = 0.010417 \text{ m}^4$$

$$E_{cs} = 271900 \text{ kg/ m}^2$$

$$K_{sb} = \frac{k_{NF} E_{cs} I_s}{l_1} = 0.005732E$$

By interpolation, Carry over factor COF = 0.51

$$\text{Fixed end moment FEM} = 0.0847 w_u l_2 l_1^2$$

(b) Column member, K_c

$$t_a = 0.125, t_b = 0.125$$

$$H = 3.0 \text{ m}, H_c = 2.75 \text{ m}, \frac{t_a}{t_b} = 1.0, \frac{H}{H_c} = 1.09$$

By interpolation, $k_{AB} = k_{BA} = 4.986$

$$I_c = \frac{c^4}{12} = \frac{0.8^4}{12} = 0.034133 \text{ m}^4$$

$$E_{cc} = 271900 \text{ kg/ m}^2$$

$$l_c = 3 \text{ m}$$

$$K_c = \frac{4.986 E_{cc} I_c}{l_c} = 0.056734E$$

(c) Torsional member, K_t

$$C = \sum (1 - 0.63x/y)(x^3 y/3) = 0.003346 \text{ m}^4$$

$$\frac{c_2}{l_2} = \frac{0.8}{8} = 0.1$$

$$K_t = \frac{9E_{cs}C}{[l_2(1 - c_2/l_2)^3]} = 0.00516E$$

(d) Equivalent column stiffness, K_{ec}

$$K_{ec} = \frac{\sum K_c x \sum K_t}{\sum K_c + \sum K_t} = 0.009467E$$

(e) Slab-beam joint distribution factor, DF

At exterior joint,

$$DF = \frac{0.005732}{(0.005732 + 0.009467)} = 0.377$$

At interior joint,

$$DF = \frac{0.005732}{(0.005732 + 0.005732 + 0.009467)} = 0.274$$

COF for slab-beam = 0.51

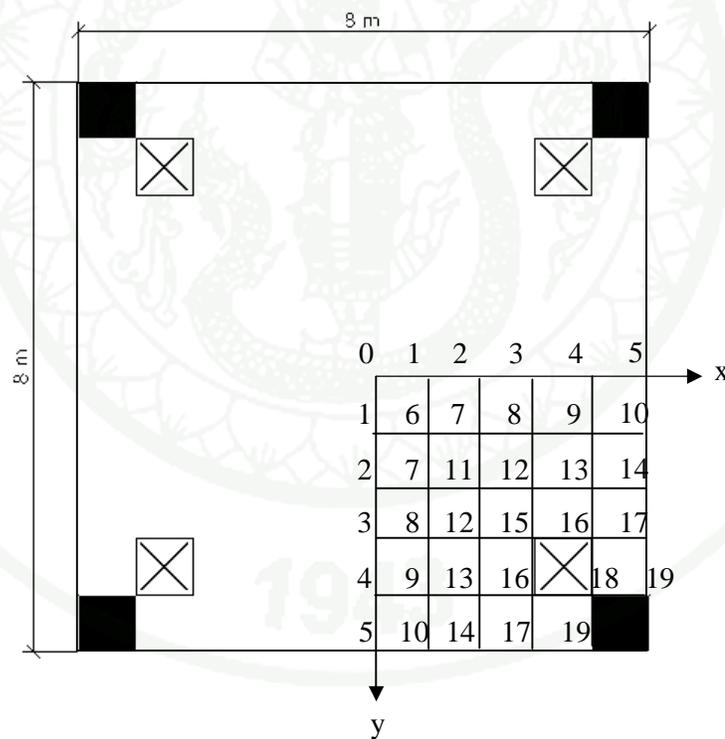
3. Partial frame analysis of equivalent frame:

Joint	A	B		C	D	
Member	A-B	B-A	B-C	C-B	C-D	D-C
DF	0.377	0.274	0.274	0.274	0.274	0.377
COF	0.51	0.51	0.51	0.51	0.51	0.51
FEM	633	-633	633	-633	633	-633
COM	0	-122	0	0	122	0
	17	0	-17	17	0	-17
	2	-3	-2	2	3	-2
Σ	652	-758	614	-614	758	-652
DM	-246	40	40	-40	-40	246
-ve M at support center	406	-719	653	-653	719	-406
+ve M at mid span	372		281		372	
V at support center	428	506	467	467	506	428
M_u^- at support face	244	-525	476	-476	525	-244
V at support face	381	459	420	420	459	381

2. Analysis of flat plate with openings by Finite Difference Method (FDM)

The data for analysis of single span flat plate with openings are as follows:

Size of flat plate	8.0 m x 8.0 m
Thickness	0.25 m
Size of columns	0.8 m x 0.8 m
Size of openings	0.8 m x 0.8 m
E	271900 kg/cm ²
ν	0.19
Uniform load	14.6 kN/m ²



Appendix Figure A2 Plan of single flat plate model

At point “0”

$$(20) w_0 + (-8) 4 w_1 + (2) 4 w_6 + (1) 4 w_2 = \frac{q\lambda^4}{D}$$

At point “1”

$$(20) w_1 + (-8) w_0 + (-8) w_2 + (-8) 2 w_6 + (2) 2 w_1 + (2) 2 w_7 + (1) 2 w_7 + (1) w_1 + (1)$$

$$w_3 = \frac{q\lambda^4}{D}$$

At point “2”

$$(20) w_2 + (-8) w_1 + (-8) w_3 + (-8) 2 w_7 + (2) 2 w_6 + (2) 2 w_8 + (1) 2 w_{11} + (1) w_0 + (1)$$

$$w_4 = \frac{q\lambda^4}{D}$$

At point “3”

$$(20) w_3 + (-8) w_2 + (-8) w_4 + (-8) 2 w_8 + (2) 2 w_7 + (2) 2 w_9 + (1) 2 w_{12} + (1) w_1 + (1)$$

$$w_5 = \frac{q\lambda^4}{D}$$

At point “4”

$$(19) w_4 + (-8) w_3 + (-8) 2 w_9 + (2) 2 w_8 + (2-\mu) 2 w_{10} + (-6+2\mu) w_5 + (1) w_2 + (1) 2$$

$$w_{13} = \frac{q\lambda^4}{D}$$

At point “5”

$$(8-4\mu-3\mu^2) w_5 + (-4+2\mu+2\mu^2) 2 w_{10} + (0.5\mu-0.5\mu^2) 2 w_{14} + (2-\mu) 2 w_9 + (-$$

$$6+2\mu) w_4 + (1) w_3 = 0.5 \frac{q\lambda^4}{D}$$

At point “6”

$$(20) w_6 + (-8) (2 w_1 + 2 w_7) + (2) (w_0 + 2 w_2 + w_{11}) + (1) (2 w_6 + 2 w_8) = \frac{q\lambda^4}{D}$$

At point “7”

$$(20) w_7 + (-8) (w_2 + w_6 + w_8 + w_{11}) + (2) (w_1 + w_3 + w_7 + w_{12}) + (1) (w_7 + w_1 + w_9 +$$

$$w_{12}) = \frac{q\lambda^4}{D}$$

At point “8”

$$(20) w_8 + (-8) (w_3 + w_7 + w_9 + w_{12}) + (2) (w_2 + w_4 + w_{11} + w_{13}) + (1) (w_6 + w_8 + w_{10} + w_{15}) = \frac{q\lambda^4}{D}$$

At point “9”

$$(19) w_9 + (-8) (w_3 + w_7 + w_9 + w_{12}) + (2) (w_2 + w_4 + w_{11} + w_{13}) + (1) (w_6 + w_8 + w_{10} + w_{15}) = \frac{q\lambda^4}{D}$$

At point “10”

$$(8-4\mu-3\mu^2) w_{10} + (-4+2\mu+2\mu^2) (w_5 + w_{14}) + (0.5\mu-0.5\mu^2) (w_{10} + w_{17}) + (2-\mu) (w_4 + w_{13}) + (-6+2\mu) w_9 + (1) w_8 = 0.5 \frac{q\lambda^4}{D}$$

At point “11”

$$(20) w_{11} + (-8) (2w_7 + 2w_{12}) + (2) (w_6 + 2w_8 + w_{15}) + (1) (2w_2 + 2w_{13}) = \frac{q\lambda^4}{D}$$

At point “12”

$$(20) w_{12} + (-8) (w_8 + w_{11} + w_{13} + w_{15}) + (2) (w_7 + w_9 + w_{12} + w_{16}) + (1) (w_3 + w_7 + w_{14} + w_{16}) = \frac{q\lambda^4}{D}$$

At point “13”

$$(19) w_{13} + (-8) (w_9 + w_{12} + w_{16}) + (2) (w_8 + w_{15}) + (1) (w_4 + w_{11} + w_{18}) + (-6+2\mu) w_{14} + (2-\mu) (w_{10} + w_{17}) = \frac{q\lambda^4}{D}$$

At point “14”

$$(8-4\mu-3\mu^2) w_{14} + (-4+2\mu+2\mu^2) (w_{10} + w_{17}) + (0.5\mu-0.5\mu^2) (w_5 + w_{19}) + (-6+2\mu) w_{13} + (2-\mu) (w_9 + w_{16}) + (1) w_{12} = 0.5 \frac{q\lambda^4}{D}$$

At point “15”

$$(20) w_{15} + (-8) (2w_{12} + 2w_{16}) + (2) (w_{11} + 2w_{13} + w_{18}) + (1) (2w_8 + 2w_{17}) = \frac{q\lambda^4}{D}$$

At point “16”

$$(19) w_{16} + (-8) (w_{13} + w_{15} + w_{18}) + (2) (w_{12} + w_{16}) + (1) (w_9 + w_{12} + w_{19}) + (-6+2\mu)$$

$$w_{17} + (2-\mu) (w_{14} + w_{19}) = \frac{q\lambda^4}{D}$$

At point “17”

$$(8-4\mu-3\mu^2) w_{17} + (-4+2\mu+2\mu^2) (w_{14} + w_{19}) + (0.5\mu-0.5\mu^2) (w_{10} + w_{20}) + (-6+2\mu)$$

$$w_{16} + (2-\mu) (w_{13} + w_{18}) + (1) w_{15} = 0.5 \frac{q\lambda^4}{D}$$

Where $w_{18} = w_{19} = w_{20} = 0$ and solving the above equations,

$$w_0 = 44.29 \frac{q\lambda^4}{D}, \quad w_6 = 41.08 \frac{q\lambda^4}{D}, \quad w_{12} = 24.47 \frac{q\lambda^4}{D}$$

$$w_1 = 42.73 \frac{q\lambda^4}{D}, \quad w_7 = 36.59 \frac{q\lambda^4}{D}, \quad w_{13} = 17.70 \frac{q\lambda^4}{D}$$

$$w_2 = 38.46 \frac{q\lambda^4}{D}, \quad w_8 = 30.44 \frac{q\lambda^4}{D}, \quad w_{14} = 12.87 \frac{q\lambda^4}{D}$$

$$w_3 = 32.60 \frac{q\lambda^4}{D}, \quad w_9 = 24.22 \frac{q\lambda^4}{D}, \quad w_{15} = 16.24 \frac{q\lambda^4}{D}$$

$$w_4 = 26.56 \frac{q\lambda^4}{D}, \quad w_{10} = 19.03 \frac{q\lambda^4}{D}, \quad w_{16} = 8.60 \frac{q\lambda^4}{D}$$

$$w_5 = 21.33 \frac{q\lambda^4}{D}, \quad w_{11} = 31.46 \frac{q\lambda^4}{D}, \quad w_{17} = 5.19 \frac{q\lambda^4}{D}$$

$$\text{Substitute the values; } q = 14.6 \text{ kN/m}^2, \lambda = 0.8 \text{ m}, D = \frac{Eh^3}{12(1-\nu^2)} = 36019 \text{ kN} \cdot \text{m}$$

$$\text{At } x=0, y=0, \quad w_0 = 44.29 \frac{q\lambda^4}{D} = 7.35 \text{ m}$$

$$M_x = \frac{D}{\lambda^2} [(2+2\mu) w_0 - 1(2w_1) - \mu(2w_1)] = 34.83 \text{ kN} \cdot \text{m/m}$$

$$M_y = \frac{D}{\lambda^2} [(2+2\mu) w_0 - 1(2w_1) - \mu(2w_1)] = 34.83 \text{ kN} \cdot \text{m/m}$$

$$V_x = \frac{D}{2\lambda^3} [-4w_1 + 4w_1 + 1(w_2 + 2w_6) - 1(w_2 + 2w_6)] = 0 \text{ kN/m}$$

$$V_y = \frac{D}{2\lambda^3} [-4w_1 + 4w_1 + 1(w_2 + 2w_6) - 1(w_2 + 2w_6)] = 0 \text{ kN/m}$$

At $x=0.8\text{m}$, $y= -0.8\text{m}$,

$$w_6 = 41.08 \frac{q\lambda^4}{D} = 6.82\text{m}$$

$$M_x = \frac{D}{\lambda^2} [(2 + 2\mu) w_6 - 1(w_1 + w_7) - \mu (w_1 + w_7)] = 32.15 \text{ kN - m/m}$$

$$M_y = \frac{D}{\lambda^2} [(2 + 2\mu) w_6 - 1(w_1 + w_7) - \mu (w_1 + w_7)] = 32.15 \text{ kN - m/m}$$

$$V_x = \frac{D}{2\lambda^3} [-4w_1 + 4w_7 + 1(w_0 + w_2 + w_6) - 1(w_2 + w_8 + w_{11})] = 6.33 \text{ kN/m}$$

$$V_y = \frac{D}{2\lambda^3} [-4w_1 + 4w_7 + 1(w_0 + w_2 + w_6) - 1(w_2 + w_8 + w_{11})] = 6.33 \text{ kN/m}$$

At $x=1.6\text{m}$, $y= 0$

$$w_2 = 38.46 \frac{q\lambda^4}{D} = 6.38\text{m}$$

$$M_x = \frac{D}{\lambda^2} [(2 + 2\mu) w_2 - 1(w_1 + w_3) - \mu (2w_7)] = 21.26 \text{ kN - m/m}$$

$$M_y = \frac{D}{\lambda^2} [(2 + 2\mu) w_2 - \mu(w_1 + w_3) - 1(2w_7)] = 37.67 \text{ kN - m/m}$$

$$V_x = \frac{D}{2\lambda^3} [-4w_1 + 4w_3 + 1(w_0 + 2w_6) - 1(w_4 + 2w_8)] = 8.44 \text{ kN/m}$$

$$V_y = \frac{D}{2\lambda^3} [-4w_7 + 4w_7 + 1(w_6 + w_8 + w_{11}) - 1(w_6 + w_8 + w_{11})] = 0 \text{ kN/m}$$

At $x=0$, $y= -1.6\text{m}$

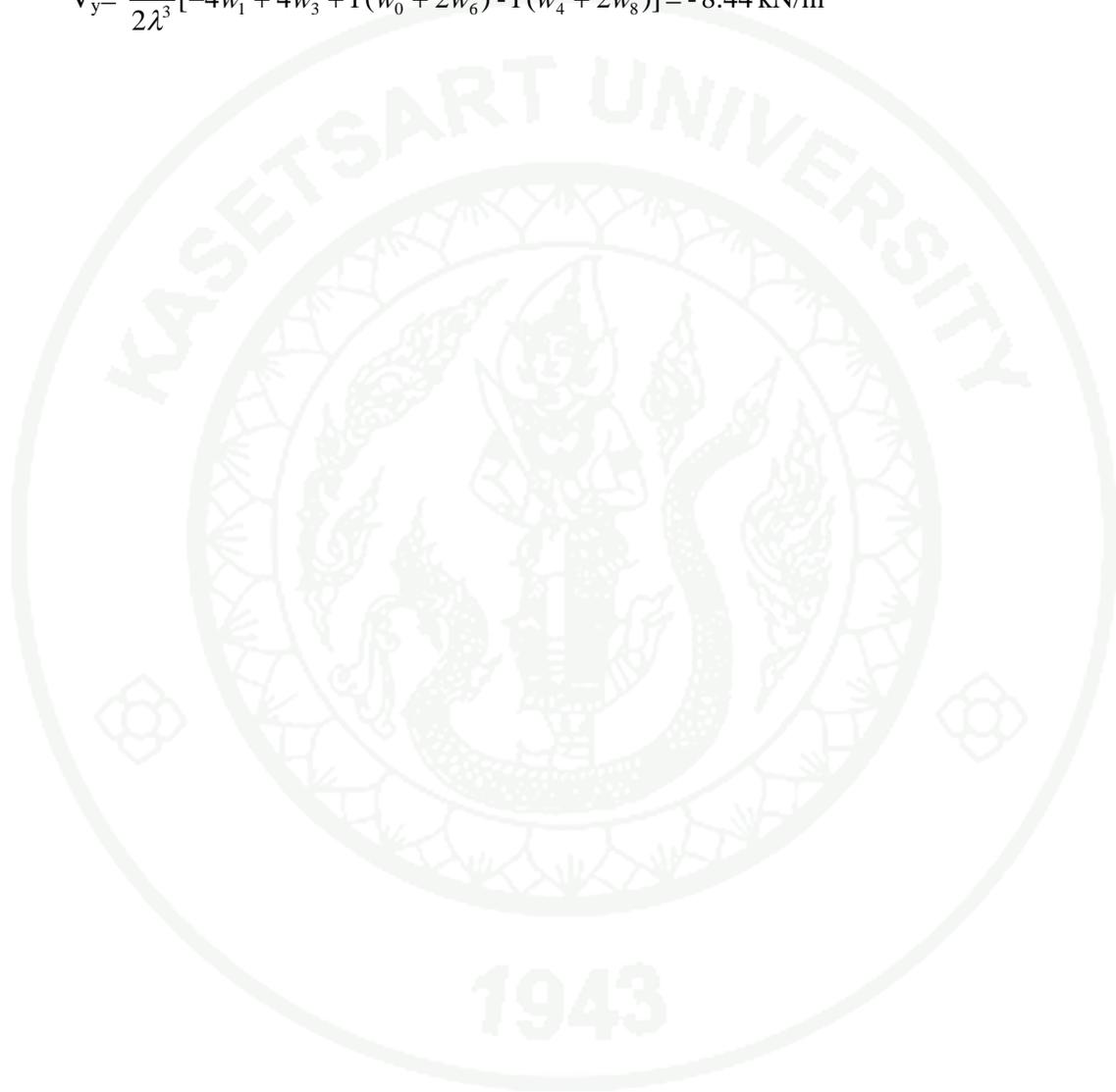
$$w_2 = 38.46 \frac{q\lambda^4}{D} = 6.38\text{m}$$

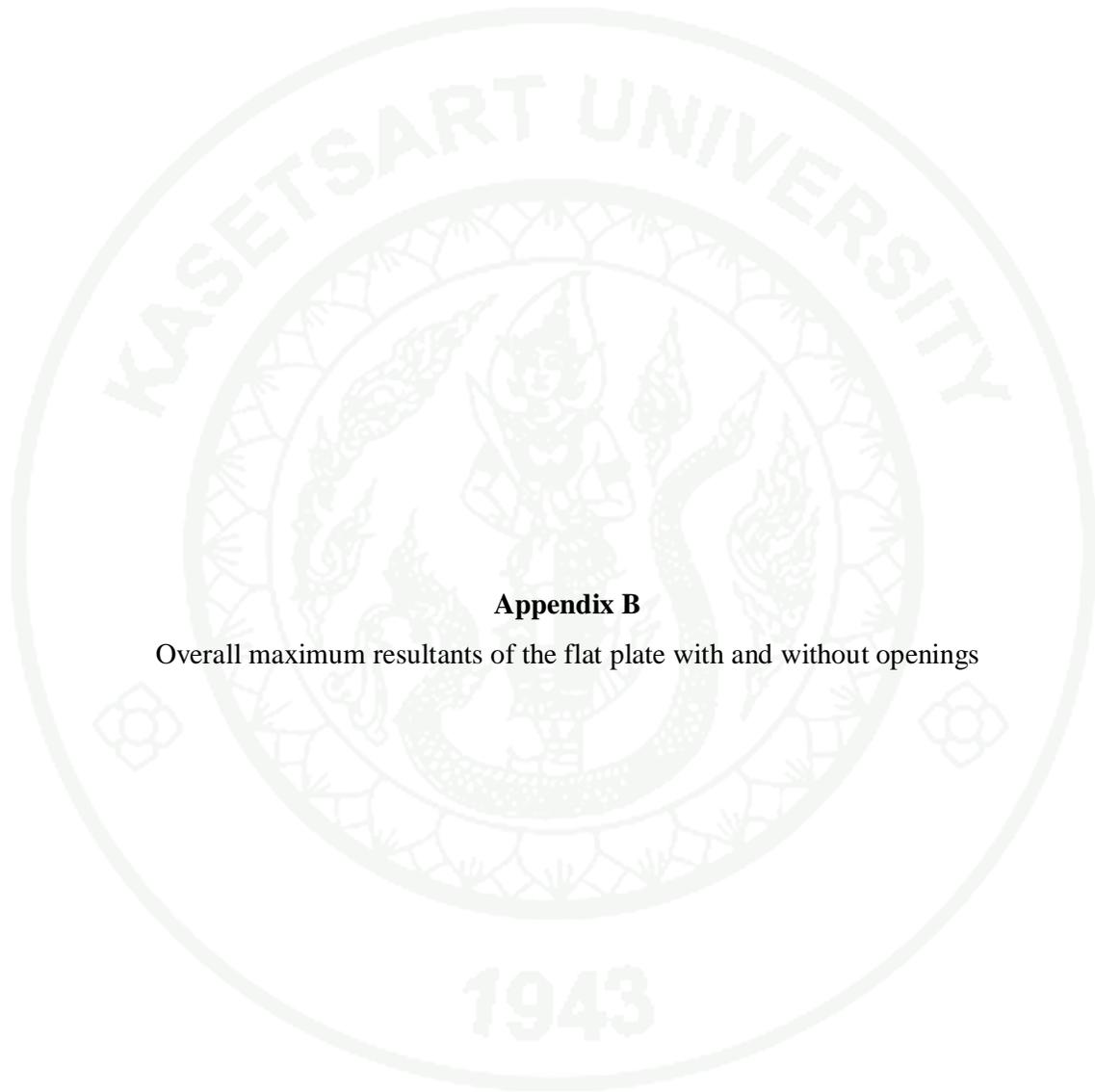
$$M_x = \frac{D}{\lambda^2} [(2 + 2\mu) w_2 - 1(w_7 + w_7) - \mu (w_1 + w_3)] = 37.67 \text{ kN - m/m}$$

$$M_y = \frac{D}{\lambda^2} [(2 + 2\mu) w_2 - \mu(w_7 + w_7) - 1(w_1 + w_3)] = 21.26 \text{ kN - m/m}$$

$$V_x = \frac{D}{2\lambda^3} [-4w_7 + 4w_7 + 1(w_6 + w_8 + w_{11}) - 1(w_6 + w_8 + w_{11})] = 0 \text{ kN/m}$$

$$V_y = \frac{D}{2\lambda^3} [-4w_1 + 4w_3 + 1(w_0 + 2w_6) - 1(w_4 + 2w_8)] = -8.44 \text{ kN/m}$$





Appendix B

Overall maximum resultants of the flat plate with and without openings

Appendix Table B1 Coefficients of maximum bending moment and shear force resultants in 49 areas of flat plate without opening

Area No.	Coefficients			
	β_x	β_y	γ_x	γ_y
1	-0.028	-0.028	0.167	0.166
2	0.006	0.003	0.057	0.029
3	-0.028	-0.029	0.210	0.232
4	0.005	0.003	0.054	0.029
5	-0.028	-0.029	0.210	0.232
6	0.006	0.003	0.058	0.029
7	-0.028	-0.028	0.167	0.166
8	0.003	0.006	0.029	0.057
9	0.006	0.006	0.029	0.029
10	-0.006	0.007	0.032	0.064
11	0.005	0.005	0.026	0.029
12	-0.006	0.007	0.032	0.064
13	0.006	0.006	0.029	0.029
14	0.003	0.006	0.029	0.057
15	-0.029	-0.028	0.232	0.210
16	0.007	-0.006	0.064	0.032
17	-0.031	-0.031	0.324	0.324
18	0.006	-0.006	0.060	0.032
19	-0.031	-0.031	0.323	0.323
20	0.007	-0.006	0.064	0.032
21	-0.029	-0.028	0.232	0.210
22	0.003	0.005	0.029	0.054
23	0.005	0.005	0.029	0.026
24	-0.006	0.006	0.032	0.060
25	0.005	0.005	0.026	0.026
26	-0.006	0.006	0.032	0.060
27	0.005	0.005	0.029	0.026
28	0.003	0.005	0.029	0.054
29	-0.029	-0.028	0.232	0.210
30	0.007	-0.006	0.064	0.032

Appendix Table B1 (Continued)

Area No.	Coefficients			
	β_x	β_y	γ_x	γ_y
31	-0.031	-0.031	0.323	0.323
32	0.006	-0.006	0.060	0.032
33	-0.031	-0.031	0.324	0.324
34	0.007	-0.006	0.064	0.032
35	-0.029	-0.028	0.232	0.210
36	0.003	0.006	0.029	0.057
37	0.006	0.006	0.029	0.029
38	-0.006	0.007	0.032	0.064
39	0.005	0.005	0.026	0.029
40	-0.006	0.007	0.032	0.064
41	0.006	0.006	0.029	0.029
42	0.003	0.006	0.029	0.058
43	-0.028	-0.028	0.167	0.166
44	0.006	0.003	0.058	0.029
45	-0.028	-0.029	0.210	0.232
46	0.005	0.003	0.054	0.029
47	-0.028	-0.029	0.210	0.232
48	0.006	0.003	0.058	0.029
49	-0.028	-0.028	0.166	0.167

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Appendix Table B2 Overall maximum bending moment and shear force resultants of the flat plate with opening at the exterior face of interior column [O-7]

Opening size $a \times b$ (m x m)	M_x (kN-m/m)	M_y (kN-m/m)	V_x (kN/m)	V_y (kN/m)
0.4 x 0.4	256	274	328	511
0.4 x 0.8	310	308	385	581
0.4 x 1.2	404	335	654	500
0.4 x 1.6	396	292	573	455
0.8 x 0.4	263	264	327	490
0.8 x 0.8	321	270	380	552
0.8 x 1.2	414	301	633	469
0.8 x 1.6	389	267	552	423
1.2 x 0.4	269	258	325	481
1.2 x 0.8	327	249	376	540
1.2 x 1.2	418	283	620	455
1.2 x 1.6	383	254	539	408
1.6 x 0.4	274	252	324	475
1.6 x 0.8	330	239	373	531
1.6 x 1.2	419	271	611	446
1.6 x 1.6	377	245	529	398

Appendix Table B3 Overall maximum bending moment and shear force resultants of the flat plate with opening at the interior face of interior column [O-8]

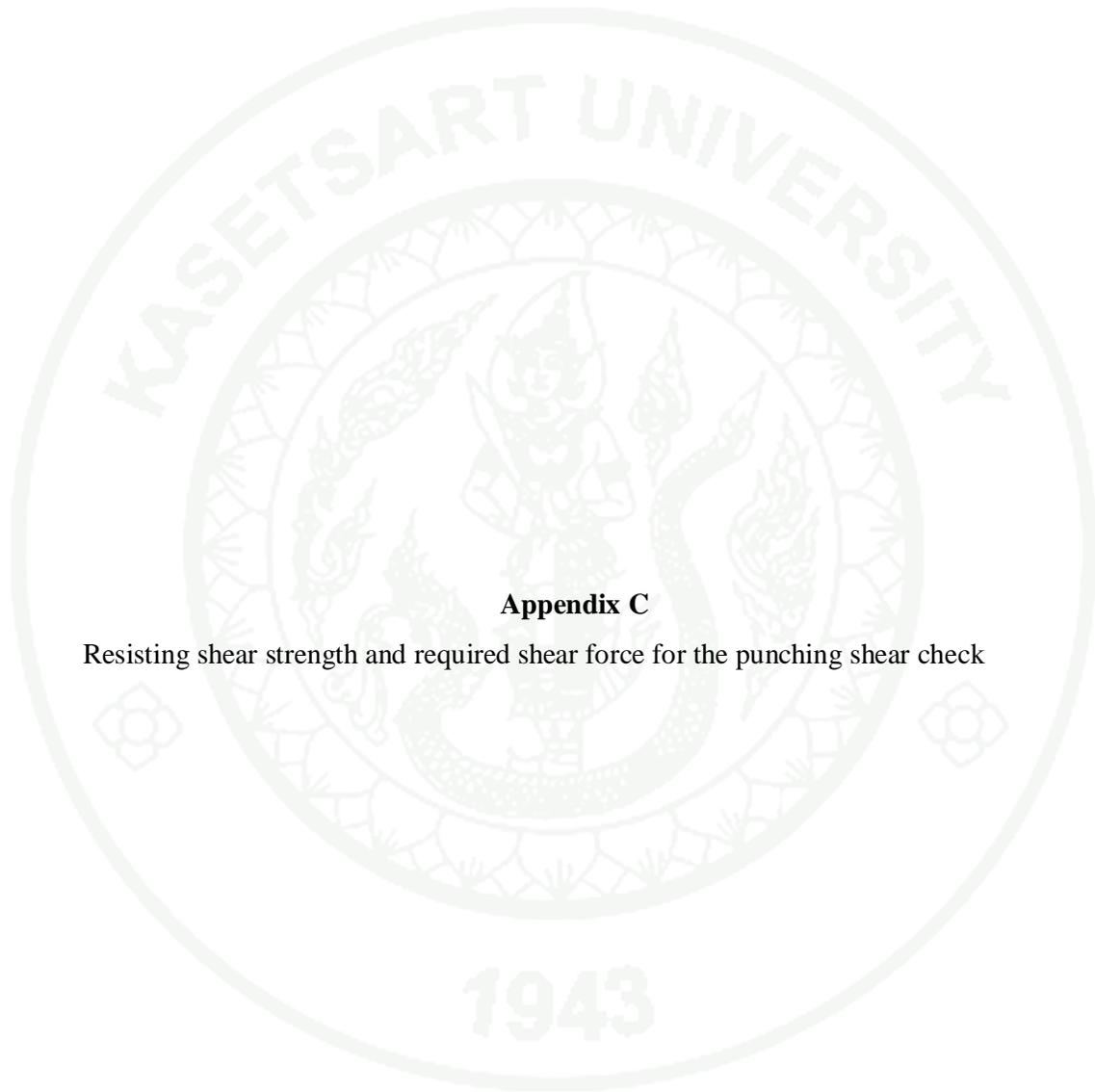
Opening size $a \times b$ (m x m)	M_x (kN-m/m)	M_y (kN-m/m)	V_x (kN/m)	V_y (kN/m)
0.4 x 0.4	253	245	503	328
0.4 x 0.8	283	294	570	382
0.4 x 1.2	309	384	491	647
0.4 x 1.6	270	373	445	566
0.8 x 0.4	243	251	482	327
0.8 x 0.8	246	304	542	378
0.8 x 1.2	276	393	461	627
0.8 x 1.6	246	366	414	545
1.2 x 0.4	238	257	473	325
1.2 x 0.8	239	310	529	373
1.2 x 1.2	259	397	447	614
1.2 x 1.6	240	360	399	532
1.6 x 0.4	238	261	467	324
1.6 x 0.8	239	313	521	370
1.6 x 1.2	247	398	437	604
1.6 x 1.6	240	354	389	522

Appendix Table B4 Overall maximum bending moment and shear force resultants of the flat plate with opening at the face of edge column [O-9]

Opening size $a \times b$ (m x m)	M_x (kN-m/m)	M_y (kN-m/m)	V_x (kN/m)	V_y (kN/m)
0.4 x 0.4	239	255	304	375
0.4 x 0.8	280	294	307	447
0.4 x 1.2	367	313	476	404
0.4 x 1.6	375	267	452	391
0.8 x 0.4	240	247	305	357
0.8 x 0.8	291	260	307	422
0.8 x 1.2	380	285	455	376
0.8 x 1.6	372	259	430	361
1.2 x 0.4	240	242	305	349
1.2 x 0.8	299	246	307	409
1.2 x 1.2	386	270	442	362
1.2 x 1.6	369	258	416	346
1.6 x 0.4	245	242	305	343
1.6 x 0.8	303	246	307	401
1.6 x 1.2	389	260	431	352
1.6 x 1.6	365	257	404	335

Appendix Table B5 Overall maximum bending moment and shear force resultants of the flat plate with opening at the corner of corner column [O-10]

Opening size $a \times b$ (m x m)	M_x (kN-m/m)	M_y (kN-m/m)	V_x (kN/m)	V_y (kN/m)
0.4 x 0.4	239	239	304	304
0.4 x 0.8	239	248	304	304
0.4 x 1.2	240	259	304	304
0.4 x 1.6	240	268	304	304
0.8 x 0.4	248	239	304	304
0.8 x 0.8	240	240	304	304
0.8 x 1.2	240	240	304	304
0.8 x 1.6	240	239	304	304
1.2 x 0.4	259	240	304	304
1.2 x 0.8	240	240	304	304
1.2 x 1.2	239	239	304	304
1.2 x 1.6	239	239	304	304
1.6 x 0.4	268	240	304	304
1.6 x 0.8	239	240	304	304
1.6 x 1.2	239	239	304	304
1.6 x 1.6	239	239	303	303



Appendix C

Resisting shear strength and required shear force for the punching shear check

Appendix Table C1 Required shear force (V_u) used in punching shear check around the column region for the openings [O-7, O-8, O-9 and O-10] without shear strengthening

Opening size $a \times b$ (m x m)	V_u (kN/m)			
	O-7	O-8	O-9	O-10
without	303	303	216	155
0.4 x 0.4	511	503	375	209
0.4 x 0.8	581	570	447	243
0.4 x 1.2	654	647	476	264
0.4 x 1.6	573	566	452	280
0.8 x 0.4	490	482	357	243
0.8 x 0.8	552	542	422	207
0.8 x 1.2	633	627	455	226
0.8 x 1.6	552	545	430	241
1.2 x 0.4	481	473	349	264
1.2 x 0.8	540	529	409	226
1.2 x 1.2	620	614	442	191
1.2 x 1.6	539	532	416	204
1.6 x 0.4	475	467	343	280
1.6 x 0.8	531	521	401	241
1.6 x 1.2	611	604	431	204
1.6 x 1.6	529	522	404	170

Appendix Table C2 Maximum shear strength (ϕV_n) permitted with bar and shearheads reinforcement for the openings at the face of interior column and edge column [O-7, O-8, and O-9]

Opening size (m)		Opening type	Critical section b_0 (m)	ϕV_n (kN)	
a	b			Bar reinforcement	Shearheads reinforcement
any	0.4	O-7, O-8	3.75	1778	2080
any	0.8	O-7, O-8	3.5	1660	1941
any	1.2	O-7, O-8	2.733	1296	1516
any	1.6	O-7, O-8	2.65	1257	1470
any	0.4	O-9	2.55	1209	1414
any	0.8	O-9	2.3	1091	1276
any	1.2	O-9	1.533	727	851
any	1.6	O-9	1.45	688	804

Appendix Table C3 Step by step drop panel designation for the various sizes of opening at the exterior face of interior column [O-7]

Opening size $a \times b$ (m x m)	Drop size		1 st critical perimeter				2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	ϕV_c (kN/m)	V_u (kN/m)	d (m)	ϕV_c (kN/m)	V_u (kN/m)
0.4 x 0.4	-	0.25	-	0.1	316	510	-	-	-
	1.2 x 1.6	0.3	0.2	0.125	395	557	0.1	283	216
	1.2 x 1.6	0.35	0.2	0.15	474	593	0.1	283	213
	1.2 x 1.6	0.4	0.2	0.175	553	622	0.1	283	209
	1.2 x 1.6	0.45	0.2	0.2	632	392	0.1	283	207
0.4 x 0.8	-	0.25	-	0.1	316	581	-	-	-
	1.2 x 1.6	0.3	0.2	0.125	395	619	0.1	314	224
	1.2 x 1.6	0.35	0.2	0.15	474	653	0.1	314	221
	1.2 x 1.6	0.4	0.2	0.175	553	684	0.1	314	218
	1.2 x 1.6	0.45	0.2	0.2	632	487	0.1	314	215
0.4 x 1.2	-	0.25	-	0.1	316	654	-	-	-
	1.6 x 1.6	0.3	0.2	0.125	395	663	0.1	307	225
	1.6 x 1.6	0.35	0.2	0.15	474	695	0.1	307	224
	1.6 x 1.6	0.4	0.2	0.175	553	723	0.1	307	222
	1.6 x 1.6	0.45	0.2	0.2	632	746	0.1	307	220
	2.0 x 2.0	0.45	0.4	0.2	632	373	0.1	279	168

Appendix Table C3 (Continued)

Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	ϕV_c (kN/m)	V_u (kN/m)	d (m)	ϕV_c (kN/m)	V_u (kN/m)
0.4 x 1.6	-	0.25	-	0.1	316	573	-	-	-
	2.0 x 1.6	0.3	0.2	0.125	395	485	0.1	298	200
	2.0 x 1.6	0.35	0.2	0.15	474	510	0.1	298	202
	2.0 x 1.6	0.4	0.2	0.175	553	531	0.1	298	203
0.8 x 0.4	-	0.25	-	0.1	316	490	-	-	-
	1.2 x 2.0	0.3	0.2	0.125	395	542	0.1	283	216
	1.2 x 2.0	0.35	0.2	0.15	474	584	0.1	283	213
	1.2 x 2.0	0.4	0.2	0.175	553	619	0.1	283	210
	1.2 x 2.0	0.45	0.2	0.2	632	349	0.1	283	207
0.8 x 0.8	-	0.25	-	0.1	316	552	-	-	-
	1.2 x 2.0	0.25	0.2	0.125	395	590	0.1	314	224
	1.2 x 2.0	0.3	0.2	0.15	474	627	0.1	314	221
	1.2 x 2.0	0.35	0.2	0.175	553	661	0.1	314	218
	1.2 x 2.0	0.4	0.2	0.2	632	405	0.1	314	215

Appendix Table C3 (Continued)

Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	ϕV_c (kN/m)	V_u (kN/m)	d (m)	ϕV_c (kN/m)	V_u (kN/m)
0.8 x 1.2	-	0.25	-	0.1	316	633	-	-	-
	1.6 x 2.0	0.3	0.2	0.125	395	674	0.1	307	223
	1.6 x 2.0	0.35	0.2	0.15	474	709	0.1	307	223
	1.6 x 2.0	0.4	0.2	0.175	553	739	0.1	307	221
	1.6 x 2.0	0.45	0.2	0.2	632	736	0.1	307	219
	2.0 x 2.4	0.45	0.4	0.2	632	628	0.1	279	167
0.8 x 1.6	-	0.25	-	0.1	316	552	-	-	-
	2.0 x 2.0	0.3	0.2	0.125	395	474	0.1	298	198
	2.0 x 2.0	0.35	0.2	0.15	474	500	0.1	298	201
	2.0 x 2.0	0.4	0.2	0.175	553	521	0.1	298	202
1.2 x 0.4	-	0.25	-	0.1	316	481	-	-	-
	1.2 x 2.4	0.3	0.2	0.125	395	535	0.1	283	215
	1.2 x 2.4	0.35	0.2	0.15	474	580	0.1	283	213
	1.2 x 2.4	0.4	0.2	0.175	553	617	0.1	283	210
	1.2 x 2.4	0.45	0.2	0.2	632	349	0.1	283	208

Appendix Table C3 (Continued)

Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	ϕV_c (kN/m)	V_u (kN/m)	d (m)	ϕV_c (kN/m)	V_u (kN/m)
1.2 x 0.8	-	0.25	-	0.1	316	540	-	-	-
	1.2 x 2.4	0.3	0.2	0.125	395	577	0.1	314	223
	1.2 x 2.4	0.35	0.2	0.15	474	614	0.1	314	220
	1.2 x 2.4	0.4	0.2	0.175	553	649	0.1	314	217
	1.2 x 2.4	0.45	0.2	0.2	632	394	0.1	314	215
1.2 x 1.2	-	0.25	-	0.1	316	620	-	-	-
	1.6 x 2.4	0.3	0.2	0.125	395	661	0.1	307	221
	1.6 x 2.4	0.35	0.2	0.15	474	696	0.1	307	221
	1.6 x 2.4	0.4	0.2	0.175	553	727	0.1	307	220
	1.6 x 2.4	0.45	0.2	0.2	632	659	0.1	307	218
	2.0 x 2.8	0.45	0.4	0.2	632	740	0.1	279	169
	2.0 x 2.8	0.5	0.4	0.225	711	766	0.1	279	167
	2.0 x 2.8	0.55	0.4	0.25	790	382	0.1	279	166
1.2 x 1.6	-	0.25	-	0.1	316	539	-	-	-
	2.0 x 2.4	0.3	0.2	0.125	395	466	0.1	298	196
	2.0 x 2.4	0.35	0.2	0.15	474	492	0.1	298	198
	2.0 x 2.4	0.4	0.2	0.175	553	514	0.1	298	200

Appendix Table C3 (Continued)

Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	ϕV_c (kN/m)	V_u (kN/m)	d (m)	ϕV_c (kN/m)	V_u (kN/m)
1.6 x 0.4	-	0.25	-	0.1	316	475	-	-	-
	1.2 x 2.8	0.3	0.2	0.125	395	530	0.1	283	215
	1.2 x 2.8	0.35	0.2	0.15	474	576	0.1	283	212
	1.2 x 2.8	0.4	0.2	0.175	553	615	0.1	283	210
	1.2 x 2.8	0.45	0.2	0.2	632	355	0.1	283	207
1.6 x 0.8	-	0.25	-	0.1	316	531	-	-	-
	1.2 x 2.8	0.3	0.2	0.125	395	569	0.1	314	222
	1.2 x 2.8	0.35	0.2	0.15	474	605	0.1	314	219
	1.2 x 2.8	0.4	0.2	0.175	553	640	0.1	314	217
	1.2 x 2.8	0.45	0.2	0.2	632	388	0.1	314	214
1.6 x 1.2	-	0.25	-	0.1	316	610	-	-	-
	1.6 x 2.8	0.3	0.2	0.125	395	651	0.1	307	218
	1.6 x 2.8	0.35	0.2	0.15	474	686	0.1	307	219
	1.6 x 2.8	0.4	0.2	0.175	553	717	0.1	307	218
	1.6 x 2.8	0.45	0.2	0.2	632	647	0.1	307	216
	2.0 x 3.2	0.45	0.4	0.2	632	607	0.1	279	168

Appendix Table C3 (Continued)

Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)	d (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)
1.6 x 1.6	-	0.25	-	0.1	316	529	-	-	-
	2.0 x 2.8	0.3	0.2	0.125	395	459	0.1	298	193
	2.0 x 2.8	0.35	0.2	0.15	474	485	0.1	298	196
	2.0 x 2.8	0.4	0.2	0.175	553	507	0.1	298	198

Appendix Table C4 Step by step drop panel designation for the various sizes of opening at the interior face of interior column [O-8]

Opening size $a \times b$ (m x m)	Drop size		1 st critical perimeter				2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	ϕV_c (kN/m)	V_u (kN/m)	d (m)	ϕV_c (kN/m)	V_u (kN/m)
0.4 x 0.4	-	0.25	-	0.1	316	503	-	-	-
	1.6 x 1.2	0.3	0.2	0.125	395	548	0.1	283	221
	1.6 x 1.2	0.35	0.2	0.15	474	584	0.1	283	218
	1.6 x 1.2	0.4	0.2	0.175	553	612	0.1	283	215
	1.6 x 1.2	0.45	0.2	0.2	632	634	0.1	283	168
	2.0 x 1.6	0.45	0.4	0.2	632	632	0.1	257	166
0.4 x 0.8	-	0.25	-	0.1	316	571	-	-	-
	1.6 x 1.2	0.3	0.2	0.125	395	607	0.1	314	229
	1.6 x 1.2	0.35	0.2	0.15	474	641	0.1	314	226
	1.6 x 1.2	0.4	0.2	0.175	553	671	0.1	314	223
	1.6 x 1.2	0.45	0.2	0.2	632	698	0.1	314	220
	2.0 x 1.6	0.45	0.4	0.2	632	646	0.1	280	171
	2.0 x 1.6	0.5	0.4	0.225	711	438	0.1	280	169
0.4 x 1.2	-	0.25	-	0.1	316	647	-	-	-
	1.6 x 1.6	0.3	0.2	0.125	395	687	0.1	307	224
	1.6 x 1.6	0.35	0.2	0.15	474	721	0.1	307	223

Appendix Table C4 (Continued)

Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)	d (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)
0.4 x 1.2	1.6 x 1.6	0.4	0.2	0.175	553	750	0.1	307	221
	1.6 x 1.6	0.45	0.2	0.2	632	691	0.1	307	218
	1.6 x 1.6	0.45	0.4	0.2	632	639	0.1	279	170
	1.6 x 1.6	0.5	0.4	0.225	711	444	0.1	279	167
0.4 x 1.6	-	0.25	-	0.1	316	566	-	-	-
	1.6 x 2.0	0.3	0.2	0.125	395	586	0.1	298	197
	1.6 x 2.0	0.35	0.2	0.15	474	507	0.1	298	199
	1.6 x 2.0	0.4	0.2	0.175	553	528	0.1	298	200
0.8 x 0.4	-	0.25	-	0.1	316	482	-	-	-
	2.0 x 1.2	0.3	0.2	0.125	395	533	0.1	283	221
	2.0 x 1.2	0.35	0.2	0.15	474	574	0.1	283	218
	2.0 x 1.2	0.4	0.2	0.175	553	609	0.1	283	215
	2.0 x 1.2	0.45	0.2	0.2	632	637	0.1	283	212
	2.4 x 1.6	0.45	0.4	0.2	632	631	0.1	257	166

Appendix Table C4 (Continued)

Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)	d (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)
0.8 x 0.8	-	0.25	-	0.1	316	542	-	-	-
	2.0 x 1.2	0.3	0.2	0.125	395	579	0.1	314	229
	2.0 x 1.2	0.35	0.2	0.15	474	614	0.1	314	226
	2.0 x 1.2	0.4	0.2	0.175	553	647	0.1	314	223
	2.0 x 1.2	0.45	0.2	0.2	632	678	0.1	314	220
	2.4 x 1.6	0.45	0.4	0.2	632	630	0.1	280	171
0.8 x 1.2	-	0.25	-	0.1	316	627	-	-	-
	2.0 x 1.6	0.3	0.2	0.125	395	667	0.1	307	223
	2.0 x 1.6	0.35	0.2	0.15	474	701	0.1	307	222
	2.0 x 1.6	0.4	0.2	0.175	553	731	0.1	307	220
	2.0 x 1.6	0.45	0.2	0.2	632	661	0.1	307	218
	2.4 x 2.0	0.45	0.4	0.2	632	615	0.1	279	235
0.8 x 1.6	-	0.25	-	0.1	316	545	-	-	-
	2.0 x 2.0	0.3	0.2	0.125	395	471	0.1	298	196
	2.0 x 2.0	0.35	0.2	0.15	474	497	0.1	298	198
	2.0 x 2.0	0.4	0.2	0.175	553	581	0.1	298	199
	2.0 x 2.0	0.45	0.2	0.2	632	708	0.1	298	199

Appendix Table C4 (Continued)

Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	ϕV_c (kN/m)	V_u (kN/m)	d (m)	ϕV_c (kN/m)	V_u (kN/m)
0.8 x 1.6	2.4 x 2.4	0.45	0.4	0.2	632	711	0.1	274	154
	2.4 x 2.4	0.5	0.4	0.225	711	741	0.1	274	154
	2.4 x 2.4	0.55	0.4	0.25	790	768	0.1	274	153
1.2 x 0.4	-	0.25	-	0.1	316	473	-	-	-
	2.4 x 1.2	0.3	0.2	0.125	395	526	0.1	283	220
	2.4 x 1.2	0.35	0.2	0.15	474	570	0.1	283	218
	2.4 x 1.2	0.4	0.2	0.175	553	606	0.1	283	215
	2.4 x 1.2	0.45	0.2	0.2	632	638	0.1	283	213
	2.8 x 1.6	0.45	0.4	0.2	632	632	0.1	257	167
1.2 x 0.8	-	0.25	-	0.1	316	529	-	-	-
	2.4 x 1.2	0.3	0.2	0.125	395	566	0.1	314	228
	2.4 x 1.2	0.35	0.2	0.15	474	601	0.1	314	225
	2.4 x 1.2	0.4	0.2	0.175	553	635	0.1	314	222
	2.4 x 1.2	0.45	0.2	0.2	632	667	0.1	314	220
	2.8 x 1.6	0.45	0.4	0.2	632	623	0.1	280	171

Appendix Table C4 (Continued)

Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	ϕV_c (kN/m)	V_u (kN/m)	d (m)	ϕV_c (kN/m)	V_u (kN/m)
1.2 x 1.2	-	0.25	-	0.1	316	614	-	-	-
	2.4 x 1.6	0.3	0.2	0.125	395	654	0.1	307	220
	2.4 x 1.6	0.35	0.2	0.15	474	688	0.1	307	220
	2.4 x 1.6	0.4	0.2	0.175	553	719	0.1	307	219
	2.4 x 1.6	0.45	0.2	0.2	632	644	0.1	307	217
	2.8 x 2.0	0.45	0.4	0.2	632	603	0.1	279	166
1.2 x 1.6	-	0.25	-	0.1	316	532	-	-	-
	2.4 x 2.0	0.3	0.2	0.125	395	463	0.1	298	193
	2.4 x 2.0	0.35	0.2	0.15	474	489	0.1	298	196
	2.4 x 2.0	0.4	0.2	0.175	553	561	0.1	298	197
	2.4 x 2.0	0.45	0.2	0.2	632	694	0.1	298	198
	2.8 x 2.4	0.45	0.4	0.2	632	699	0.1	274	153
	2.8 x 2.4	0.5	0.4	0.225	711	730	0.1	274	153
	2.8 x 2.4	0.55	0.4	0.25	790	759	0.1	274	153
	2.8 x 2.4	0.6	0.4	0.275	869	788	0.1	274	153
1.6 x 0.4	-	0.25	-	0.1	316	467	-	-	-
	2.8 x 1.2	0.3	0.2	0.125	395	520	0.1	283	220
	2.8 x 1.2	0.35	0.2	0.15	474	565	0.1	283	217

Appendix Table C4 (Continued)

Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)	d (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)
1.6 x 0.4	2.8 x 1.2	0.4	0.2	0.175	553	604	0.1	283	215
	2.8 x 1.2	0.45	0.2	0.2	632	637	0.1	283	213
	3.2 x 1.6	0.45	0.4	0.2	632	632	0.1	257	167
1.6 x 0.8	-	0.25	-	0.1	316	520	-	-	-
	2.8 x 1.2	0.3	0.2	0.125	395	557	0.1	314	227
	2.8 x 1.2	0.35	0.2	0.15	474	592	0.1	314	224
	2.8 x 1.2	0.4	0.2	0.175	553	626	0.1	314	222
	2.8 x 1.2	0.45	0.2	0.2	632	658	0.1	314	219
	3.2 x 1.6	0.45	0.4	0.2	632	617	0.1	280	171
1.6 x 1.2	-	0.25	-	0.1	316	604	-	-	-
	2.8 x 1.6	0.3	0.2	0.125	395	644	0.1	307	218
	2.8 x 1.6	0.35	0.2	0.15	474	678	0.1	307	218
	2.8 x 1.6	0.4	0.2	0.175	553	709	0.1	307	217
	2.8 x 1.6	0.45	0.2	0.2	632	632	0.1	307	215

Appendix Table C4 (Continued)

Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)	d (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)
1.6 x 1.6	-	0.25	-	0.1	316	522	-	-	-
	2.8 x 2.0	0.3	0.2	0.125	395	457	0.1	298	191
	2.8 x 2.0	0.35	0.2	0.15	474	482	0.1	298	194
	2.8 x 2.0	0.4	0.2	0.175	553	548	0.1	298	195

Appendix Table C5 Step by step drop panel designation for the various sizes of opening at the face of edge column [O-9]

Opening size $a \times b$ (m x m)	Drop size		1 st critical perimeter				2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	ϕV_c (kN/m)	V_u (kN/m)	d (m)	ϕV_c (kN/m)	V_u (kN/m)
0.4 x 0.4	-	0.25	-	0.1	316	375	-	-	-
	1.2 x 1.4	0.3	0.2	0.125	395	408	0.1	285	110
	1.2 x 1.4	0.35	0.2	0.15	474	432	0.1	285	103
0.4 x 0.8	-	0.25	-	0.1	316	447	-	-	-
	1.2 x 1.4	0.3	0.2	0.125	395	479	0.1	316	153
	1.2 x 1.4	0.35	0.2	0.15	474	508	0.1	316	147
	1.2 x 1.4	0.4	0.2	0.175	553	535	0.1	316	141
0.4 x 1.2	-	0.25	-	0.1	316	476	-	-	-
	1.6 x 1.4	0.3	0.2	0.125	395	501	0.1	316	187
	1.6 x 1.4	0.35	0.2	0.15	474	524	0.1	316	185
	1.6 x 1.4	0.4	0.2	0.175	553	544	0.1	316	182
0.4 x 1.6	-	0.25	-	0.1	316	452	-	-	-
	2.0 x 1.4	0.3	0.2	0.125	395	333	0.1	316	178
0.8 x 0.4	-	0.25	-	0.1	316	357	-	-	-
	1.2 x 1.8	0.3	0.2	0.125	395	394	0.1	285	111

Appendix Table C5 (Continued)

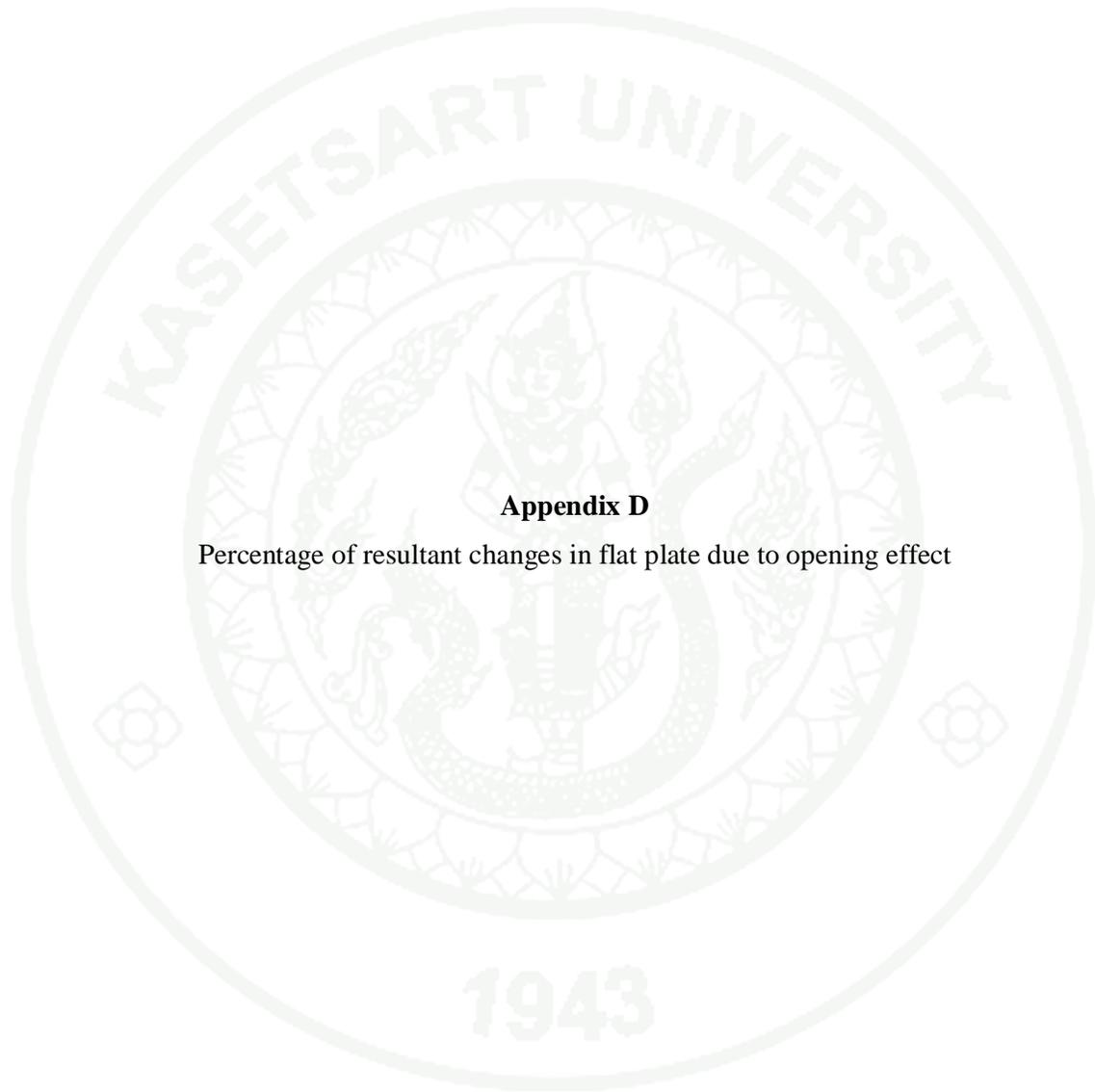
Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	ϕV_c (kN/m)	V_u (kN/m)	d (m)	ϕV_c (kN/m)	V_u (kN/m)
0.8 x 0.8	-	0.25	-	0.1	316	422	-	-	-
	1.2 x 1.8	0.3	0.2	0.125	395	454	0.1	316	151
	1.2 x 1.8	0.35	0.2	0.15	474	485	0.1	316	147
	1.2 x 1.8	0.4	0.2	0.175	553	514	0.1	316	144
0.8 x 1.2	-	0.25	-	0.1	316	455	-	-	-
	1.6 x 1.8	0.3	0.2	0.125	395	481	0.1	316	184
	1.6 x 1.8	0.35	0.2	0.15	474	504	0.1	316	183
	1.6 x 1.8	0.4	0.2	0.175	553	526	0.1	316	181
0.8 x 1.6	-	0.25	-	0.1	316	430	-	-	-
	2.0 x 1.8	0.3	0.2	0.125	395	321	0.1	316	176
1.2 x 0.4	-	0.25	-	0.1	316	349	-	-	-
	1.2 x 2.2	0.3	0.2	0.125	395	388	0.1	285	110
1.2 x 0.8	-	0.25	-	0.1	316	409	-	-	-
	1.2 x 2.2	0.3	0.2	0.125	395	441	0.1	316	145
	1.2 x 2.2	0.35	0.2	0.15	474	472	0.1	316	143

Appendix Table C5 (Continued)

Opening size $a \times b$ (m x m)	Drop size			1 st critical perimeter			2 nd critical perimeter		
	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)	d (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)
1.2 x 1.2	-	0.25	-	0.1	316	442	-	-	-
	1.6 x 2.2	0.3	0.2	0.125	395	467	0.1	316	181
	1.6 x 2.2	0.35	0.2	0.15	474	491	0.1	316	180
	1.6 x 2.2	0.4	0.2	0.175	553	513	0.1	316	178
1.2 x 1.6	-	0.25	-	0.1	316	416	-	-	-
	2.0 x 2.2	0.3	0.2	0.125	395	312	0.1	316	173
1.6 x 0.4	-	0.25	-	0.1	316	343	-	-	-
	1.2 x 2.6	0.3	0.2	0.125	395	382	0.1	285	108
1.6 x 0.8	-	0.25	-	0.1	316	401	-	-	-
	1.2 x 2.6	0.3	0.2	0.125	395	432	0.1	316	142
	1.2 x 2.6	0.35	0.2	0.15	474	463	0.1	316	140
1.6 x 1.2	-	0.25	-	0.1	316	431	-	-	-
	1.6 x 2.6	0.3	0.2	0.125	395	456	0.1	316	178
	1.6 x 2.6	0.35	0.2	0.15	474	480	0.1	316	177
	1.6 x 2.6	0.4	0.2	0.175	553	502	0.1	316	175

Appendix Table C5 (Continued)

Opening size	Drop size		1 st critical perimeter			2 nd critical perimeter			
	$a \times b$ (m x m)	$x \times y$ (m x m)	h_d (m)	w_d (m)	d_p (m)	$\emptyset V_c$ (kN/m)	V_u (kN/m)	d (m)	$\emptyset V_c$ (kN/m)
1.6 x 1.6	-	0.25	-	0.1	316	404	-	-	-
	2.0 x 2.6	0.3	0.2	0.125	395	305	0.1	316	169



Appendix D

Percentage of resultant changes in flat plate due to opening effect

Appendix Table D1 Changes in percentage of maximum bending moment and shear force resultants in flat plate with openings
[O-1, O-2, O-3 and O-4]

Area No.	O-1				O-2				O-3				O-4			
	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y
1	0	0	0	0	1	0	0	0	0	0	0	0	-1	0	0	0
2	0	0	1	1	0	0	0	1	0	0	1	1	0	1	0	0
3	1	1	1	1	0	1	1	1	1	1	1	1	-1	0	0	0
4	0	2	1	1	0	1	0	1	0	0	0	1	0	0	0	0
5	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0
6	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	1	1	0	0	2	1	0	0	1	0	-3	1	58	-3
9	1	1	-3	-3	2	1	-4	-3	1	1	-4	-1	13	3	330	160
10	-2	1	-2	-3	-1	1	-4	-4	-1	1	-5	-3	-10	1	87	12
11	-3	3	-9	0	-2	2	-4	1	1	1	1	0	2	1	1	0
12	-2	1	-2	-3	0	1	0	-1	1	0	0	0	1	0	0	0
13	1	1	-3	-3	0	0	-1	-1	0	0	0	0	0	0	0	0
14	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
15	1	1	1	1	2	1	2	1	1	1	0	0	-25	-9	-28	-20
16	1	-2	-3	-2	3	-4	-5	-2	1	-8	6	73	-	-	-	-

Appendix Table D1 (Continued)

Area No.	O-1				O-2				O-3				O-4			
	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y
17	0	0	-5	-5	0	-2	-8	-8	0	-1	-11	-8	-9	-4	-10	-11
18	-13	-15	-12	2	93	-5	-6	4	1	-1	3	60	2	1	1	0
19	0	0	-5	-5	0	0	-2	-2	0	0	0	0	0	0	0	0
20	1	-2	-3	-2	0	-1	-1	-1	0	0	0	0	0	0	0	0
21	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
22	2	0	1	1	4	2	3	1	3	0	0	0	-3	2	46	1
23	3	-3	0	-9	7	-1	1	-8	3	11	145	341	9	4	301	166
24	-15	-13	2	-12	-2	-14	57	83	-	-	-	-	-1	2	75	10
25	-	-	-	-	20	-14	-17	38	4	6	150	309	2	1	1	1
26	-15	-13	2	-12	-4	-6	1	-3	-1	0	0	0	1	0	0	0
27	3	-3	0	-9	1	-3	0	-3	0	0	0	0	0	0	0	0
28	2	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
29	1	1	1	1	2	1	2	1	1	1	0	0	0	0	0	0
30	1	-2	-3	-2	3	-4	-5	-2	1	-8	6	73	0	-1	0	0
31	0	0	-5	-5	0	-2	-8	-8	0	-1	-11	-8	0	0	0	0
32	-13	-15	-12	2	93	-5	-6	4	1	-1	3	60	0	0	0	0
33	0	0	-5	-5	0	0	-2	-2	0	0	0	0	0	0	0	0

Appendix Table D1 (Continued)

Area No.	O-1				O-2				O-3				O-4			
	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y
34	1	-2	-3	-2	0	-1	-1	-1	0	0	0	0	0	0	0	0
35	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	1	1	0	0	2	1	0	0	1	0	0	0	0	0
37	1	1	-3	-3	2	1	-4	-3	1	1	-4	-1	0	0	0	0
38	-2	1	-2	-3	-1	1	-4	-4	-1	1	-5	-3	0	0	0	0
39	-3	3	-9	0	-2	2	-3	1	1	1	1	0	0	0	0	0
40	-2	1	-2	-3	0	1	-1	-1	1	0	0	0	0	0	0	0
41	1	1	-3	-3	0	0	-1	-1	0	0	0	0	0	0	0	0
42	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
44	0	0	1	1	0	0	0	1	0	0	1	1	0	0	0	0
45	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	0
46	0	2	1	1	0	1	1	1	0	0	1	1	0	0	0	0
47	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0
48	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

[+sign: increase, -sign: decrease, Unit: %]

Appendix Table D2 Changes in percentage of maximum bending moment and shear force resultants in flat plate with openings
[O-5, O-6, O-7 and O-8]

Area No.	O-5				O-6				O-7				O-8			
	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y
1	1	1	0	0	1	0	0	0	2	2	0	0	1	0	0	0
2	1	0	3	5	0	1	1	2	2	1	4	10	-1	0	1	2
3	3	4	2	2	1	3	1	2	5	10	5	6	0	3	2	3
4	0	1	1	2	1	0	3	4	1	0	4	9	2	-2	4	5
5	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
7	0	0	0	0	-1	0	0	0	-1	-1	0	0	-1	-1	0	0
8	0	1	5	3	-1	0	1	1	-2	2	6	4	-2	0	0	0
9	3	3	-11	-11	0	5	-2	16	3	10	-10	25	-1	4	-3	16
10	151	23	413	71	139	19	404	69	94	11	127	-9	16	6	55	14
11	0	5	1	15	4	3	7	3	4	10	8	22	12	3	27	-1
12	1	0	0	0	3	1	0	2	5	2	0	2	6	1	1	2
13	0	0	0	0	0	0	1	1	0	0	1	2	-1	0	1	2
14	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0
15	4	3	2	2	2	1	0	1	7	6	3	3	1	1	0	0
16	23	151	71	411	0	5	3	14	6	19	14	64	0	4	7	16

Appendix Table D2 (Continued)

Area No.	O-5				O-6				O-7				O-8			
	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y
17	16	16	-2	-2	7	19	0	-2	60	3	75	31	-3	51	29	73
18	1	5	3	12	31	150	70	381	8	19	13	59	12	95	9	110
19	0	0	0	0	0	1	1	1	0	1	1	2	1	1	2	3
20	0	0	0	0	0	0	1	1	0	0	1	2	-1	1	2	2
21	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	-1	-1
22	1	0	2	1	-1	0	0	0	0	-1	2	1	-2	0	0	0
23	5	0	15	1	0	0	1	0	4	-1	16	0	-1	4	-1	15
24	5	1	12	3	3	1	1	2	4	0	16	8	16	7	48	13
25	0	0	1	0	6	0	14	1	5	-1	16	0	12	4	23	8
26	0	0	0	0	2	0	0	0	1	0	0	0	6	1	1	2
27	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	2
28	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0
29	0	-1	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0
30	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
31	0	0	0	0	0	0	0	0	0	-1	0	0	-1	0	1	1
32	0	0	0	0	0	1	0	0	0	0	0	0	2	4	2	0
33	0	0	0	0	0	0	0	0	0	-1	0	0	1	0	0	0

Appendix Table D2 (Continued)

Area No.	O-5				O-6				O-7				O-8			
	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y	M _x	M _y	V _x	V _y
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	1
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
43	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	1	1	0	0	-1	0	0	0
46	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	1	0	0	-1	0	0	0

[+sign: increase, -sign: decrease, Unit: %]

Appendix Table D3 Changes in percentage of maximum bending moment and shear force resultants in flat plate with various sizes of opening at the exterior face of interior column [O-7]

Area No.	$a = 0.4 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
1	0	0	0	0	1	1	0	0	2	1	0	0	2	2	0	0				
2	0	0	0	1	0	1	2	4	1	2	3	7	1	2	4	10				
3	1	1	1	1	2	4	2	2	4	7	4	5	5	10	5	6				
4	0	0	0	1	0	1	2	3	1	1	3	7	1	2	5	10				
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
7	0	0	0	0	0	0	0	0	0	-1	0	0	-1	-1	0	0				
8	0	0	0	0	-1	1	1	1	-2	1	3	2	-3	2	4	3				
9	0	2	-8	4	0	5	-17	7	1	8	-14	7	1	11	-13	8				
10	-7	2	-11	-8	-11	5	-19	-16	-10	9	-18	-13	-9	11	-17	-10				
11	0	2	0	0	0	5	2	2	1	9	4	3	1	12	6	4				
12	0	0	0	0	1	0	0	1	3	1	0	1	4	1	0	2				
13	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1				
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
15	1	0	0	0	2	2	1	1	4	4	1	2	6	5	2	2				
16	0	4	2	8	1	10	5	21	2	15	9	36	4	22	15	61				

Appendix Table D3 (Continued)

Area No.	<i>a</i> = 0.4 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
17	8	15	8	68	30	30	27	92	70	41	116	65	67	23	89	50				
18	1	4	1	2	2	10	4	14	3	15	7	28	4	23	14	51				
19	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1				
20	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1				
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
22	0	0	0	0	0	0	0	0	0	-1	1	0	0	-1	1	0				
23	0	0	3	0	0	0	7	0	2	-1	12	0	2	-1	18	0				
24	0	0	4	1	0	0	9	3	1	0	14	6	1	0	19	9				
25	0	0	1	0	1	0	5	0	2	-1	11	0	2	-1	17	0				
26	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0				
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
29	0	0	0	0	0	0	0	0	-1	-1	0	0	-1	-1	0	0				
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
31	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0				
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
33	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0				

Appendix Table D3 (Continued)

Area No.	<i>a</i> = 0.4 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

Appendix Table D3 (Continued)

Area No.	<i>a</i> = 0.8 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
1	0	0	0	0	1	1	0	0	2	1	0	0	2	2	0	0				
2	0	0	1	2	1	1	2	4	1	2	4	8	1	2	5	10				
3	1	2	1	1	2	4	2	3	4	8	4	5	6	10	5	6				
4	0	0	1	1	1	1	2	4	1	1	4	8	1	2	5	10				
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
7	0	0	0	0	0	0	0	0	-1	-1	0	0	-1	-1	0	0				
8	0	0	1	1	-1	1	2	1	-2	1	4	3	-3	2	5	3				
9	0	2	-9	5	1	5	-16	9	2	9	-13	10	2	12	-12	13				
10	-3	2	-14	-13	-7	6	-19	-16	-9	10	-18	-12	-9	12	-18	-10				
11	0	2	1	1	1	5	3	4	2	9	5	5	2	12	7	9				
12	1	0	0	0	2	1	0	1	3	1	0	2	4	1	0	2				
13	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	2				
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
15	1	1	0	0	2	2	1	1	5	4	2	2	6	5	2	3				
16	0	4	3	10	2	9	6	25	3	13	9	42	5	20	15	67				
17	11	11	8	62	35	13	25	82	74	27	109	55	63	12	82	40				
18	1	4	2	5	3	9	5	18	4	14	8	35	6	21	15	59				

Appendix Table D3 (Continued)

Area No.	$a = 0.8 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
19	0	0	0	0	0	0	0	1	0	1	1	1	0	1	1	1	0	1	1	1
20	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	2	0	0	1	2
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	1	0	0	-1	1	0	0	-1	2	0	0	-1	2	0
23	0	0	3	0	1	0	7	0	2	-1	12	0	3	-1	18	0	3	-1	18	0
24	0	0	4	1	0	0	9	3	2	0	13	6	2	0	18	9	2	0	18	9
25	0	0	1	0	1	0	5	0	3	-1	11	0	3	-1	17	0	3	-1	17	0
26	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	-1	0	0	-1	-1	0	0	-1	-1	0	0	-1	-1	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	-1	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	-1	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1

Appendix Table D3 (Continued)

Area No.	<i>a</i> = 0.8 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0

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Appendix Table D3 (Continued)

Area No.	<i>a</i> = 1.2 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
1	0	0	0	0	1	1	0	0	2	2	0	0	2	2	0	0	2	2	0	0
2	0	0	1	2	1	1	2	5	1	1	4	8	2	2	4	10	2	2	4	10
3	1	2	1	1	3	4	2	3	4	8	4	5	6	10	5	6	6	10	5	6
4	0	0	1	2	1	1	2	4	1	1	4	8	1	1	5	10	1	1	5	10
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
7	0	0	0	0	0	0	0	0	-1	-1	0	0	-1	-1	0	0	-1	-1	0	0
8	0	0	1	1	-1	1	3	2	-2	2	5	3	-2	2	6	4	2	2	6	4
9	0	2	-10	6	1	5	-15	11	3	9	-13	14	3	11	-11	20	3	11	-11	20
10	18	3	-15	-15	11	7	-19	-15	-4	10	-18	-12	-8	12	-18	-10	-8	12	-18	-10
11	1	2	1	2	2	5	3	7	3	9	6	10	3	11	8	16	3	11	8	16
12	1	0	0	0	2	1	0	1	4	1	0	2	5	1	0	2	5	1	0	2
13	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	2	0	0	1	2
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	1	1	1	1	3	3	1	1	6	5	2	2	7	6	3	3	7	6	3	3
16	1	4	2	11	3	9	6	26	4	13	9	43	6	20	15	67	6	20	15	67
17	13	8	7	59	37	5	24	78	76	19	104	50	61	7	78	35	61	7	78	35
18	1	4	2	6	3	9	5	21	5	13	8	37	7	20	14	60	7	20	14	60

Appendix Table D3 (Continued)

Area No.	$a = 1.2 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
19	0	0	0	0	0	0	0	1	0	1	1	1	0	1	1	2				
20	0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	2				
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
22	0	0	0	0	0	0	1	0	0	-1	2	1	0	-1	2	1				
23	1	0	3	0	1	0	6	0	3	-1	11	0	4	-1	17	0				
24	0	0	3	1	1	0	8	3	3	0	12	6	3	0	17	8				
25	1	0	1	0	2	0	5	0	3	-1	11	0	4	-1	17	0				
26	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0				
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0				
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
29	0	0	0	0	0	-1	0	0	-1	-1	0	0	-1	-1	0	0				
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
31	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0				
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
33	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0				
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
35	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0				
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1				

Appendix Table D3 (Continued)

Area No.	<i>a</i> = 1.2 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0

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Appendix Table D3 (Continued)

Area No.	<i>a</i> = 1.6 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	<i>M_x</i>	<i>M_y</i>	<i>V_x</i>	<i>V_y</i>																
1	1	1	0	0	1	1	0	0	2	2	0	0	2	2	0	0				
2	0	0	1	2	1	1	2	5	1	1	3	8	2	1	4	10				
3	1	2	1	1	3	4	2	3	4	8	4	5	5	10	5	6				
4	0	0	1	2	1	1	2	4	1	1	3	7	1	1	4	9				
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
6	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0				
7	0	0	0	0	0	0	0	0	-1	-1	0	0	-1	-1	0	0				
8	0	1	2	1	0	1	3	2	-1	2	5	3	-2	2	6	4				
9	1	2	-11	6	2	5	-15	13	4	8	-12	17	4	10	-11	25				
10	106	4	35	-4	101	8	88	-6	99	10	110	-9	93	11	125	-8				
11	2	2	2	3	3	5	4	9	4	8	7	13	4	10	8	22				
12	1	0	0	1	2	1	0	1	4	1	0	2	5	2	0	2				
13	0	0	0	0	0	0	0	1	0	0	1	2	0	0	1	2				
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
15	2	1	1	1	4	3	1	2	6	5	3	3	8	6	3	3				
16	1	4	2	11	3	8	5	26	5	12	8	42	6	19	14	64				
17	15	6	7	57	39	-2	23	75	76	14	101	47	59	3	74	31				
18	2	4	1	7	4	8	5	22	6	12	7	37	8	19	13	58				

Appendix Table D3 (Continued)

Area No.	<i>a</i> = 1.6 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
19	0	0	0	0	0	1	1	1	0	1	1	1	0	1	1	1	2			
20	0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	2				
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
22	0	0	1	0	0	0	1	0	0	-1	2	1	0	-1	3	1				
23	1	0	2	0	2	0	6	0	3	-1	11	0	4	-1	16	0				
24	1	0	3	1	1	0	8	3	3	0	12	6	4	0	16	8				
25	1	0	1	0	2	0	5	0	4	-1	10	0	5	-1	16	0				
26	0	0	0	0	1	0	0	0	1	0	0	1	1	0	0	1				
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0				
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
29	0	0	0	0	0	-1	0	0	-1	-1	0	0	-1	-1	0	0				
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
31	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0				
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
33	0	0	0	0	0	0	0	0	0	-1	0	0	-1	-1	0	0				
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
35	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0				
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1				

Appendix Table D3 (Continued)

Area No.	<i>a</i> = 1.6 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0

[+sign: increase, -sign: decrease, Unit: %]

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Appendix Table D4 Changes in percentage of maximum bending moment and shear force resultants in flat plate with various sizes of opening at the interior face of interior column [O-8]

Area No.	$a = 0.4 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0				
2	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0				
3	0	0	0	0	0	0	0	0	0	1	1	1	-1	1	1	2				
4	0	0	0	0	0	-1	1	1	1	-2	2	3	1	-3	2	4				
5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0				
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0				
7	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0				
8	0	0	0	0	0	0	0	0	-1	0	0	0	-2	0	0	0				
9	0	0	-1	3	0	0	-2	7	-1	2	-3	13	-1	2	-3	18				
10	3	0	0	2	8	1	12	5	12	2	28	9	19	4	52	15				
11	2	0	5	0	5	0	8	0	10	1	9	0	14	1	12	0				
12	1	0	0	0	2	0	0	1	4	1	1	2	6	1	1	3				
13	0	0	0	0	0	0	0	1	-1	0	1	2	-1	0	1	2				
14	0	0	0	0	0	0	0	0	0	0	-1	0	1	0	-1	0				
15	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0				
16	0	0	1	4	0	0	3	9	0	1	6	14	-1	1	8	19				

Appendix Table D4 (Continued)

Area No.	$a = 0.4 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
17	6	3	66	8	19	24	88	26	30	62	62	113	14	57	47	87				
18	2	0	1	0	5	0	3	0	10	1	7	0	13	2	9	1				
19	0	0	0	0	0	0	1	1	1	0	2	2	1	1	2	3				
20	0	0	0	0	0	0	1	1	0	1	1	2	-1	1	2	2				
21	0	0	0	0	0	0	0	0	-1	-1	0	0	-1	-1	-1	-1				
22	0	0	0	0	0	0	0	0	-1	0	0	0	-2	0	0	0				
23	0	0	0	1	0	1	0	5	0	2	-1	10	-1	2	-1	17				
24	2	0	0	1	7	2	4	4	12	3	18	7	19	4	41	14				
25	2	0	2	0	6	0	5	2	10	1	9	4	14	1	12	6				
26	1	0	0	0	2	0	0	1	4	1	1	2	6	1	1	3				
27	0	0	0	0	0	0	0	1	0	0	1	2	0	0	1	2				
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
30	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0				
31	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	1	1				
32	0	0	0	0	0	1	0	0	1	3	1	0	1	3	2	0				
33	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0				

Appendix Table D4 (Continued)

Area No.	<i>a</i> = 0.4 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix Table D4 (Continued)

Area No.	$a = 0.8 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	1	0	0	0	1
3	0	0	0	0	0	1	0	1	0	2	1	2	0	2	1	2	0	2	1	2
4	0	0	0	0	1	-1	1	1	1	-2	2	3	1	-2	3	4	1	-2	3	4
5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
7	0	0	0	0	-1	0	0	0	-1	0	0	0	-1	-1	0	0	-1	-1	0	0
8	0	0	0	0	-1	0	0	0	-2	0	0	0	-2	0	0	0	-2	0	0	0
9	0	0	-1	3	0	1	-2	7	-1	2	-3	12	-1	3	-3	18	-1	3	-3	18
10	3	0	2	3	7	2	16	6	11	3	33	9	17	5	58	15	11	3	33	9
11	3	0	6	0	6	1	10	0	11	1	11	0	14	2	15	0	11	1	11	0
12	1	0	0	0	2	0	0	1	5	1	1	2	6	1	1	3	5	1	1	3
13	0	0	0	0	0	0	1	1	-1	0	1	2	-1	0	1	2	-1	0	1	2
14	0	0	0	0	0	0	0	0	0	0	-1	0	1	0	-1	0	0	0	-1	0
15	0	0	0	0	1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0
16	0	0	1	4	0	0	3	9	0	2	6	13	0	2	8	18	0	2	8	18
17	2	6	59	8	3	28	79	25	16	65	52	107	3	54	37	80	3	54	37	80
18	3	0	2	0	7	1	4	0	11	2	7	0	14	2	10	1	11	2	7	0

Appendix Table D4 (Continued)

Area No.	<i>a</i> = 0.8 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
19	0	0	0	0	0	0	1	1	1	1	2	2	1	1	3	3				
20	0	0	0	0	0	0	1	1	-1	1	1	2	-1	1	2	2				
21	0	0	0	0	-1	0	0	0	-1	-1	0	0	-1	-1	-1	-1				
22	0	0	0	0	-1	0	0	0	-1	0	0	0	-2	0	0	0				
23	0	0	0	1	0	1	0	5	-1	2	-1	11	-1	3	-2	17				
24	2	1	0	2	7	2	8	5	11	4	24	8	17	5	48	14				
25	3	0	2	1	6	1	5	3	11	2	10	5	14	2	13	7				
26	1	0	0	0	2	0	0	1	5	1	1	2	6	1	1	3				
27	0	0	0	0	0	0	1	1	0	0	1	2	-1	0	1	2				
28	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0				
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
30	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0				
31	0	0	0	0	0	0	0	0	0	0	1	1	-1	0	1	1				
32	0	0	0	0	1	1	1	0	1	3	1	0	1	4	2	0				
33	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0				
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
35	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0				
36	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0				

Appendix Table D4 (Continued)

Area No.	<i>a</i> = 0.8 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0

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Appendix Table D4 (Continued)

Area No.	$a = 1.2 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0
2	0	0	0	0	0	0	0	1	0	0	1	2	-1	0	1	2	-1	0	1	2
3	0	0	0	0	0	1	1	1	0	2	1	2	0	2	1	2	0	2	1	2
4	0	0	0	1	1	-1	1	2	1	-2	3	4	2	-2	3	5	2	-2	3	5
5	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0
6	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0
7	0	0	0	0	-1	0	0	0	-1	0	0	0	-1	-1	-1	0	-1	-1	-1	0
8	0	0	0	0	-1	0	0	0	-2	0	0	0	-2	0	0	0	-2	0	0	0
9	0	0	-1	3	0	1	-2	6	-1	3	-3	11	-1	4	-3	17	-1	4	-3	17
10	3	1	2	2	7	2	17	6	11	4	34	9	17	5	57	14	17	5	57	14
11	3	0	6	0	6	1	12	0	10	2	15	0	13	3	21	0	13	3	21	0
12	1	0	0	0	3	1	0	1	5	1	1	2	6	1	1	3	6	1	1	3
13	0	0	0	0	0	0	1	1	-1	0	1	2	-1	0	1	2	-1	0	1	2
14	0	0	0	0	0	0	0	0	0	0	-1	0	1	0	-1	-1	1	0	-1	-1
15	0	0	0	0	1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0
16	0	0	1	4	0	1	3	8	0	2	5	12	0	3	8	17	0	3	8	17
17	0	8	56	7	-3	30	74	23	9	67	47	102	-2	51	32	76	-2	51	32	76
18	4	18	2	0	8	12	4	0	12	2	7	0	14	3	9	0	14	3	9	0

Appendix Table D4 (Continued)

Area No.	$a = 1.2 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
19	0	0	0	1	0	0	1	1	1	1	2	2	1	1	2	3				
20	0	0	0	0	0	1	1	1	-1	1	1	2	-1	1	2	2				
21	0	0	0	0	-1	0	0	0	-1	-1	-1	0	-1	-1	-1	-1				
22	0	0	0	0	-1	0	0	0	-2	0	0	0	-2	0	0	0				
23	0	1	0	1	0	2	0	5	-1	3	-1	10	-1	4	-1	16				
24	3	1	0	2	6	3	11	5	10	5	27	8	16	6	49	14				
25	3	1	3	1	7	2	8	3	11	3	11	6	14	3	17	8				
26	1	0	0	1	3	1	0	1	5	1	1	2	6	1	1	3				
27	0	0	0	0	0	0	1	1	0	0	1	2	-1	0	1	2				
28	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0				
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
30	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0				
31	0	0	0	0	0	0	0	0	-1	0	1	1	-1	0	1	1				
32	0	1	0	0	1	2	1	0	1	3	2	0	1	4	2	0				
33	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0				
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
35	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0				
36	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0				

Appendix Table D4 (Continued)

Area No.	<i>a</i> = 1.2 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
39	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	2	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0

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Appendix Table D4 (Continued)

Area No.	<i>a</i> = 1.6 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0
2	0	0	0	1	0	0	0	1	0	0	1	2	-1	0	1	2	-1	0	1	2
3	0	1	0	1	0	1	1	1	0	2	1	2	0	3	2	3	0	3	2	3
4	0	0	1	1	1	0	2	2	2	-1	3	5	2	-2	4	5	2	-2	4	5
5	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	1	1	0	0
6	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0
7	0	0	0	0	-1	0	0	0	-1	0	0	0	-1	-1	-1	0	-1	-1	-1	0
8	-1	0	0	0	-1	0	0	0	-2	0	0	0	-2	0	0	0	-2	0	0	0
9	0	1	-1	3	0	1	-2	6	-1	3	-3	11	-1	4	-3	16	-1	4	-3	16
10	3	1	2	2	7	3	17	5	11	5	32	8	16	6	54	13	16	6	54	13
11	3	1	7	0	6	2	14	0	9	3	18	0	12	3	27	-1	12	3	27	-1
12	1	0	0	1	3	1	0	1	5	1	1	2	6	1	1	2	6	1	1	2
13	0	0	0	0	0	0	1	1	-1	0	1	2	-1	0	1	2	-1	0	1	2
14	0	0	0	0	0	0	0	0	0	0	-1	0	1	0	-1	-1	0	0	-1	-1
15	0	0	0	0	1	0	0	0	1	1	0	0	2	1	0	0	2	1	0	0
16	0	1	1	3	0	1	3	8	0	3	5	12	0	3	7	16	0	3	7	16
17	-1	10	54	7	-3	32	72	22	4	67	44	99	-3	49	28	72	-3	49	28	72
18	5	105	2	27	8	101	4	75	12	99	7	94	14	94	9	107	14	94	9	107

Appendix Table D4 (Continued)

Area No.	<i>a</i> = 1.6 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
19	0	0	0	1	0	0	1	1	1	1	2	2	1	1	2	3				
20	0	0	0	0	0	1	1	1	-1	1	1	2	-1	1	2	2				
21	0	0	0	0	-1	0	0	0	-1	-1	-1	0	-1	-1	-1	-1				
22	-1	0	0	0	-1	0	0	0	-2	0	0	0	-2	0	0	0				
23	0	1	0	1	0	2	-1	5	-1	4	-1	10	-1	4	-1	15				
24	3	2	0	2	6	4	11	5	10	6	26	7	16	7	47	13				
25	3	1	3	2	6	3	10	4	9	4	14	7	12	4	23	8				
26	1	0	0	1	3	1	0	1	5	1	1	2	6	1	1	3				
27	0	0	0	0	0	0	1	1	0	0	1	2	-1	0	1	2				
28	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0				
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
30	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0				
31	0	0	0	0	0	0	0	0	-1	0	1	1	-1	0	1	1				
32	0	1	0	0	1	2	1	0	1	4	2	0	1	5	2	0				
33	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0				
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
35	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0				
36	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0				

Appendix Table D4 (Continued)

Area No.	<i>a</i> = 1.6 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m				
	<i>M_x</i>	<i>M_y</i>	<i>V_x</i>	<i>V_y</i>																	
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
39	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	2	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0

[+sign: increase, -sign: decrease, Unit: %]

Appendix Table D5 Changes in percentage of maximum bending moment and shear force resultants in flat plate with various sizes of opening at the face of edge column [O-9]

Area No.	$a = 0.4 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
1	0	0	0	0	2	2	1	1	4	4	2	2	6	5	3	3				
2	0	2	4	8	2	6	10	20	5	19	18	36	7	36	30	59				
3	8	16	11	74	34	33	39	107	76	42	142	87	80	21	130	81				
4	0	2	2	4	2	6	7	13	5	18	14	28	7	35	26	50				
5	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1				
6	0	0	0	0	0	0	0	0	0	-1	0	1	-1	-1	1	1				
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
8	0	0	0	0	-1	0	0	0	-2	1	1	0	-3	1	1	0				
9	0	2	0	1	0	5	0	4	1	10	1	8	2	13	1	11				
10	0	2	0	1	1	5	0	3	2	10	1	6	2	13	1	9				
11	0	2	0	1	1	5	1	4	1	10	1	8	2	14	1	11				
12	0	0	0	0	1	0	0	0	1	1	0	0	1	1	0	0				
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
15	0	0	0	0	1	0	0	0	1	1	0	0	2	1	0	0				
16	0	1	0	1	0	3	1	3	1	6	2	7	1	8	3	9				

Appendix Table D5 (Continued)

Area No.	$a = 0.4 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
17	1	1	0	1	2	3	1	2	4	6	2	3	5	9	3	4				
18	0	1	0	1	0	3	1	3	1	6	2	6	1	8	3	9				
19	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0				
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
21	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0				
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1				
23	0	0	0	0	0	0	1	1	0	-1	2	1	0	-1	2	2				
24	0	0	0	0	0	0	1	1	1	-1	1	1	1	-1	2	2				
25	0	0	0	0	0	0	1	0	0	-1	2	1	0	-1	3	1				
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
29	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0				
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
31	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0				
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
33	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0				

Appendix Table D5 (Continued)

Area No.	$a = 0.4 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0

Appendix Table D5 (Continued)

Area No.	<i>a</i> = 0.8 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	<i>M_x</i>	<i>M_y</i>	<i>V_x</i>	<i>V_y</i>																
1	1	1	0	0	3	2	1	1	5	4	3	3	7	5	3	3				
2	1	3	4	10	3	8	10	23	7	22	18	40	9	38	30	65				
3	12	12	10	65	40	18	33	95	82	29	132	74	78	12	119	67				
4	1	3	2	5	3	8	8	17	7	20	15	33	9	36	27	58				
5	0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	2				
6	0	0	0	0	0	0	0	1	0	-1	1	1	-1	-1	1	1				
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
8	0	0	0	0	-1	1	1	0	-2	1	1	0	-2	1	1	0				
9	0	2	0	2	1	6	0	5	2	10	1	9	2	13	1	11				
10	0	2	0	2	1	6	0	4	2	11	1	7	3	14	1	9				
11	0	2	0	2	1	6	1	5	2	10	1	8	2	13	2	11				
12	0	0	0	0	1	0	0	0	1	1	0	0	2	1	0	0				
13	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0				
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
15	0	0	0	0	1	0	0	0	1	1	0	0	2	1	0	0				
16	0	1	0	2	0	3	1	4	1	6	2	7	1	8	3	9				
17	1	1	1	1	2	4	1	2	4	7	2	3	5	9	3	4				
18	0	1	0	1	1	3	1	4	1	6	2	7	1	9	3	9				

Appendix Table D5 (Continued)

Area No.	<i>a</i> = 0.8 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
19	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0				
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
21	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0				
22	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	1				
23	0	0	0	0	0	0	1	1	0	-1	2	1	0	-1	2	2				
24	0	0	0	0	1	0	1	1	1	-1	2	1	1	-1	2	2				
25	0	0	0	0	0	0	1	0	0	-1	2	1	0	-1	3	1				
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
29	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0				
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
31	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0				
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
33	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0				
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

Appendix Table D5 (Continued)

Area No.	$a = 0.8 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0

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Appendix Table D5 (Continued)

Area No.	<i>a</i> = 1.2 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	<i>M_x</i>	<i>M_y</i>	<i>V_x</i>	<i>V_y</i>																
1	1	1	1	1	3	3	2	2	6	5	3	3	8	6	4	4				
2	2	4	4	11	5	10	10	23	9	27	17	40	11	45	28	64				
3	15	10	9	61	43	10	29	89	85	23	125	67	77	8	112	60				
4	2	4	2	6	5	9	8	19	10	25	15	35	12	43	26	58				
5	0	0	0	0	0	0	1	1	0	0	1	2	0	1	1	2				
6	0	0	0	0	0	0	0	1	-1	-1	1	1	-1	-1	1	2				
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
8	0	0	0	0	-1	1	1	0	-1	1	1	0	-2	1	1	0				
9	0	2	0	2	1	6	0	5	2	9	0	9	2	12	1	11				
10	6	3	0	2	1	7	0	4	2	11	1	7	3	13	1	9				
11	1	2	0	2	1	6	1	5	2	9	2	8	2	12	2	11				
12	0	0	0	0	1	1	0	0	1	1	0	0	2	1	0	0				
13	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0				
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
15	0	0	0	0	1	1	0	0	1	1	0	0	2	1	0	0				
16	0	1	1	2	1	3	1	4	1	6	2	7	1	8	3	9				
17	1	2	1	1	2	4	1	2	4	7	2	3	5	9	3	4				
18	0	1	0	1	1	4	1	4	1	6	2	7	1	8	3	9				

Appendix Table D5 (Continued)

Area No.	$a = 1.2 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
19	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0				
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0				
22	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	1				
23	0	0	0	0	0	-1	1	1	0	-1	2	1	0	-1	2	2				
24	0	0	0	0	1	0	1	1	1	-1	2	1	1	-1	2	2				
25	0	0	0	0	0	0	1	0	0	-1	2	1	0	-1	2	1				
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
29	0	0	0	0	0	1	0	0	0	1	0	0	1	1	0	0				
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
31	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0				
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
33	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0				
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

Appendix Table D5 (Continued)

Area No.	$a = 1.2 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	-1	0	0	-1	-1	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0

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Appendix Table D5 (Continued)

Area No.	$a = 1.6 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
1	2	1	1	1	4	3	2	2	7	5	4	4	9	6	5	4				
2	3	5	3	10	6	12	9	23	10	34	15	38	12	56	26	60				
3	17	7	8	59	45	4	26	85	86	18	119	63	75	5	106	55				
4	3	5	2	7	6	11	7	19	11	32	14	34	13	54	25	54				
5	0	0	0	1	0	0	1	1	0	0	1	2	1	1	2	2				
6	0	0	0	0	0	0	0	1	-1	-1	1	2	-1	-1	1	2				
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
8	0	0	0	0	-1	1	1	0	-1	1	1	0	-2	1	1	0				
9	1	2	0	2	1	5	0	5	2	8	0	9	2	11	0	11				
10	81	4	10	2	77	7	54	4	77	10	72	7	70	19	86	8				
11	1	2	0	2	1	5	1	5	3	8	2	8	3	11	2	10				
12	0	0	0	0	1	1	0	0	1	1	0	0	2	1	0	0				
13	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0				
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
15	0	0	0	0	1	1	0	0	2	1	0	0	2	1	0	0				
16	0	2	1	2	1	3	1	4	1	6	2	7	1	8	3	9				
17	1	2	1	1	2	4	1	2	4	6	2	3	5	8	3	4				
18	0	2	0	2	1	3	1	4	1	6	2	7	1	8	2	8				

Appendix Table D5 (Continued)

Area No.	<i>a</i> = 1.6 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
19	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	1	0	0	0	1
23	0	0	0	0	0	-1	1	1	0	-1	2	1	0	-1	2	2	0	0	0	2
24	0	0	0	0	1	0	1	1	1	-1	1	1	1	-1	2	2	0	0	0	2
25	0	0	0	0	0	0	1	0	0	-1	2	1	0	-1	2	1	0	0	0	1
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	1	0	0	0	1	0	0	1	1	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix Table D5 (Continued)

Area No.	<i>a</i> = 1.6 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	-1	0	0	-1	-1	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0

[+sign: increase, -sign: decrease, Unit: %]

Appendix Table D6 Changes in percentage of maximum bending moment and shear force resultants in flat plate with various sizes of opening at the corner of corner column [O-10]

Area No.	$a = 0.4 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
1	10	10	34	34	-13	18	28	57	-25	23	40	70	-30	28	48	80				
2	4	6	2	1	5	7	3	1	6	13	3	19	6	169	26	246				
3	3	2	1	1	3	2	1	1	3	2	2	1	4	2	2	1				
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1				
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
8	6	4	1	2	8	6	1	3	9	8	2	4	10	8	2	4				
9	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1				
10	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0				
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
15	2	3	1	1	2	4	1	2	2	4	1	2	3	4	2	2				
16	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0	1				

Appendix Table D6 (Continued)

Area No.	$a = 0.4 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
17	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix Table D6 (Continued)

Area No.	$a = 0.4 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix Table D6 (Continued)

Area No.	$a = 0.8 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
1	18	-13	57	28	-6	-6	33	33	-18	0	16	46	-27	4	24	55				
2	6	8	3	1	7	9	4	5	7	9	10	52	10	185	43	312				
3	4	2	2	1	4	2	2	1	4	3	2	1	4	2	2	1				
4	0	0	0	1	0	0	1	1	0	0	1	1	0	0	1	1				
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
8	7	5	1	3	9	7	5	4	10	8	20	4	13	9	32	5				
9	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1				
10	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0				
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
15	2	3	1	1	2	4	1	2	3	5	2	2	3	5	2	2				
16	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0	1				
17	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0				
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

Appendix Table D6 (Continued)

Area No.	$a = 0.8 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix Table D6 (Continued)

Area No.	$a = 0.8 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Appendix Table D6 (Continued)

Area No.	$a = 1.2 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
1	23	-25	70	40	0	-18	46	16	-13	-13	23	23	-22	-8	4	31				
2	8	9	4	2	8	10	4	20	8	10	18	77	24	211	57	360				
3	4	2	2	1	5	3	2	2	5	3	2	2	4	3	2	1				
4	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1				
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
8	13	6	19	3	9	7	52	10	10	8	77	18	26	8	94	25				
9	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1				
10	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0				
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
15	2	3	1	2	3	4	1	2	3	5	2	2	3	5	2	2				
16	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0	1				
17	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0				
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

Appendix Table D6 (Continued)

Area No.	<i>a</i> = 1.2 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix Table D6 (Continued)

Area No.	$a = 1.2 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Appendix Table D6 (Continued)

Area No.	<i>a</i> = 1.6 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m			
	M_x	M_y	V_x	V_y																
1	28	-30	80	48	4	-27	55	24	-8	-22	31	4	-18	-18	9	9				
2	8	10	4	2	9	13	5	32	8	26	25	94	35	240	69	396				
3	4	3	2	2	5	3	2	2	5	3	2	2	4	3	2	1				
4	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1				
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
8	169	6	246	26	185	10	312	43	211	24	360	57	240	35	397	69				
9	2	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1				
10	1	1	1	0	1	1	1	0	1	1	1	0	1	1	0	0				
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
15	2	4	1	2	2	4	1	2	3	4	1	2	3	4	1	2				
16	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0	0				
17	1	1	0	0	1	1	0	0	1	1	0	0	0	0	0	0				
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				

Appendix Table D6 (Continued)

Area No.	$a = 1.6 \text{ m}$				$b = 0.4 \text{ m}$				$b = 0.8 \text{ m}$				$b = 1.2 \text{ m}$				$b = 1.6 \text{ m}$			
	M_x	M_y	V_x	V_y																
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix Table D6 (Continued)

Area No.	<i>a</i> = 1.6 m				<i>b</i> = 0.4 m				<i>b</i> = 0.8 m				<i>b</i> = 1.2 m				<i>b</i> = 1.6 m				
	<i>M_x</i>	<i>M_y</i>	<i>V_x</i>	<i>V_y</i>																	
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

[+sign: increase, -sign: decrease, Unit: %]

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