Design example: Designing for openings in wood diaphragm

Canadian Wood Council
Conseil canadien du bois

FPINNOVATIONS

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PROJECT DESCRIPTION

A 20 m x 30 m building has a wood diaphragm on CMU walls, as shown in Figure 1. Except that two 3 m x 10 m openings are required in the diaphragm for architectural reasons, the rest of the building is the same as in Design Example: Wood diaphragm on reinforced CMU shearwalls (Neylon et al., 2013).

The introduction of openings into a diaphragm changes the forces from those for a diaphragm without openings. The design example below follows a design method developed by the Applied Technology Council (ATC) in the US on how to determine forces around openings. The method assumes that a diaphragm with openings behaves similarly to a Vierendeel Truss.

The procedure for designing a diaphragm with openings is as follows:

1. The diaphragm is first analysed without consideration of openings.
2. The diaphragm segments above and below the openings, as shown in Figure 2, are analysed for the local effect of the lateral force on the elements based on Vierendeel Truss assumption.
3. Net changes to chord force due to openings are determined by superimposing the results from steps 1 and 2.
4. Net shears in the portions of diaphragm beyond the openings are determined to distribute the net changes in the chord force into the diaphragm.
5. Resultant shears in the diaphragm are determined by superimposing the net shears from step 4 on those obtained from step 1.
6. The force in the framing members bordering the openings is determined.

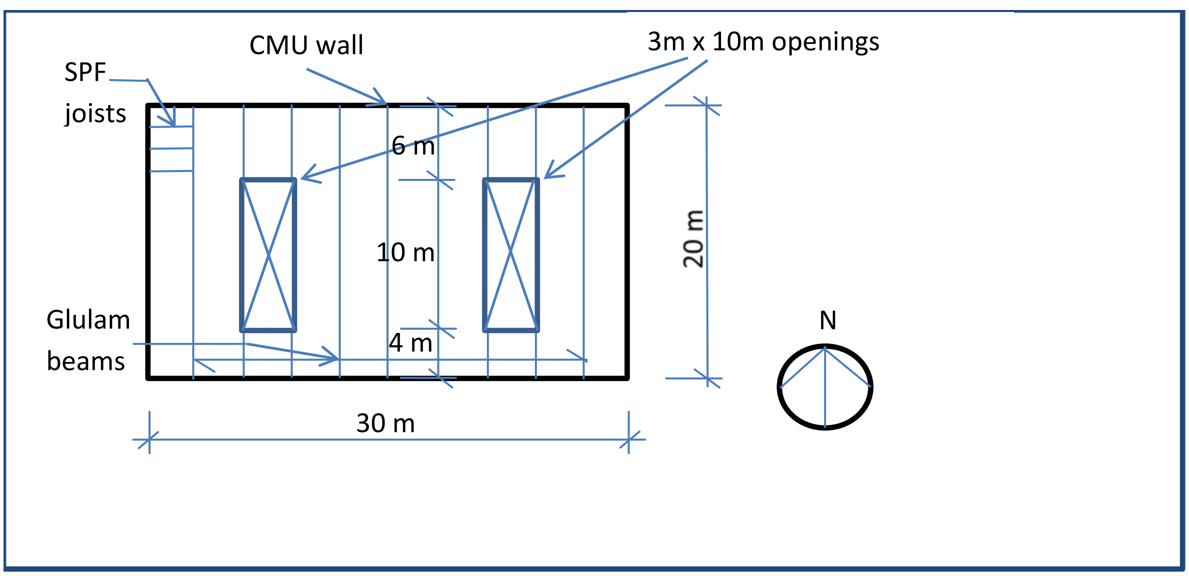


Figure 1

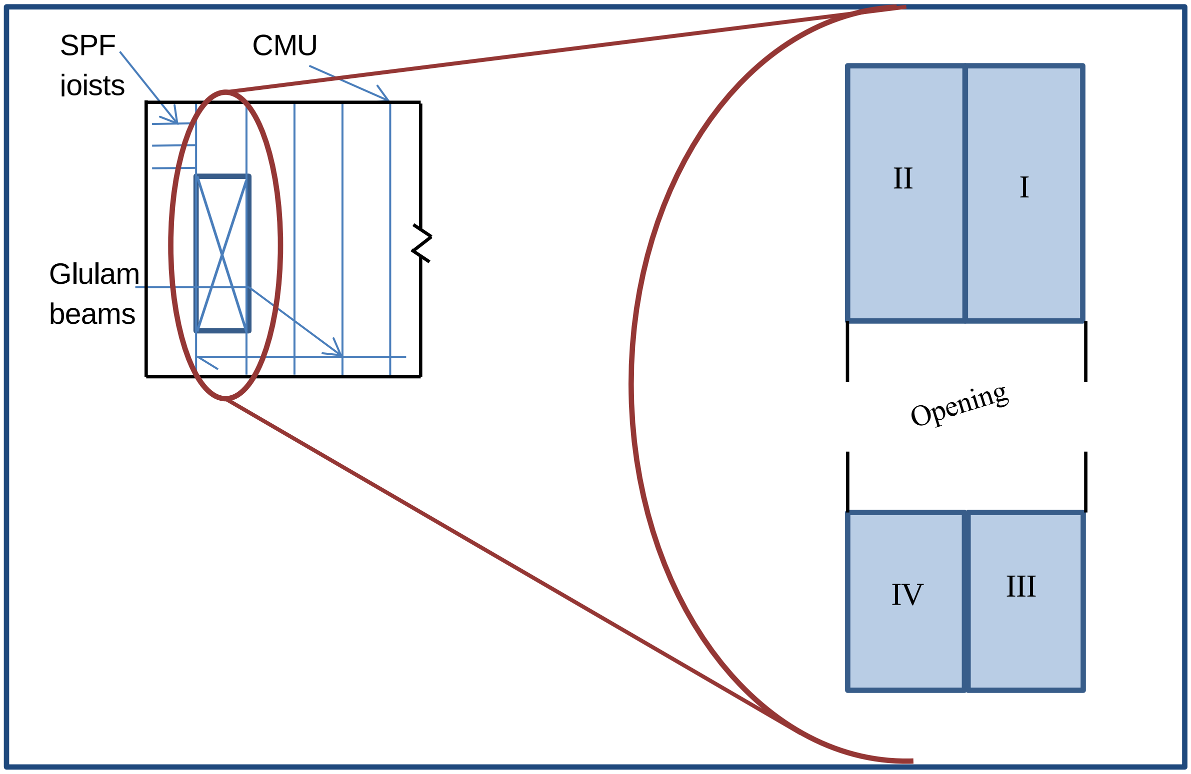


Figure 2

In the analysis, the clockwise shear and moment are considered positive, tension is considered negative and compression is considered positive.

This design example only addresses the force in the N-S direction. Designers can follow the same procedure for the E-W direction. Forces derived from example #1 are used however the 5% offset for accidental torsion is ignored, i.e. a total lateral load of 22.1 kN/m, which is assumed to be equally applied on both edges of the diaphragm (11.05 kN/m). Note that for wind load cases, the load would be distributed based on pressure/suction.

1. Determine forces at locations of interest without consideration of openings

Shear forces

V_1 = 22.1 x 30 x 1/2 = 332 kN or 332 / 20 = 16.6 kN/m
V_2 = 22.1 x (30/2 - 6) = 199 kN or 199/20 = 9.95 kN/m
V_3 = 22.1 x (30/2 - 7.5) = 166 kN or 166/20 = 8.29 kN/m
V_4 = 22.1 x (30/2 - 9) = 133 kN or 133/20 = 6.63 kN/m
V_5 = 22.1 x (30/2 - 15) = 0 kN or 0 kN/m

Moment

M_1 = 0 kN·m
M_2 = 22.1 x 1/2 x 6 (30 - 6) = 1591 kN·m
M_3 = 22.1 x 1/2 x 7.5 (30 - 7.5) = 1865 kN·m
M_4 = 22.1 x 1/2 x 9.0 (30 - 9.0) = 2088 kN·m

$M_5 = 22.1 \times 1/2 \times 15 (30 - 15) = 2486$ kN·m

Chord forces

$T_1 = C_1 = 0$ kN

$T_2 = -M_2 / 20 = -79.6$ kN, $C_2 = M_2 / 20 = 79.6$ kN

$T_3 = -M_3 / 20 = -93.2$ kN, $C_3 = M_3 / 20 = 93.2$ kN

$T_4 = -M_4 / 20 = -104$ kN, $C_4 = M_4 / 20 = 104$ kN

$T_5 = -M_5 / 20 = -124$ kN, $C_5 = M_5 / 20 = 124$ kN

2. Determine forces around openings based on Vierendeel Truss assumption

In Vierendeel Truss, it is assumed that the points of contraflexure occur at mid-length of the opening. Therefore, the force in the chords at mid-length of the opening (gridline 3) is zero. The shear and chord forces in the diaphragm segments on each side of the opening are shown in the free-body diagrams as in Figure 3.

To make portions of the diaphragms above and below the openings (segments I, II, III and IV) statically determinate, a further assumption is made that the diaphragm segment stiffnesses are proportional to their depth in the direction of load. Therefore, the shear is distributed to the segments based on their relative depth.

Segment I:

$F_{3,a} = C_3 = 93.2$ kN

$F_{3,b} = 0$ kN

$V_{4,a\text{-}b} = V_4 \times L_{a\text{-}b} / (L_{a\text{-}b} + L_{c\text{-}d}) \rightarrow V_{4,a\text{-}b} = 133 \text{ kN} \times 6 / (6 + 4) = 79.6$ kN, or $79.6/6 = 13.3$ kN/m

$V_{3,a\text{-}b} = V_{4,a\text{-}b} + w \times L_{3\text{-}4} \rightarrow V_{3,a\text{-}b} = 79.6 \text{ kN} + 11.05 \text{ kN/m} \times 1.5 \text{ m} = 96.1$ kN, or $96.1/6 = 16.0$ kN/m

$\sum M_{3,b} = 0$: $93.2 \times 6 + 11.05 \times 1.5^2 / 2 + 79.6 \times 1.5 - F_{4,a} \times 6 = 0 \rightarrow F_{4,a} = 115$ kN

$\sum F_{chord} = 0$: $115 - 93.2 + F_{4,b} = 0 \rightarrow F_{4,b} = -22.0$ kN

Segment II:

$F_{3,a} = C_3 = 93.2$ kN

$F_{3,b} = 0$ kN

$V_{3,a\text{-}b} = 96.1$ kN, from Segment I

$V_{2,a\text{-}b} = V_{3,a\text{-}b} + w \times L_{2\text{-}3} \rightarrow V_{2,a\text{-}b} = 96.1 \text{ kN} + 11.05 \text{ kN/m} \times 1.5 \text{ m} = 113$ kN, or $113/6 = 18.8$ kN/m

$\sum M_{3,b} = 0$: $113 \times 1.5 - 11.05 \times 1.5^2 / 2 - 93.2 \times 6 + F_{2,a} \times 6 = 0 \rightarrow F_{2,a} = 67.1$ kN

$\sum F_{chord} = 0$: $67.1 - 93.2 + F_{2,b} = 0 \rightarrow F_{2,b} = 26.1$ kN

Segment III:

$F_{3,d} = T_3 = -93.2$ kN

$F_{3,c} = 0$ kN

$V_{4,c\text{-}d} = V_4 - V_{4,a\text{-}b} \rightarrow V_{4,c\text{-}d} = 133 \text{ kN} - 79.6 \text{ kN} = 53.0$ kN, or $53.0/4 = 13.3$ kN/m

$V_{3,c\text{-}d} = V_{4,c\text{-}d} + w \times L_{3\text{-}4} \rightarrow V_{3,c\text{-}d} =$ 53.0 kN + 11.05 kN/m x 1.5 m = 69.6 kN, or 69.6/4 = 17.4 kN/m
$\sum M_{3,c} = 0$: $93.2 \times 4 + 11.05 \times 1.5^2 / 2 + 53.0 \times 1.5 + F_{4,d} \times 4 = 0 \rightarrow F_{4,d} = -116$ kN

$\sum F_{chord} = 0$: $-116 + 93.2 + F_{4,c} = 0 \rightarrow F_{4,c} = 23.0$ kN

Segment IV:
$F_{3,d} = T_3 = -93.2$ kN
$F_{3,c} = 0$ kN
$V_{3,c\text{-}d} =$ 69.6 kN, from Segment III
$V_{2,c\text{-}d} =$ 69.6 kN + 11.05 kN/m x 1.5 m = 86.2 kN, or 86.2/4 = 21.5 kN/m

$\sum M_{3,c} = 0$: $86.2 \times 1.5 - 11.05 \times 1.5^2 / 2 - 93.2 \times 4 - F_{2,d} \times 4 = 0 \rightarrow F_{2,d} = -64.0$ kN

$\sum F_{chord} = 0$: $-64.0 + 93.2 + F_{2,c} = 0 \rightarrow F_{2,c} = -29.2$ kN

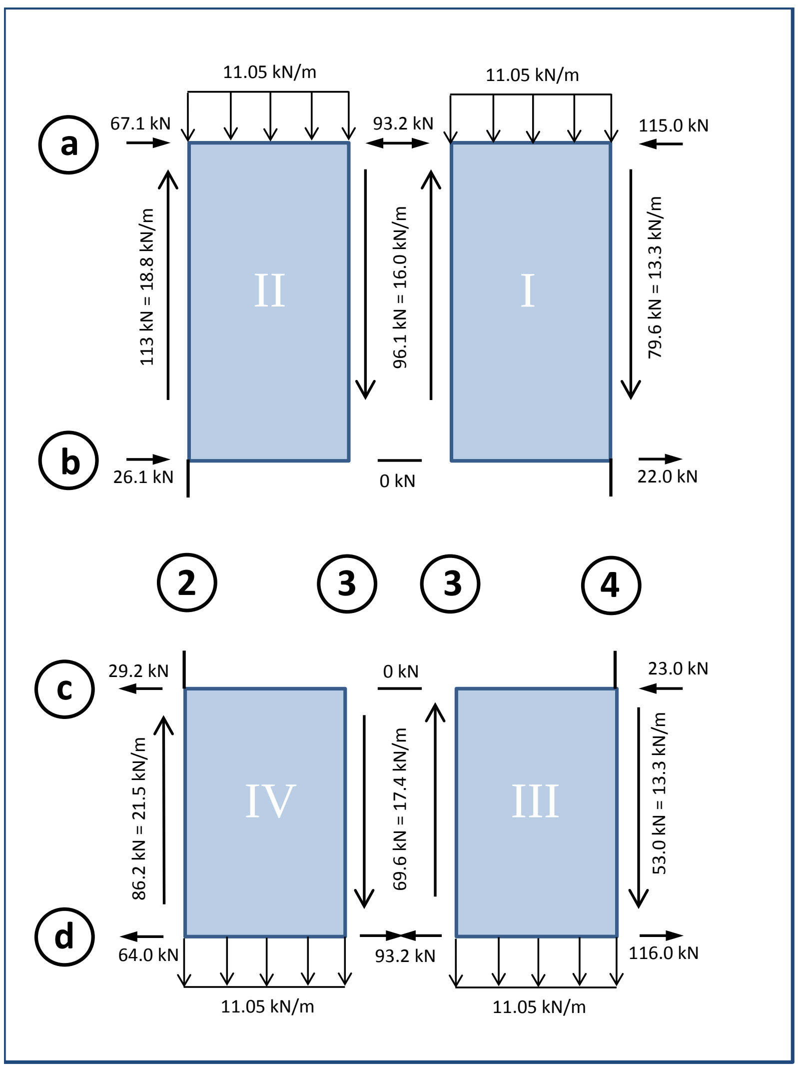


Figure 3

3. Determine net changes to the chord forces due to the openings in the diaphragm (difference between steps 1. and 2. at each location)

Calculate the net changes to chord forces due to openings in the diaphragm.

On Gridline 2:

$C_2 \rightarrow F_{2,a}$: 79.6 kN → 67.1 kN= -12.4 kN
$0 \rightarrow F_{2,b}$: 0 → 26.1 kN = 26.1 kN
$0 \rightarrow F_{2,c}$: 0 → -29.2 kN = -29.2 kN
$T_2 \rightarrow F_{2,d}$: -79.6 kN → -64.0 kN = 15.5 kN

On Gridline 4:

$C_4 \rightarrow F_{4,a}$: 104 kN → 115 kN= 10.8 kN
$0 \rightarrow F_{4,b}$: 0 kN → -22.0 kN = -22.0 kN
$0 \rightarrow F_{4,c}$: 0 kN → 23.0 kN = 23.0 kN
$T_4 \rightarrow F_{4,d}$: -104 kN → -116 kN = -11.8

Tension straps at the corners of the opening should be provided to prevent it from pulling apart.

4. Distribute net shear into available diaphragm sheathing

The net changes in the chord forces due to the opening must be distributed into the diaphragm sheathing beyond the opening. The minimum distance beyond the opening should be greater than the diaphragm depth divided by the maximum aspect ratio of the diaphragm. In this example the distance beyond the opening on each side is 6 m, and thus 20/4 = 5 <6 m.

On Gridline 2:

The diaphragm dimension to the wall is 6 m.

@ 1, a-b & @ 2, a-b	-12.4 / 6 = -2.07 kN/m
@ 1, b-c & @ 2, b-c	-12.4 + 26.1 / 6 = 2.28 kN/m
@ 1, c-d & @ 2, c-d	-12.4 + 26.1 -29.2 / 6 = -2.59 kN/m

On Gridline 4:

The dimension to Gridline 5 is 6.0 m. Assume the shear can be distributed across this width.

@ 4, a-b & @ 5, a-b	-10.8 / 6 = -1.80 kN/m
@ 4, b-c & @ 5, b-c	-(10.8-22.0) / 6 = 1.86 kN/m
@ 4, c-d & @ 5, c-d	-(10.8-22.0+23.0) / 6 = -1.97 kN/m

The net shear distributed into the diaphragm due to the net changes in the chord forces on Gridlines 2 and 4 is depicted in Figures 4a and 4b respectively The mechanism is explained in Figure 4c and 4d.

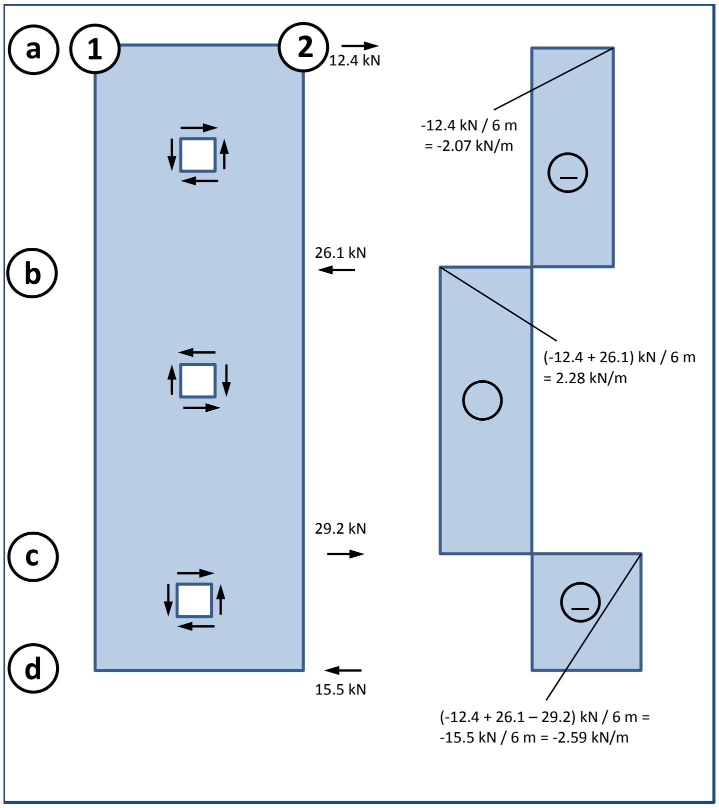
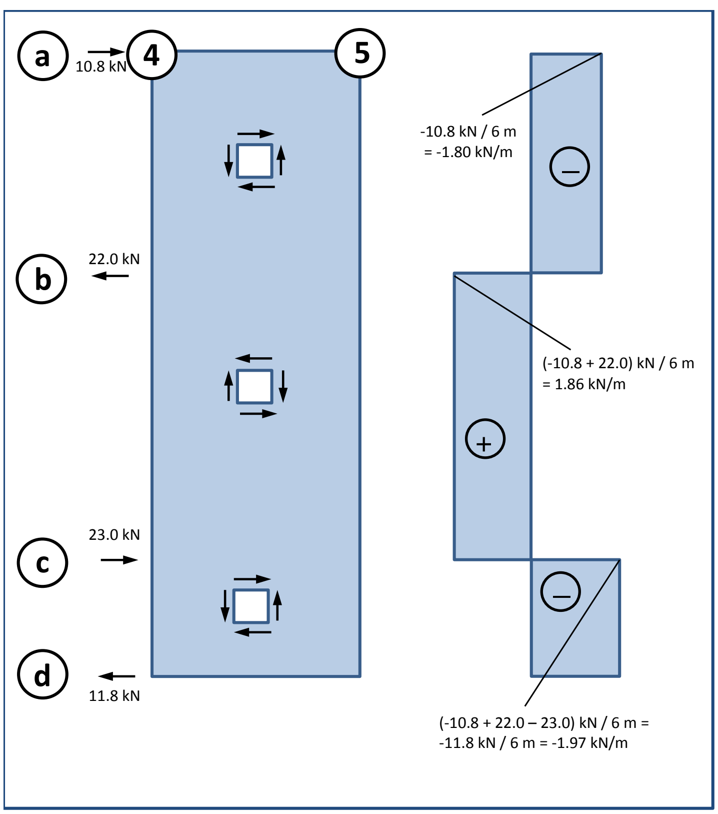


Figure 4a (above) and Figure 4b (below)



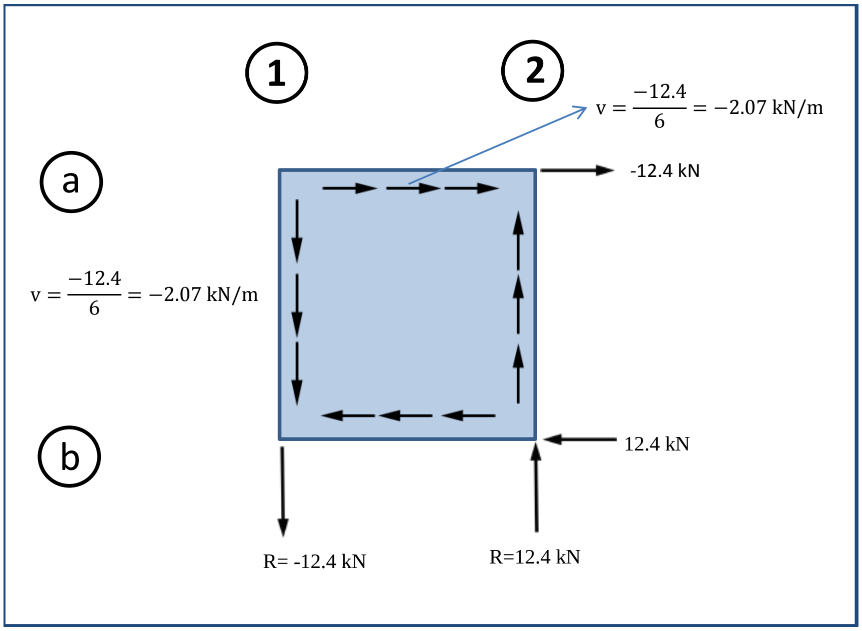


Figure 4c

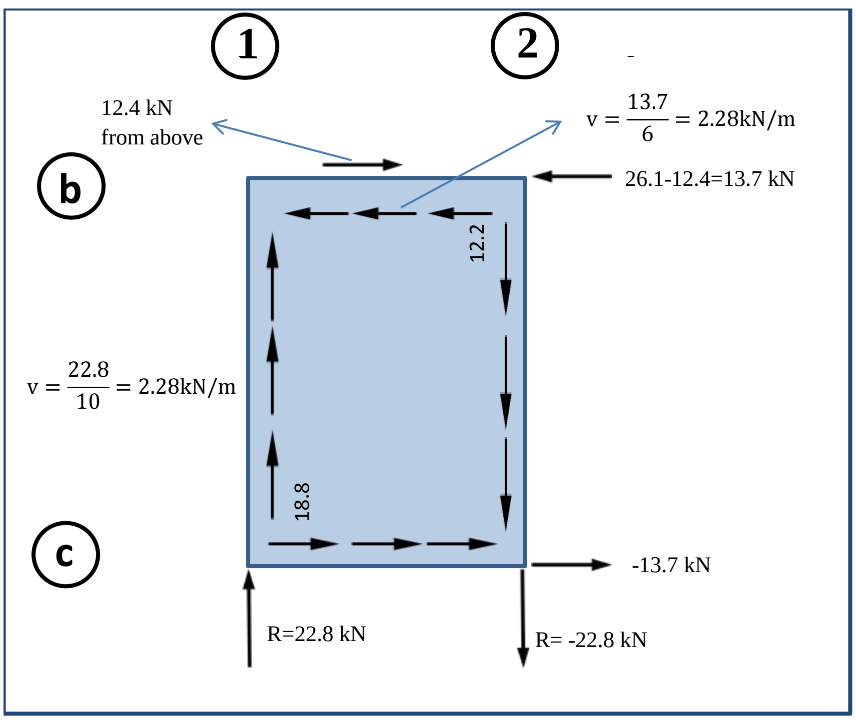


Figure 4d

Figure 4c shows the free-body diagram of the diaphragm portion between gridlines a-b and 1-2. The net change in chord force due to opening generated a force of 12.4 kN in tension.

$$\sum M_{2-b} = 0$$

$$R_{2b} = \frac{-12.4 \times 6}{6} = -12.4\ \mathrm{kN}$$

Change in diaphragm shear is:

$$\Delta \text{v} = \frac{-12.4}{6} = -2.07 \text{ kN/m}$$

Figure 4d shows the free-body diagram of the diaphragm portion between gridlines b-c and 1-2. The net change in chord force due to opening generated a force of 26.1 kN in compression.

$$\sum M_{2-c} = 0$$

$$R_{2b} = \frac{(26.1 - 12.4) \times 10}{6} = 22.8 \text{ kN}$$

Change in diaphragm shear is:

$$\Delta \text{v} = \frac{(26.1 - 12.4)}{6} = \frac{22.8}{10} = 2.28 \text{ kN/m}$$

5. Determine the resultant shear in the diaphragm

The changes in shears due to openings, from Step 4, are combined with shear for diaphragm without openings (from Step 1.) to determine the resultant shear in the diaphragm.

	Without Openings		With Openings	
@1, a-b	16.6 kN/m	+	-2.07 kN/m	= 14.5 kN/m
@1, b-c	16.6 kN/m	+	2.28 kN/m	= 18.8 kN/m
@1, c-d	16.6 kN/m	+	-2.59 kN/m	= 14.0 kN/m
@2, a-b	9.95 kN/m	+	-2.07 kN/m	= 7.87 kN/m
@2, b-c	9.95 kN/m	+	2.28 kN/m	= 12.2 kN/m
@2, c-d	9.95 kN/m	+	-2.59 kN/m	= 7.36 kN/m
@4, a-b	6.63 kN/m	+	-1.80 kN/m	= 4.83 kN/m
@4, b-c	6.63 kN/m	+	1.86 kN/m	= 8.49 kN/m
@4, c-d	6.63 kN/m	+	-1.97 kN/m	= 4.66 kN/m
@5, a-b	0 kN/m	+	-1.80 kN/m	= -1.80 kN/m
@5, b-c	0 kN/m	+	1.86 kN/m	= 1.86 kN/m
@5, c-d	0 kN/m	+	-1.97 kN/m	= -1.97 kN/m

6. Determine the forces in the framing members bordering the opening

Combine the unit shears along each side of the member to determine the force to be 'collected' in the framing members along the opening edges parallel to the lateral load. The axial forces in the framing members bordering the opening are shown in Figure 5. The joists should be spliced across glulam beams using strap ties to provide continuous framing members between Gridlines 1 and 2, and 4 and 5 to distribute the net shear forces into the diaphragm sheathing.

Gridline 2:

@2, a-b	18.8 kN/m	-	7.87 kN/m	= 10.9 kN/m x 6.0 m = 65.5 kN
@2, c-d	-21.5 kN/m	+	7.36 kN/m	= -14.1 kN/m x 4.0 m = -56.8 kN

Gridline 4:

@4, a-b	-13.3 kN/m	+	4.83 kN/m	= -8.47 kN/m x 6.0 m = -50.6 kN
@4, c-d	13.3 kN/m	-	4.66 kN/m	= 8.64 kN/m x 4.0 m = 34.4 kN

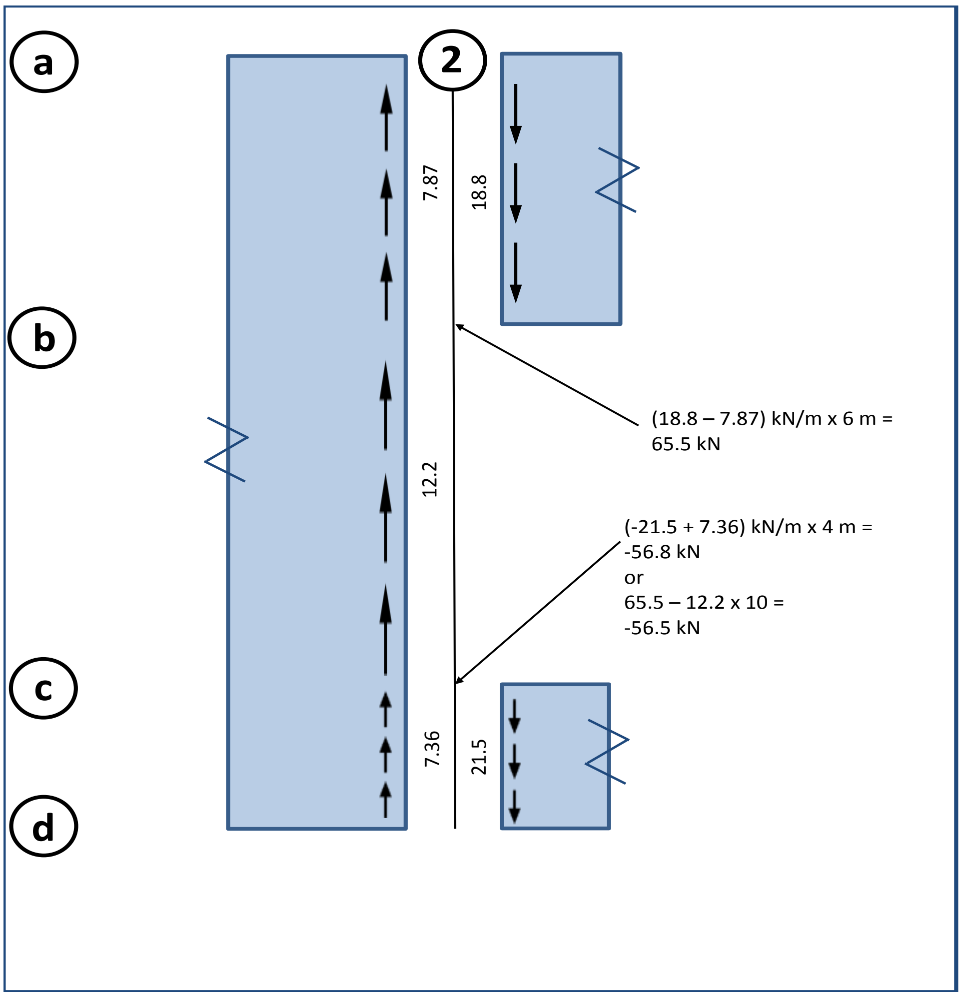


Figure 5a

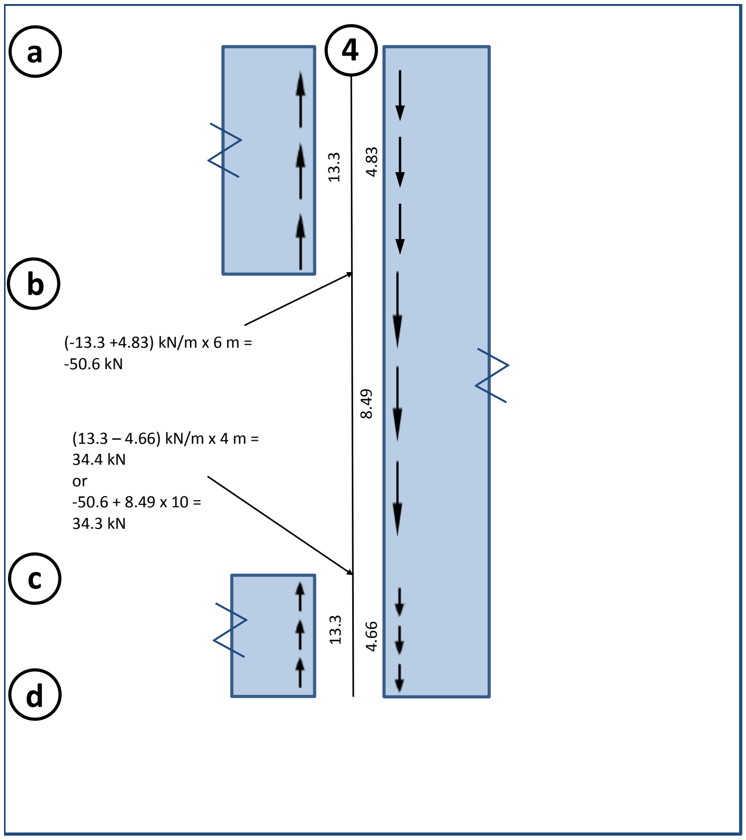
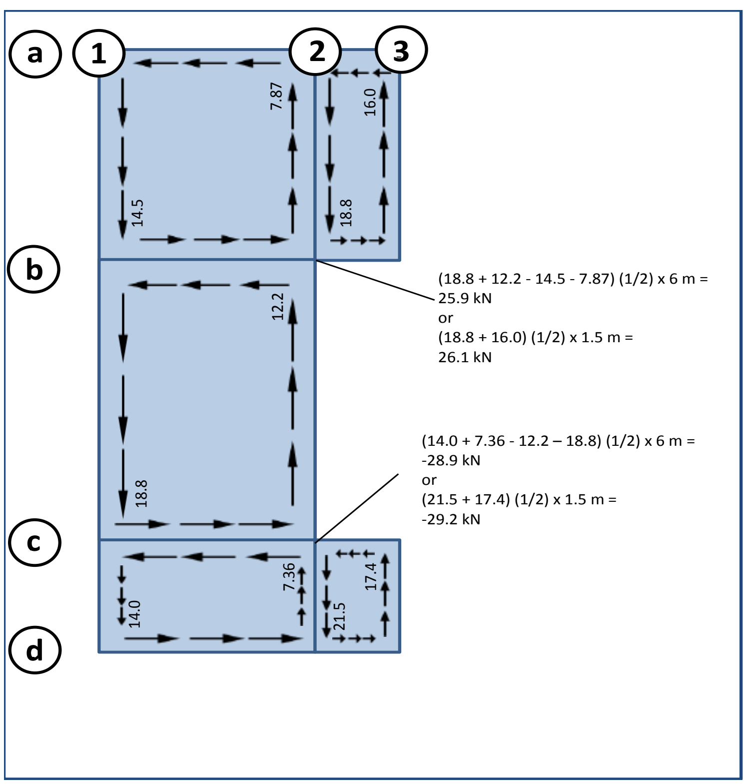


Figure 5b (above) and Figure 5c (below)



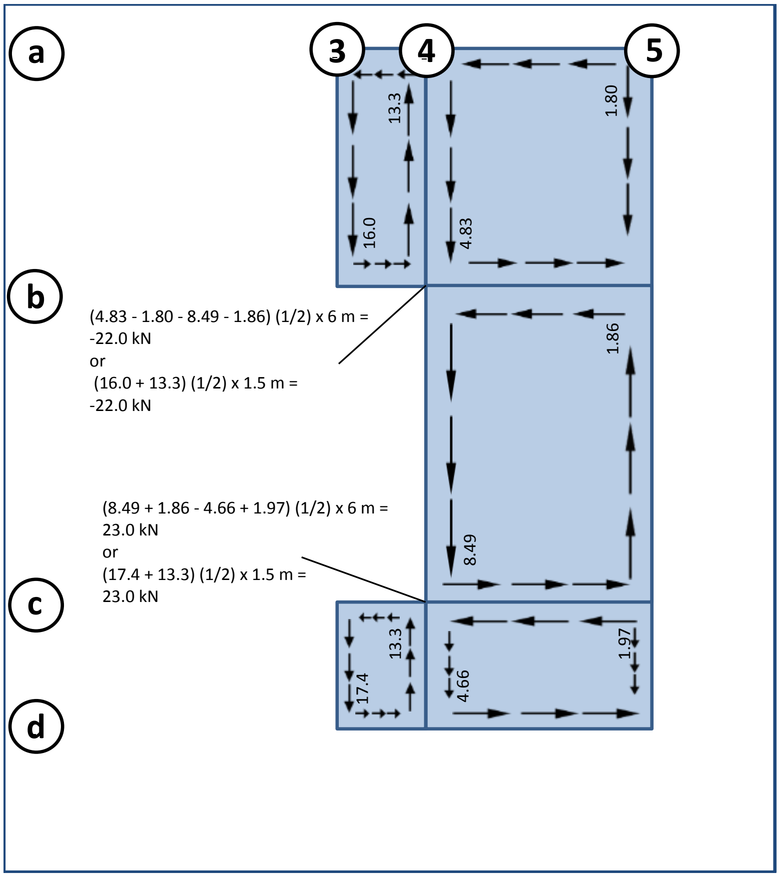


Figure 5d

Note that if the analysis starts with Gridline 2, instead of Gridline 4 as shown in this example, different results will be expected. There is 7% decrease in maximum shear in the diaphragm, and no obvious difference in the maximum chord forces at Gridline 2 and 4. However, the maximum axial forces are higher in the framing members bordering the opening if the analysis starts with Gridline 2 – in this example, a difference of 13% occurs in the force in members parallel to load. It is recommended that the more conservative values be used.

Design members to carry forces and shears in diaphragm.

In this example, the forces due to the opening have been derived. Members should now be designed to carry these forces. The maximum unit shear in the diaphragm is 21.5 kN/m; the maximum chord force is 22.1 x 30^2/(8 x 20) = 124 kN, located at mid-span; and the maximum axial force is 65.5 kN and 29.2 kN in the framing members bordering the opening parallel and perpendicular to load respectively.

Reviewing the diaphragm shear forces, the maximum unit shear is 21.5 kN/m. Different from Example #1, DF-L framing members are chosen. Use 18.5 mm plywood with 3" (3.66 mm diameter) nails spaced @ 64 mm o.c. at the blocked diaphragm boundaries and at continuous panel edges and 100 mm o.c. at other panel edges, and the minimum width of framing member is 89 mm. Two lines of fasteners are required. The factored shear resistance is:

v_r = 23.5 kN/m > 21.5 kN/m

Although the opening causes an increase in the tension and compression forces in the chords at the boundary of the diaphragm at Gridline 4, the maximum force is still located at mid-span (equal to 22.1 x 30^2/(8 x 20) = 124 kN). By inspection, the CMU wall bond beam capacity is adequate.

It is logical to place primary roof members on either side of the opening, to carry joists, frame the opening edges and carry drag forces. In this example, the primary roof members are GL 175x1102, sized for gravity loads. By inspection, these will have adequate capacity to carry the tension/compression force that develops along Gridline 2 and 4 (maximum 65.5 kN, from Step 6 above).

There is also an increase in force in the framing members bordering the opening in the direction perpendicular to load, D.Fir-L No.1 89x235 joists frame the opening, and have sufficient tensile resistance to resist the tendency at the corners of the opening to pull apart under lateral load. From the analysis above, the maximum tensile force, at $F_{2,c}$, is 29.2 kN, so a Simpson CMST14 steel strap is ok (capacity = 37.5 kN). The strap is 75 mm wide, using 10d nails, therefore a minimum edge distance of 19 mm is required – an 89x235 joist is ok, providing an edge distance of 25 mm for this strap. The connection detailing is shown in Figure 6. The D.Fir-L joists framing the opening should be continuous between Gridline 1 and 2, and Gridline 4 and 5, and therefore the tension straps are also required to transfer these forces over the glulam beams. When the framing members are in compression, the joists bear against the glulam beam and the connections do not need to be designed to transfer this compression.

As shown in example #1, a check should be completed to ensure that the anchorage forces due to wall components can be carried i.e. subdiaphragms and/or cross-ties.

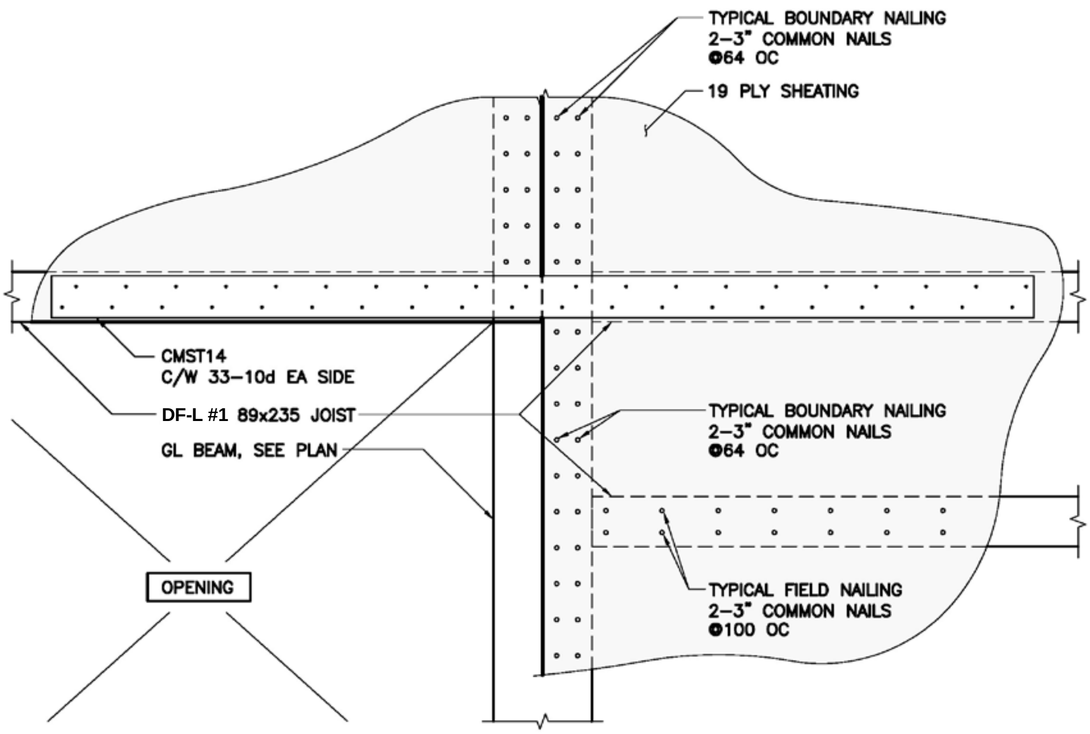


Figure 6

How to determine if analysis of diaphragm with opening is necessary

The appendix to this factsheet studies the effects of opening size and opening location on chord forces, diaphragm shear and forces in members around the opening for diaphragms with different aspect ratios. The main points from this analysis are summarised below:

1. Maximum diaphragm shear increases with the introduction of openings. This increase can be reduced significantly by increasing the distance between the opening and diaphragm edge.
2. Tension forces develop at the corners of openings, and ties/straps are necessary to distribute this force into the diaphragm where members are discontinuous.
3. It is strongly recommended that analysis for a diaphragm with an opening should be carried out except where all four of the following items are satisfied:

    a. Opening depth no greater than 15% of diaphragm depth;
    b. Opening length no greater than 15% of diaphragm length;
    c. Distance from diaphragm edge to the nearest opening edge is a minimum of 3 times the larger opening dimension; and
    d. The diaphragm portion between opening and diaphragm edge satisfies the maximum aspect ratio requirement.

If these criteria are fulfilled, no analysis is required; however, the maximum diaphragm design shear should be increased by 10% compared with the nominal maximum shear, as defined in the following:

$$\mathrm{v_{norm}} = \max(\mathrm{v_1}, \mathrm{v_2}, \mathrm{v_4})$$

$$\mathrm{v_1} = \frac{\mathrm{wL}}{2\mathrm{L_D}}$$

$$\mathrm{v_2} = \frac{\mathrm{V_2}}{(\mathrm{L_D} - \mathrm{D_{OPN}})}$$

$$\mathrm{v_4} = \frac{\mathrm{V_4}}{(\mathrm{L_D} - \mathrm{D_{OPN}})}$$

Where V_2 and V_4 are the shear at Gridline 2 and 4 in the diaphragm without consideration of opening, L and L_D are the dimension of the diaphragm perpendicular and parallel to load respectively, and D_{OPN} is the dimension of the opening parallel to load.

Reference:

ATC-7. Guidelines for the design of horizontal wood diaphragms. (1981) Applied Technology Council. Redwood City, OR, U.S.A.

ICC Guide to the design of diaphragms, chords and collectors – based on the 2006 IBC and ASCE/SEI 7-05. (2009) International Code Council.

Diekmann, E. F. (1999) Diaphragms and Shearwalls, Wood Engineering and Construction Handbook, 3rd ed., McGraw-Hill, New York, CH.8.

Tissell, J. R. and Elliott, J. R. (2004) Plywood Diaphragms – Research Report-138. APA, Tacoma, WA, U.S.A.

Neylon, B., Wang, J. and Ni, C. (2013) Design Example: Wood diaphragm on reinforced CMU shearwalls. FPInnovations and CWC joint publication.

APPENDIX

The influence of the size of opening and the location of opening on forces in the framing members and shear in diaphragm were investigated. The analytical method in Example #2 was used. The same diaphragm in Example #2 was used here except that the size and the location of the opening were changed. In describing the size of the opening, depth refers to the dimension parallel to the load while length refers to the dimension perpendicular to the load. In Case I, the effect of the size of opening was investigated while the location of the opening remained the same. The maximum shear in the diaphragm, the forces in chord members, and the forces in the framing members bordering the opening were studied when the depth and length of the opening were changed. They were further investigated for diaphragms with different aspect ratios, wherein the aspect ratio is calculated as the ratio of diaphragm depth to diaphragm length. In Case II, the influence of the location of opening was investigated while the size of the opening remained the same. The effect on the forces of interest was also studied for diaphragms with different aspect ratios. In both cases single opening was assumed and accidental torsional effect was ignored.

Case I: The effect of the size of opening

In Case I, the location of the opening was set the same as in the example, i.e. the West edge of the opening (Gridline 2) is 6 m inward from the boundary of the diaphragm (Gridline 1), the South edge of the opening (Axis C) is 4 m upward from Axis D, and the length of the opening remains the same (3 m), while the depth of the opening is expressed as a ratio of the depth of the diaphragm. The forces in the framing members bordering the opening and in the chords as well as shear in the diaphragm are summarized in Table A-1.

Table A-1									
		Depth ratio of opening							
		0.05	**0.10**	**0.15**	**0.20**	**0.30**	**0.40**	**0.50**	**0.60**
Chord forces (ratio to maximum at mid-span)	F2 (@ A & D)	0.65	0.64	0.63	0.63	0.61	0.58	0.54	0.48
	F4 (@ A & D)	0.86	0.86	0.87	0.88	0.89	0.91	0.94	0.98
Forces in the framing members bordering the opening (kN)	F2 - perp	19.79	20.37	21.02	21.75	23.53	25.90	29.21	34.19
	F4 - perp	13.58	14.16	14.81	15.54	17.31	19.68	23.00	27.97
	F2 - para	25.36	27.30	29.47	31.91	37.83	52.07	65.47	73.34
	F4 - para	5.51	12.06	18.39	24.45	35.52	44.61	50.55	50.97
Max. shear in diaphragm (ratio to w/o opening)		1.14	1.14	1.14	1.14	1.14	1.17	1.30	1.50

Forces in the chord members

The ratios of chord forces at Gridline 2 and 4 locations at the boundary of diaphragm with opening ($F_{2,a}$ or $F_{2,d}$, $F_{4,a}$ or $F_{4,d}$) to the maximum chord force at mid-span of diaphragm without opening are shown in Figure A-1. It can be seen that the chord force at Gridline 4 increases with increasing depth of the opening. Take a further look at how this force (F4-boundary) changes when the length of the opening is increased from 3 m to 6 m, as shown in Figure A-2a. It is observed that when the length of the opening is 3 m, which is 10% of the length of the diaphragm, the maximum chord force at mid-span governs when the depth ratio is less than 60%. However, when the length of opening is 6 m, 20% of the diaphragm length, the chord force at Gridline 4 exceeds the maximum chord force in the diaphragm without opening regardless of the diaphragm depth. The chord force is more sensitive to the dimension of the opening perpendicular to the load. This was confirmed for diaphragms with different aspect ratios, as shown in Figure A-2b, where the depth of the opening kept constant (10 m) and the length of the opening was expressed as a ratio to diaphragm length, with the vertical axis showing the ratio of the greater of the chord forces at Gridline 2 and 4 to the maximum force at mid-span. With the geometry of the diaphragm in Example #2, i.e. the aspect ratio 20/30=0.67, when the depth and length of the opening are both less than 15% of the corresponding dimension of the diaphragm, the maximum chord force at mid-span still governs. And therefore if the preliminary design is based on diaphragm without opening, the chord members do not need to be re-designed. Diaphragms with different aspect ratios were investigated. As shown in Figure A-3, where the length of the opening is set as 15% of the length of the diaphragm, the chord force at Gridline 4 is less than the maximum chord force at mid-span for diaphragms with different aspect ratios when the depth ratio is no greater than 15%.

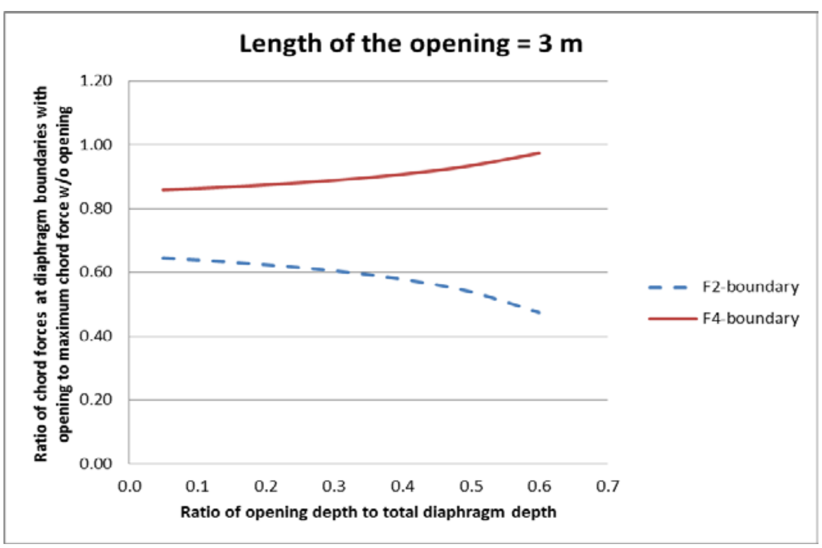


Figure A-1

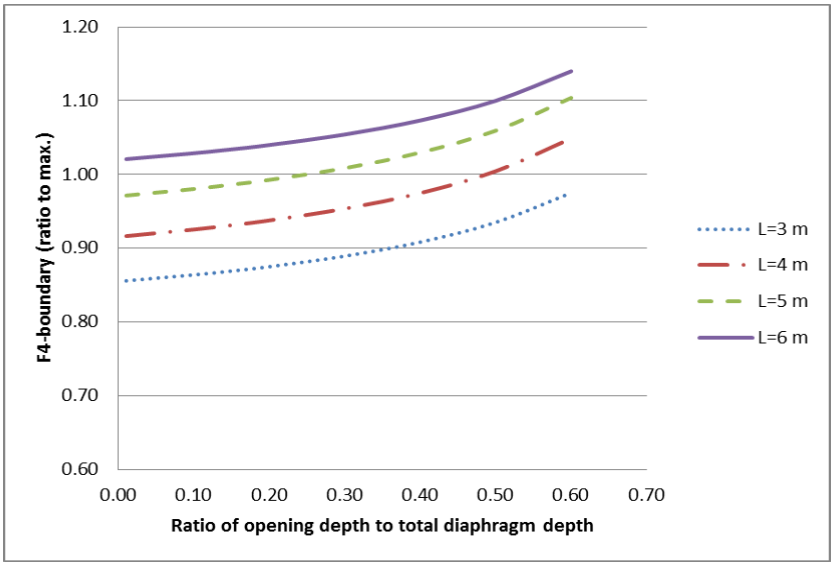


Figure A-2a

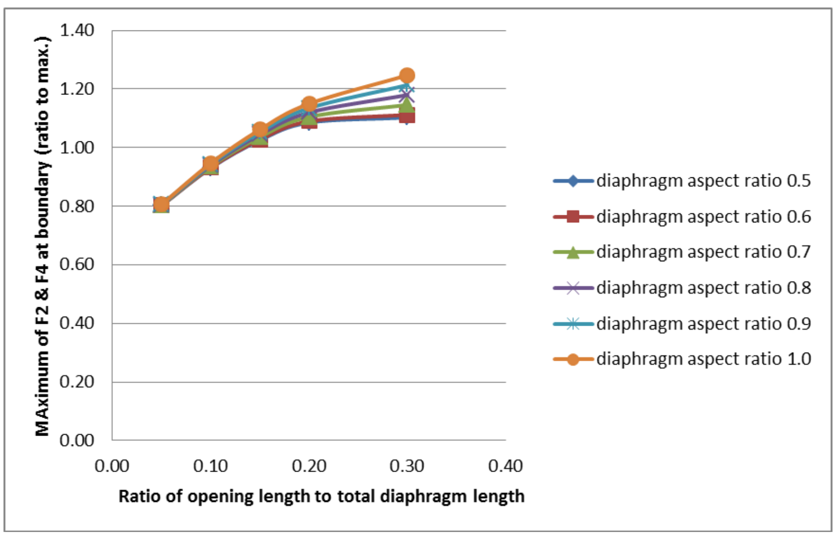


Figure A-2b

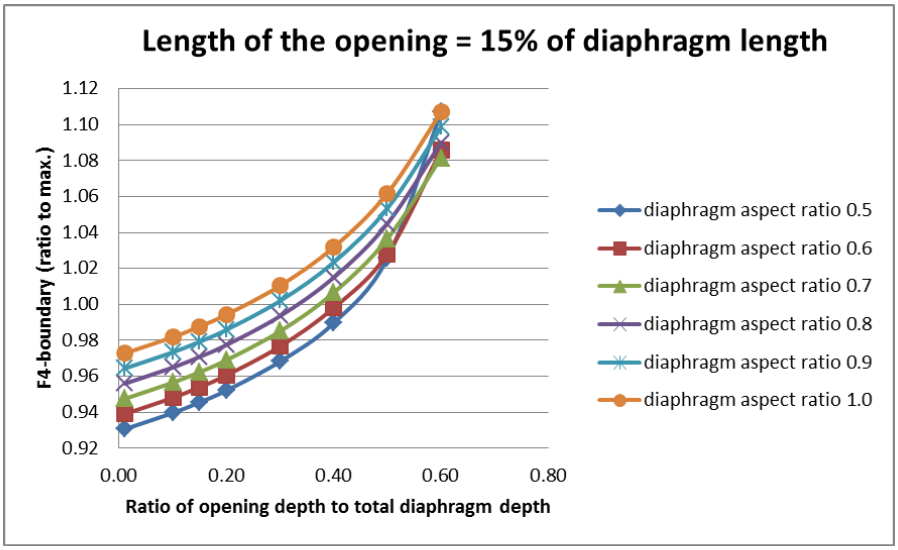


Figure A-3

Forces in the framing members bordering the opening

The forces in all framing members bordering the opening increase with increasing depth of the opening. However, the depth of the opening has more significant influence on the force in the framing members parallel to load than on the perpendicular members, as shown in Figure A-4. Furthermore, these forces are shown in Figures A-5a to A-5d respectively when the length of the opening is increased from 3 m to 6 m, where the vertical axis is expressed as the ratio of the force in framing members to the maximum chord force at mid-span of the diaphragm without opening. It can be seen that the forces typically increase with increasing length of the opening. The exception is the framing member parallel to load at Gridline 4 ($F_{4,a\text{-}b}$, or $F_{4,c\text{-}d}$): as the opening starting location (Gridline 2) is held constant with reference to the diaphragm edge, the opening edge on Gridline 4 moves into a lower shear zone as the opening length increases. The results show that tension connections are required at the corners of the opening to prevent it from pulling apart.

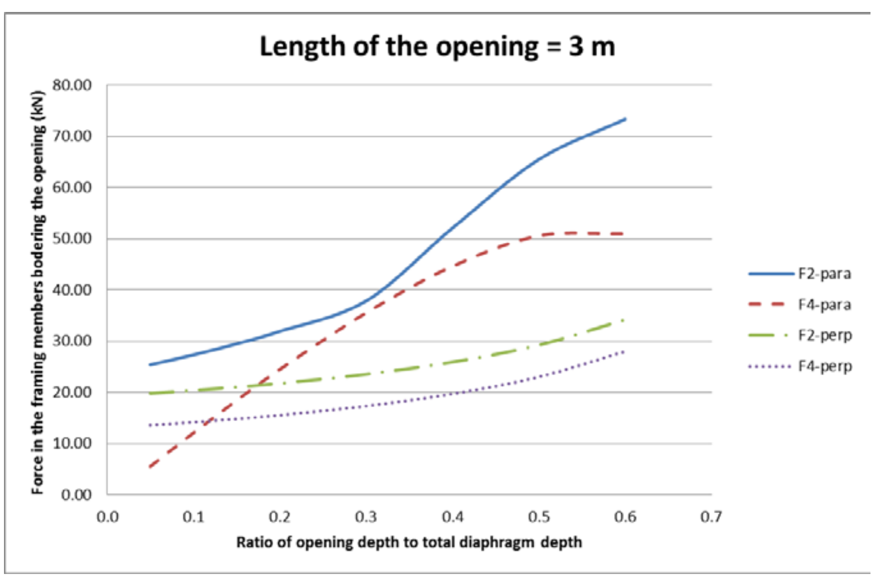


Figure A-4

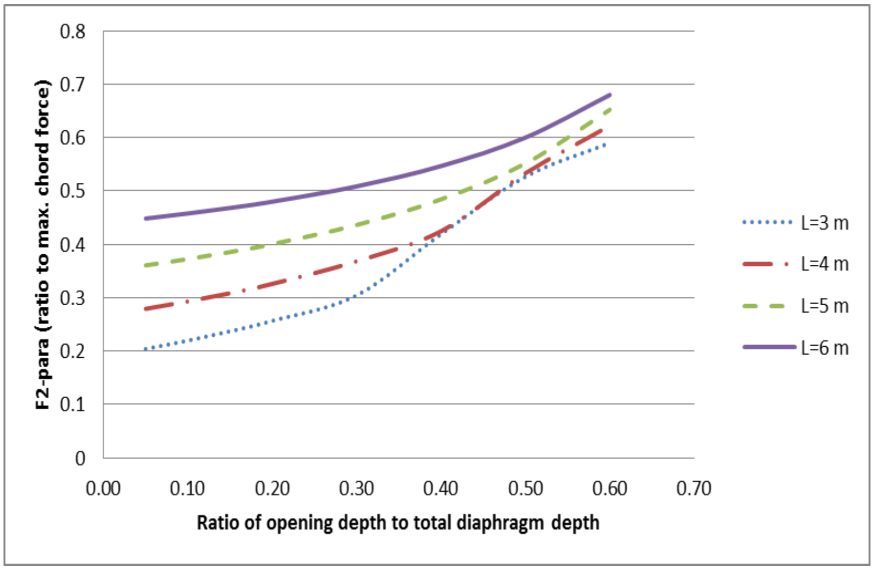


Figure A-5a

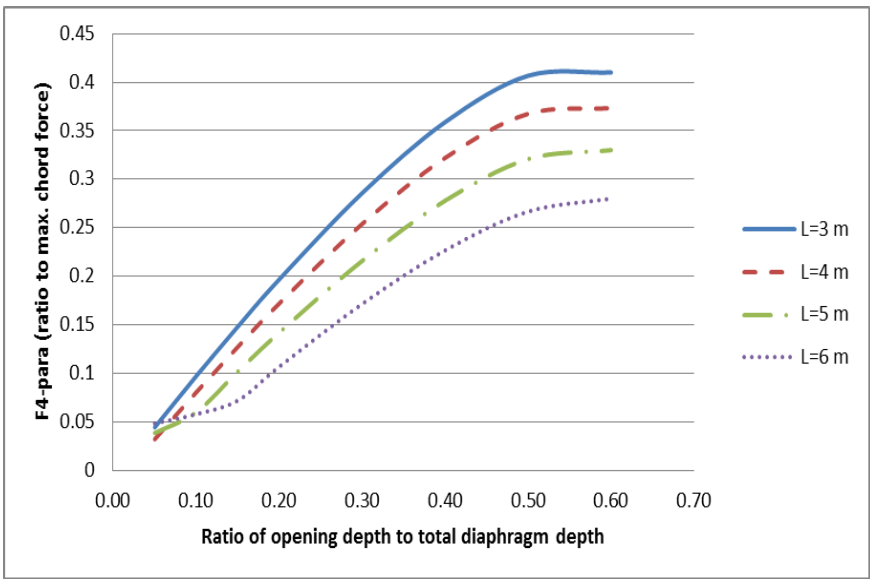


Figure A-5b

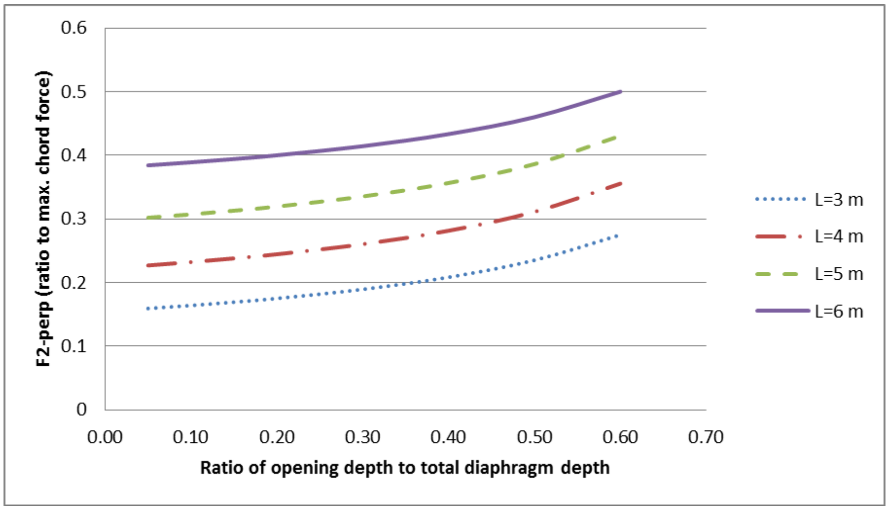


Figure A-5c

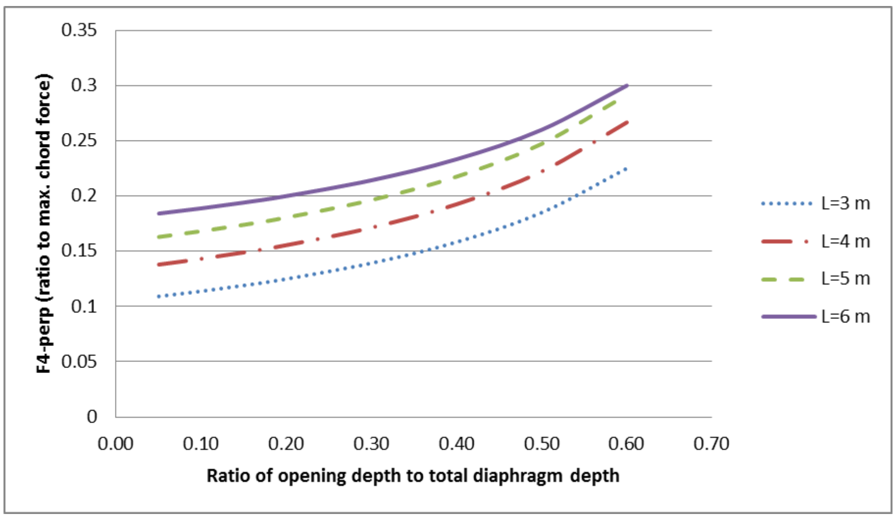


Figure A-5d

The axial forces in the framing members were further investigated for diaphragms with different aspect ratios. It can be seen from Figures A-6a to 6d that for the opening of the same size, the axial forces in the framing members bordering the opening increase with increasing aspect ratio of the diaphragm. When the dimension of the opening is no greater than 15% of the corresponding dimension of the diaphragm, the axial force in the framing members is no greater than 60% of the maximum chord force at mid-span with the current location of the opening.

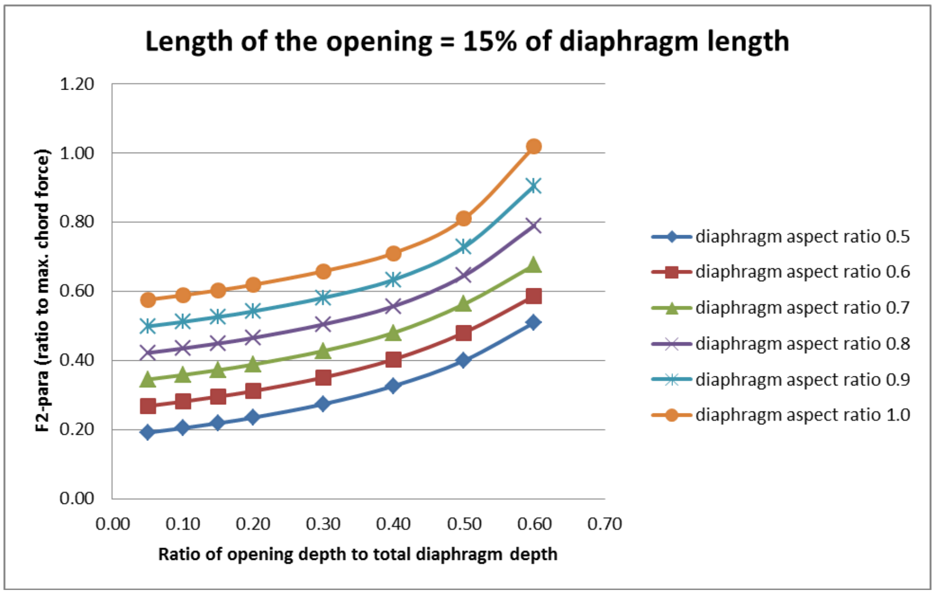


Figure A-6a

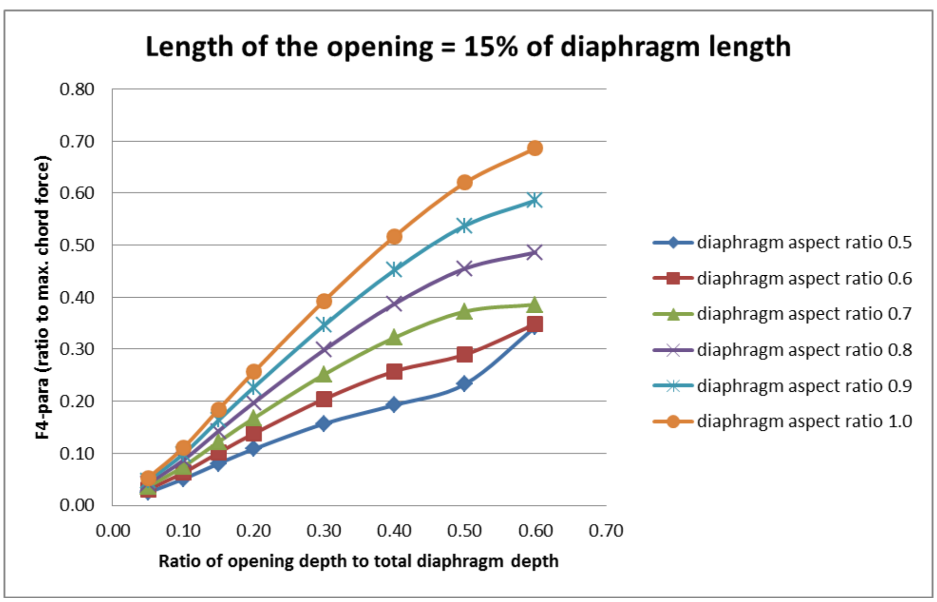


Figure A-6b

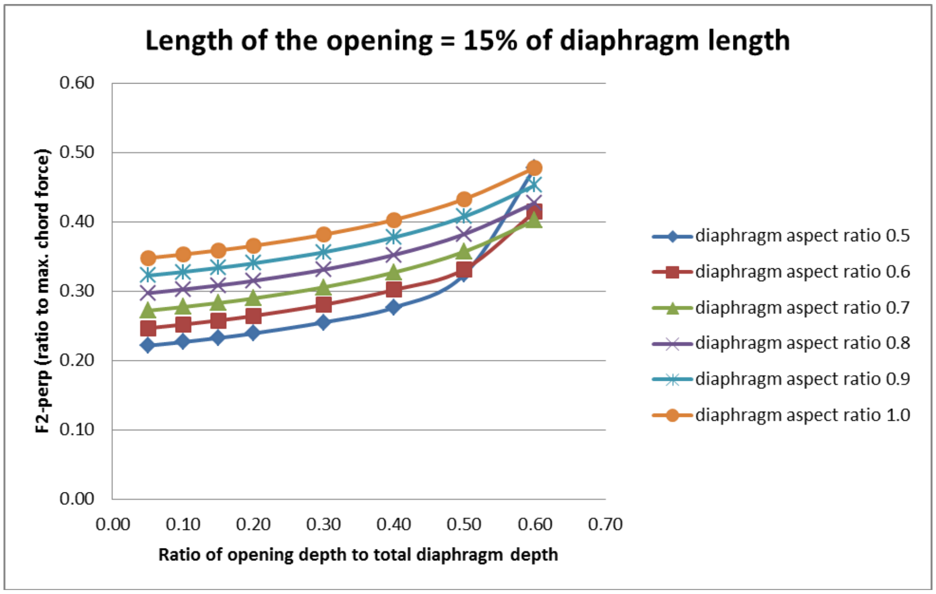


Figure A-6c

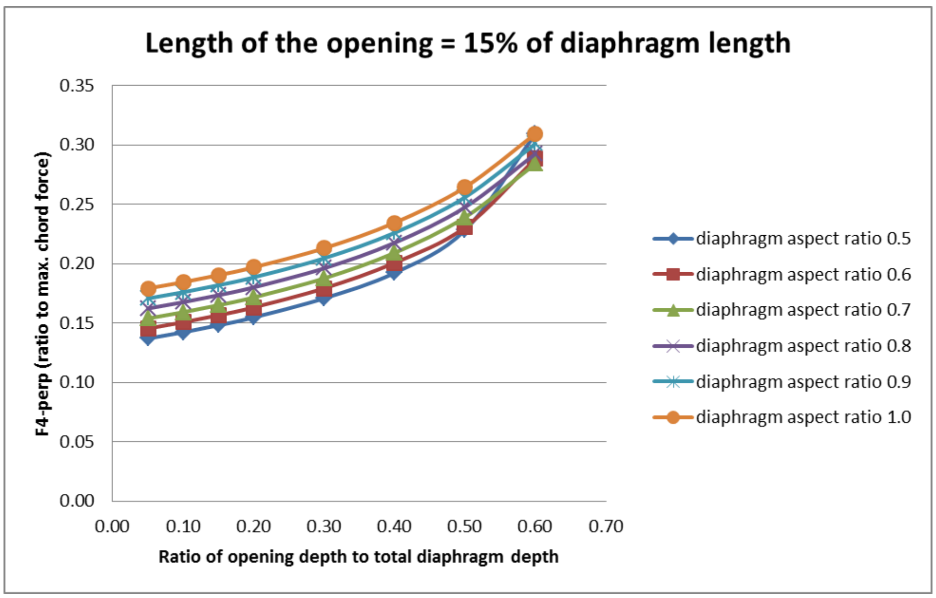


Figure A-6d

Shear in the diaphragm

The analysis shows when the depth of the opening is less than 40% of the depth of diaphragm, the maximum shear in the diaphragm due to opening occurred at the boundary of the diaphragm (Gridline 1) between Axis B and C; while when the depth ratio is equal to or greater than 40% the maximum shear in the diaphragm due to opening occurred in Segment IV at the east side of Gridline 2 between Axis C and D, and it is greater than the maximum shear in the diaphragm without opening. And therefore the shear resistance of the diaphragm needs to be checked if the preliminary design is based on diaphragm without opening. When the location and length of the opening are set, the maximum shear in the diaphragm beyond the opening does not change with the depth of the opening. It can be explained that the net shear in the diaphragm due to opening is caused by the net changes to chord forces, and the net shear in the portion of the diaphragm defined by Gridline 1, 2, C and B is:

$$\frac{\left(F_{2,a}^{OPN} - F_{2,a}\right) + \left(F_{2,b}^{OPN} - F_{2,b}\right)}{x_2} = \frac{F_{3,a}^{OPN} - F_{2,a} - F_{2,b}}{x_2} = \frac{\frac{M_3}{L_D} - \frac{M_2}{L_D} - 0}{x_2} = \frac{M_3 - M_2}{L_D x_2}$$

Where M_2 and M_3 are the original moments at Gridline 2 and 3, and x_2 is the distance between Gridline 1 and 2, and L_D is the depth of the diaphragm. Therefore when the location and length of the opening are set, i.e. the location of Gridline 2 and 3 is set, the net shear does not change with the depth of the opening.

However, the maximum shear in the segments above or below the opening is affected by the depth of the opening greatly. When the maximum shear is governed by the shear in the diaphragm portion alongside the opening, it does not change with the depth of the opening; while when the maximum shear is governed by the shear in the segments above or below the opening, it increases with increasing depth of the opening, as shown in Figure A-7.

The maximum shear in the diaphragm also increases with increasing length of the opening, as shown in Figure A-7. In this Figure the vertical axis is expressed as the ratio of the maximum shear in the diaphragm with opening to that in the diaphragm without opening.

Figure A-8 illustrates how the maximum shear in the diaphragm changes with respect to the opening depth for diaphragms with different aspect ratios, assuming the length of the opening is 15% of the length of the diaphragm.

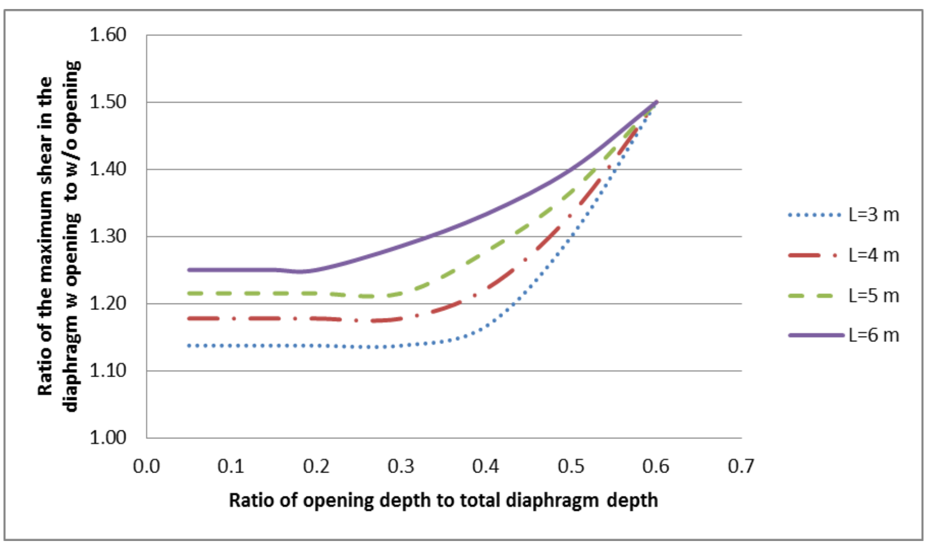


Figure A-7

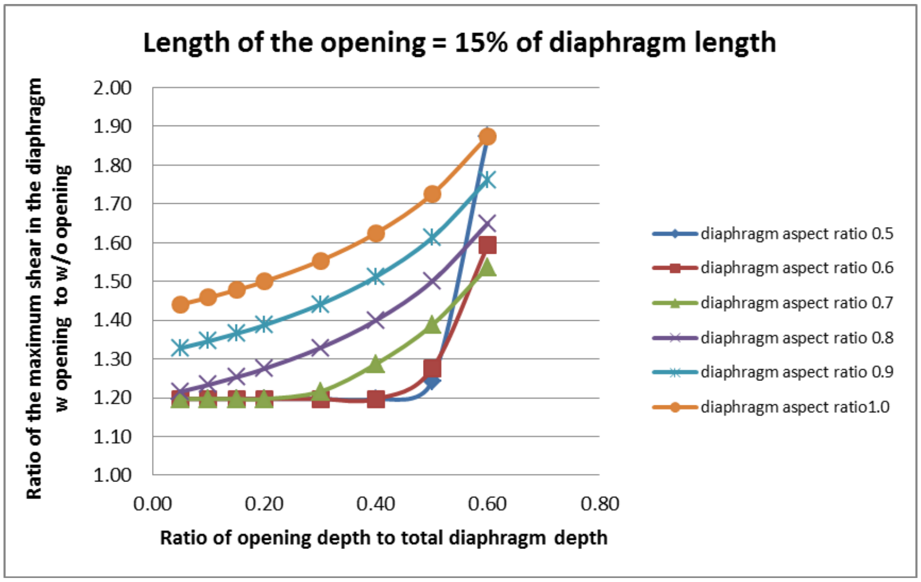


Figure A-8

Case II: The effect of the location of opening

In this case, the size of the opening kept constant, i.e. the length is 3 m and the depth is 10 m. The location of the opening in the N-S direction remained the same, i.e. the location of Axis B and C. The location of the West edge of the opening, i.e. Gridline 2, was changed from 1 m to 12 m. Please note that this is just for the purpose of analysis, and when it is too close to the boundary of the diaphragm, this portion of diaphragm does not satisfy the aspect ratio requirement anymore. The forces in the framing members bordering the opening and in the chords as well as shear in the diaphragm are summarized in Table A-2.

Table A-2

		Location (m)											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Chord forces (ratio to maximum at mid-span)	F2 (@ A & D)	0.06	0.10	0.22	0.34	0.44	0.54	0.63	0.71	0.78	0.84	0.90	0.94
	F4 (@ A & D)	0.62	0.70	0.78	0.84	0.89	0.94	0.97	1.00	1.02	1.02	1.02	1.02
Forces in the fram-ing mem-bers bor-dering the opening (kN)	F2-perp	45.8	42.5	39.2	35.8	32.5	29.2	25.9	22.6	19.3	16.0	12.6	9.32
	F4-perp	39.6	36.3	32.9	29.6	26.3	23.0	19.7	16.4	13.1	9.74	6.42	3.11
	F2-para	211	137	108	89.9	76.6	65.5	55.6	46.6	38.1	32.3	27.0	21.8
	F4-para	92.0	83.7	75.4	67.1	58.8	50.6	42.3	34.0	25.7	17.4	9.12	1.24
Max. shear in diaphragm (ratio to w/o opening)		2.33	1.83	1.70	1.57	1.43	1.30	1.17	1.08	1.06	1.04	1.03	1.02

Shear in the diaphragm

In Table A-2, the maximum shear is expressed as the ratio to the maximum shear in diaphragm without opening. The maximum shear due to the opening is greater than that in the diaphragm without opening in all cases no matter where the opening is located. However, it can be seen that the maximum shear in the diaphragm decreases significantly when the opening is moved away from the boundary of the diaphragm. When the length of the opening is 3 m, the increase in maximum shear is reduced to within 5% when the opening is 10 m away from the boundary of the diaphragm. Figure A-9 further shows how the maximum shear changes if we allow the length of the opening to change.

Increasing the distance between the edges of the opening and diaphragm can reduce the increase in maximum shear in the diaphragm due to opening effectively.

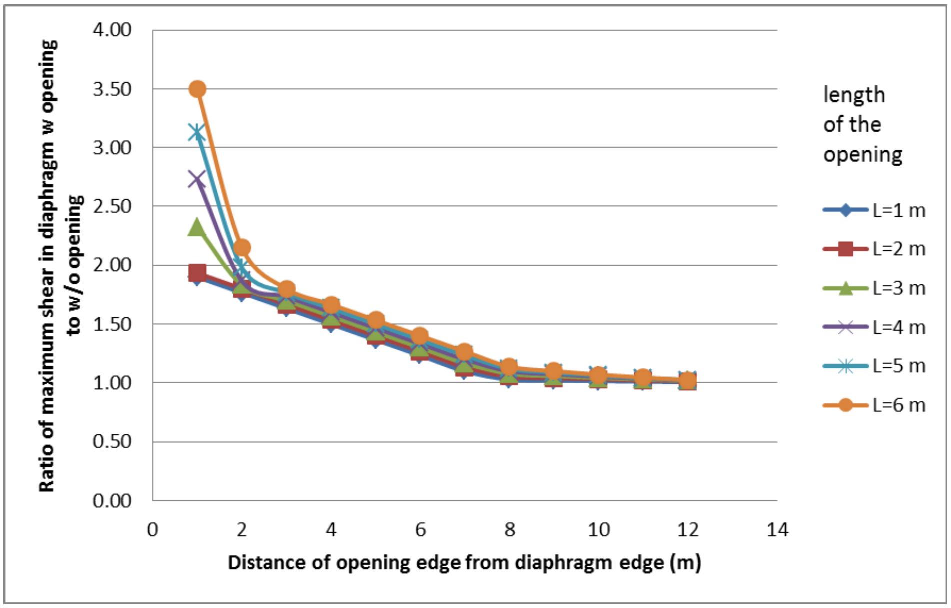


Figure A-9 (note: the depth of the opening in this figure is 10 m)

Define the nominal maximum shear as follows:

$$v_{norm} = \max(v_1, v_2, v_4)$$

$$v_1 = \frac{wL}{2L_D}$$

$$v_2 = \frac{V_2}{(L_D - D_{OPN})}$$

$$v_4 = \frac{V_4}{(L_D - D_{OPN})}$$

Where V_2 and V_4 are the shear at Gridline 2 and 4 in the diaphragm without consideration of opening, L and L_D are the length and depth of the diaphragm respectively, and D_{OPN} is the depth of the opening.

Assume the dimension of the opening is 15% of the corresponding dimension of the diaphragm in both directions, and the distance of opening edge from diaphragm edge is expressed in relation to the larger dimension of the opening, in this case it is the length of the opening. The following figure (Figure A-10) shows the relationship between the maximum shear and the location of opening for diaphragms with different aspect ratios, where the maximum shear is expressed as the ratio to the nominal maximum shear. It can be seen that when the distance is 3 times the larger dimension of the opening, the increase in maximum shear is negligible. This is also checked for opening of smaller size (less than 15%), and it was concluded that the increase in maximum shear compared with nominal maximum is less than 10% when the distance is no less than 3 times the larger dimension of the opening and that the portion of diaphragm alongside the opening satisfies the maximum aspect ratio requirement.

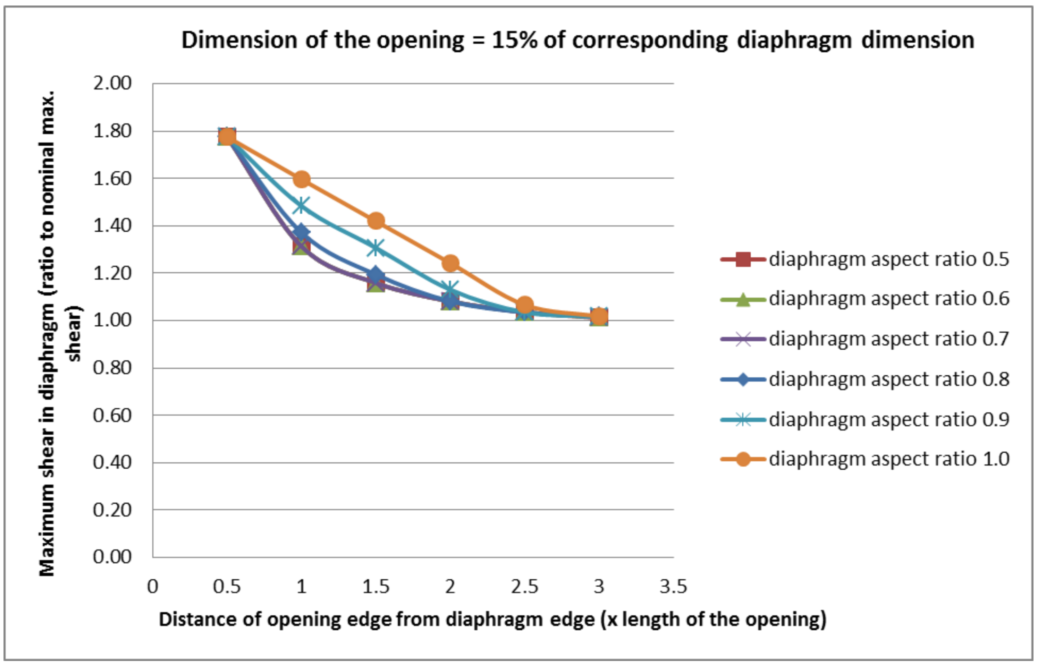


Figure A-10

Force in the framing members bordering the opening

The forces in the framing members all increase when the opening moves towards the edge of the diaphragm, especially in the framing members parallel to load, as shown in Figure A-11. When the opening is close to the edge of the diaphragm, even if it is of small size, the force in the framing member parallel to load could be significant. It is concluded that locating the opening away from the boundary of diaphragm can reduce the forces in the framing members bordering the opening effectively.

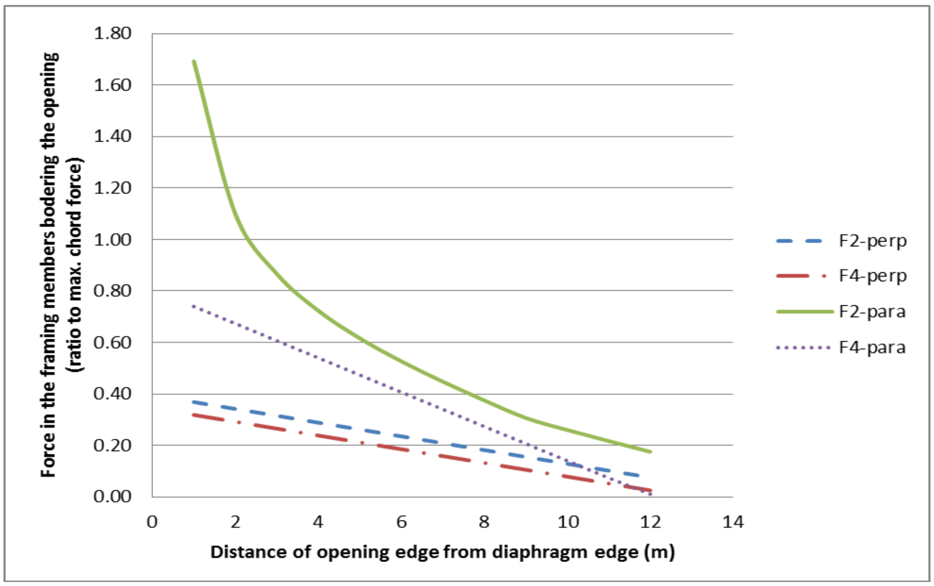


Figure A-11

Assume the dimension of the opening is 15% of the corresponding dimension of the diaphragm, the relationship between the axial forces in the framing members and the location of opening for diaphragms with different aspect ratios are illustrated in Figures A-12a to 12d. It can be seen that when the distance of opening edge from diaphragm edge is equal to or greater than 3 times the larger dimension of the opening, the maximum force in the framing members is less than 50% of the maximum chord force at mid-span of the diaphragm without opening.

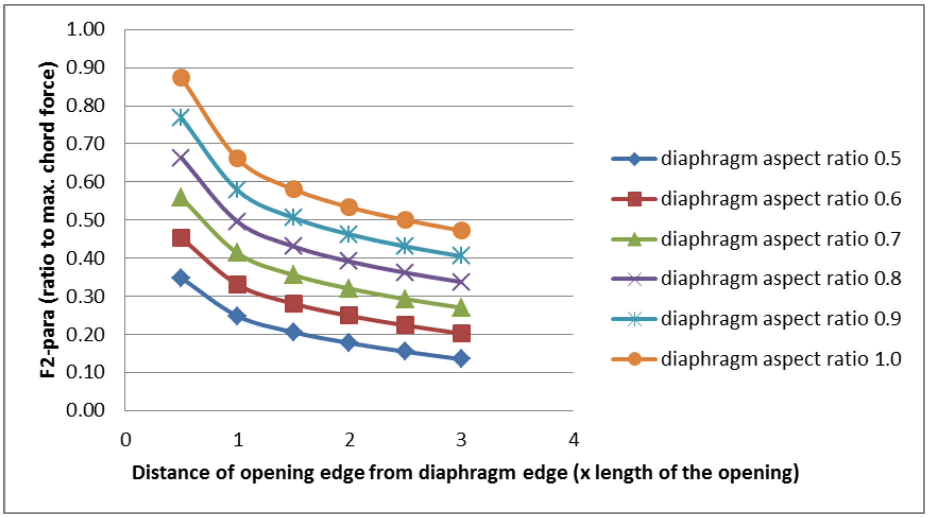


Figure A-12a

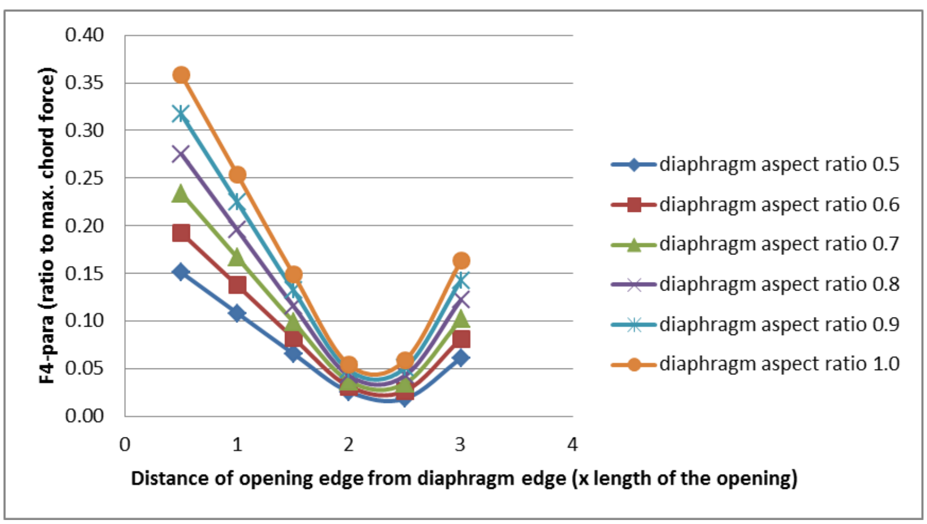


Figure A-12b

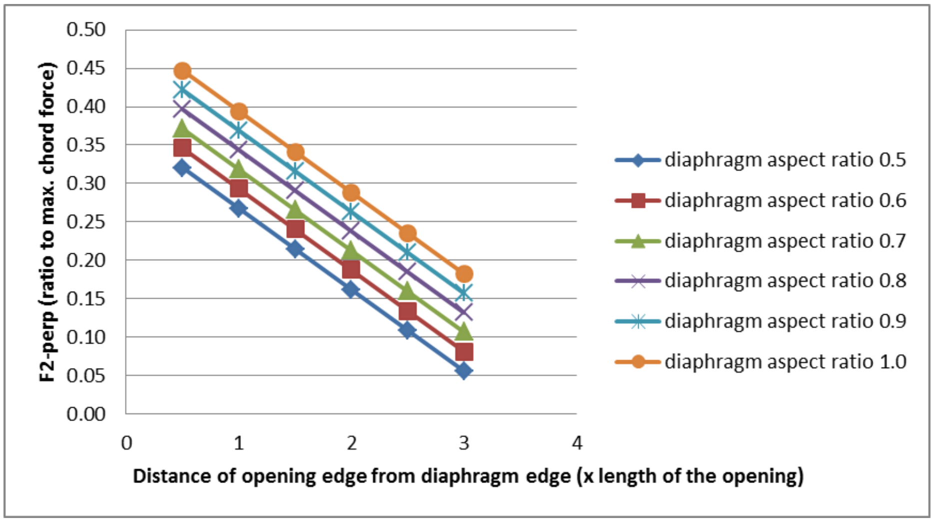


Figure A-12c

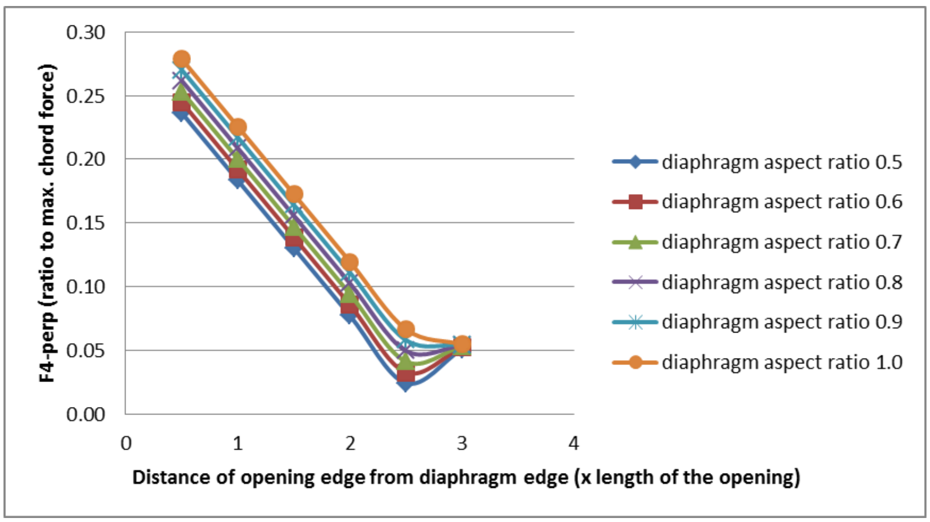


Figure A-12d

Forces in the chord members

The ratios of chord forces at Gridline 2 and 4 locations at the boundary of diaphragm with opening ($F_{2,a}$ or $F_{2,d}$, $F_{4,a}$ or $F_{4,d}$) to the maximum chord force at mid-span of diaphragm without opening vs. the location of the opening are shown in Figure A-13. It can be seen that both forces increase when the opening is moved away from the edge of the diaphragm. This makes sense, as Gridlines 2 and 4 move towards the high moment zone. When the length of the opening is 3 m, the maximum chord force at mid-span still governs in most of the cases. However, if the length of the opening is increased to 6 m, as shown in Figure A-14, the chord force at Gridline 4 at the boundary of diaphragm exceeds the maximum chord force at mid-span no matter where the opening is located except at 12 m. It also confirms the conclusion made in Case I that the chord force is more sensitive to the dimension of the opening perpendicular to load.

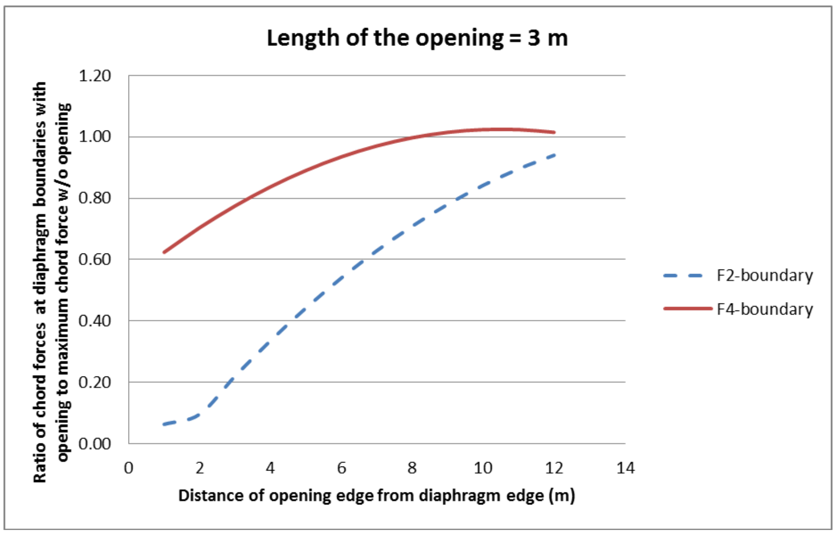


Figure A-13

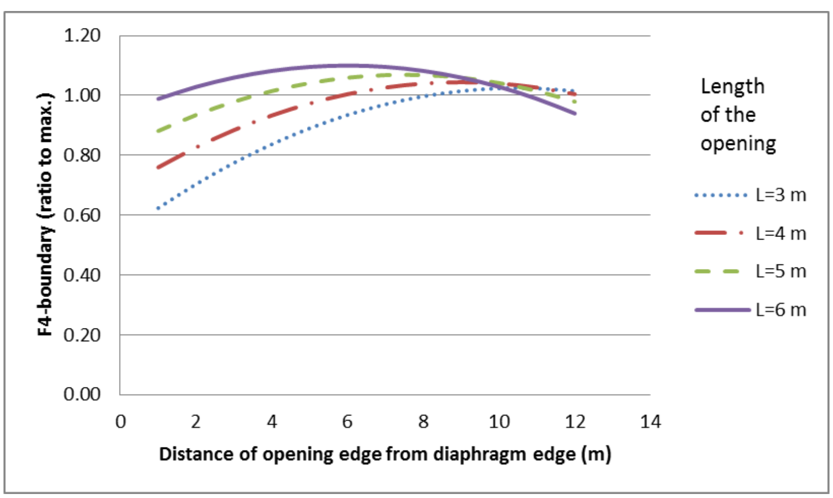


Figure A-14

Assume the dimension of the opening is 15% of the corresponding dimension of the diaphragm, the maximum chord force at Gridline 2 and 4 (maximum of $F_{2,a}$, $F_{2,d}$, $F_{4,a}$ and $F_{4,d}$) vs. the location of opening for diaphragms with different aspect ratios are illustrated in Figure A-15. It can be seen that for diaphragms with different aspect ratios, when the distance of opening edge from diaphragm edge is 3 times the bigger dimension of the opening the maximum chord forces at Gridline 2 and 4 are close to the maximum chord force at mid-span of the diaphragm without opening.

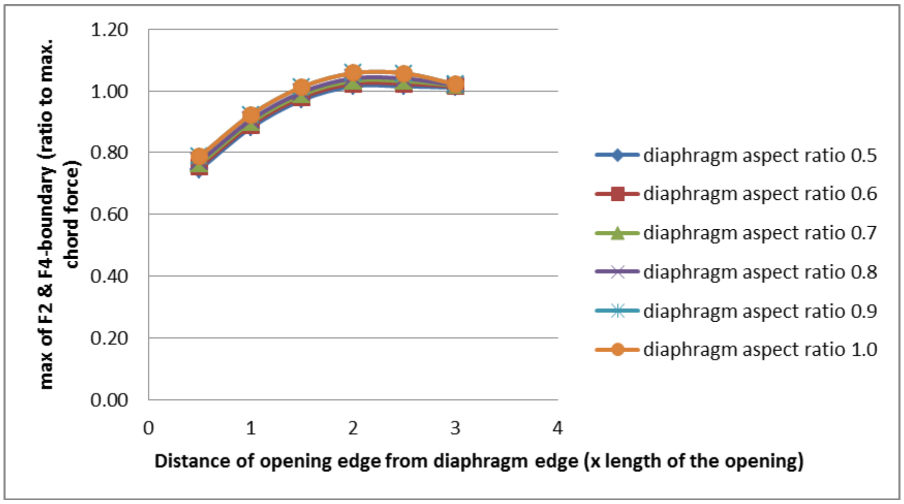


Figure A-15

Conclusion and Discussion

The effects of a single opening size and location on diaphragm shear, chord forces and framing member forces were investigated for a typical wood diaphragm. In conclusion, the maximum shear in the diaphragm with opening is greater than that in the diaphragm without opening. Increasing the distance between the edges of opening and diaphragm can reduce this increase in maximum shear significantly. When the dimension of the opening is no greater than 15% of the corresponding dimension of the diaphragm in both directions, and the distance of opening edge from diaphragm edge is no less than 3 times the larger dimension of the opening and that the portion of diaphragm alongside the opening satisfies the maximum aspect ratio requirement, the increase in maximum shear is less than 10%.

Meanwhile the maximum chord force at the Gridlines that define the opening increases with increasing size of the opening but is more sensitive to the dimension of the opening perpendicular to load. When the dimension of the opening is no greater than 15% of the corresponding dimension of the diaphragm in both directions the maximum chord forces at Gridline 2 & 4 are less than or close to the maximum chord force at mid-span of the diaphragm without opening. Note that these forces increase with increasing distance between the edges of the opening and diaphragm.

The maximum forces in the parallel and perpendicular to load framing members bordering the opening increase with increasing depth and length of the opening. The forces in the framing members parallel to load are more sensitive to the dimension of the opening parallel to load. It was also observed that when the opening is moved away from the edge of the diaphragm, the forces in the framing members bordering the opening decrease significantly. When the dimension of the opening is no greater than 15% of the corresponding dimension of the diaphragm in both directions, the maximum force in the framing members is less than 50% of the maximum chord force at mid-span of the diaphragm without opening, when the distance of opening edge from diaphragm edge is no less than 3 times the larger dimension of the opening. Tension connections are required at the corners of the opening to prevent it from pulling apart.

Bulletpoints of significant findings:

1. Maximum diaphragm shear increases with the introduction of openings. This increase could be reduced significantly when increasing the distance between the edges of the opening and diaphragm.
2. Tension forces develop at the corners of openings, and ties/straps are necessary to distribute this force into the diaphragm.
3. It is strongly recommended that analysis for a diaphragm with an opening should be carried out except where <u>all four</u> of the following items are satisfied:
    a. Depth no greater than 15% of diaphragm depth;
    b. Length no greater than 15% of diaphragm length;
    c. Distance from diaphragm edge to the nearest opening edge is a minimum of 3 times the larger opening dimension;
    d. The diaphragm portion between opening and diaphragm edge satisfies the maximum aspect ratio requirement.

If these criteria are fulfilled, no analysis is required; however, the maximum diaphragm design shear should be increased by 10% compared with the nominal maximum shear, as defined in the following:

$$v_{norm} = \max(v_1, v_2, v_4)$$

$$v_1 = \frac{wL}{2L_D}$$

$$v_2 = \frac{V_2}{(L_D - D_{OPN})}$$

$$v_4 = \frac{V_4}{(L_D - D_{OPN})}$$

Design example: Designing for openings in wood diaphragm