The Analysis of Irregular Shaped Diaphragms

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Several decades ago, the residential and commercial buildings being designed tended to be straightforward, redundant structures with simply laid out lateral resisting systems. These structures had a minimum number of horizontal and vertical offsets. In contrast, the structural configurations of many modern buildings require complex lateral load paths that incorporate diaphragms at different elevations, multiple re-entrant corners, multiple irregularities and fewer vertical lateral force-resisting elements. It is important to address these design issues and irregularities to ensure complete load paths throughout the structure; however, this doesn't have to be a daunting task.

Knowledge regarding the analysis of complex diaphragm layouts varies greatly within engineering and code enforcement communities. In some cases, it has become standard practice to treat all structures as if they were simple rectangular diaphragms, and the absence of continuous load paths, presence of discontinuities, and missing elements such as chords, collectors and drag struts are commonly overlooked. This is largely due to the lack of concise information on how to design complex diaphragms. While most relevant books and publications provide comprehensive coverage of simple rectangular diaphragms, there is very little guidance on how to analyze and design complex layouts. Further, methods of analysis for simpler diaphragms do not easily adapt to the complex layouts in irregularly shaped structures. The purpose of this paper is to bridge that information gap by providing an overview of a method, based on simple statics, which can be used to analyze complex diaphragm structures, while guiding readers to more detailed information through the references.

Principles of Effective Diaphragm Design

Diaphragms, drag struts, collectors and shear walls function the same way regardless of whether the loads applied to the diaphragm are from wind, seismic, soil or other sources. Principles of engineered design require that complete load paths with adequate strength and stiffness be provided to transfer all forces from the point of origin to the final point of resistance. The *2012 International Building Code* (IBC) [1] describes this design principle in Section 1604.4, stating:


Marselle Condominiums
Five stories of wood construction plus a wood-frame mezzanine over six levels of concrete, two of which are above ground.
STRUCTURAL ENGINEER: Yu & Trochalakis, PLLC

Matt Todd Photography
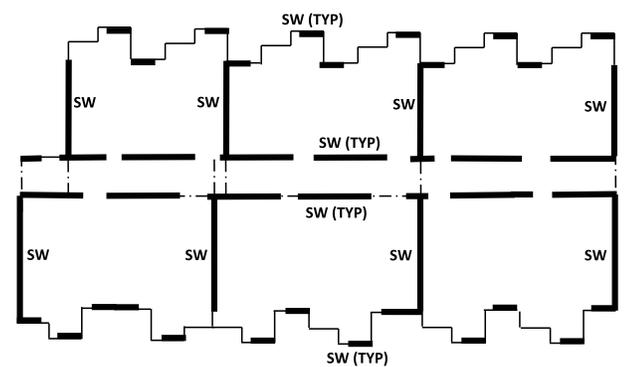
Typical plan with horizontal offsets in the diaphragm chords and struts

"Any system or method of construction to be used shall be based on a rational analysis in accordance with well-established principles of mechanics. Such analysis shall result in a system that provides a complete load path capable of transferring loads from their point of origin to the load resisting elements."

For simple and complex buildings, the load path for lateral loads typically includes:

- Development of the seismic or wind loads in the roof or floor diaphragms

- Transfer of loads acting on the diaphragms to diaphragm boundary members and internal collectors

- Collection of loads along the length of boundary members to the shear walls

- Transfer of forces within the diaphragm across areas of discontinuity

- Transfer of loads through shear walls to the resisting elements

- Resistance of loads at foundation to soil interface

Integral parts of the load path for even simple rectangular buildings are chord elements which resist the bending or moment action within a diaphragm, and struts and collectors which collect and transfer the diaphragm shears to the shear walls or frames as shown in Figure 1. All edges of diaphragms must have boundary members consisting of drag struts, chords, collectors or vertical lateral force-resisting elements. Boundary members include chords and drag struts at diaphragms and shear wall perimeters, interior openings, discontinuities and re-entrant corners. Collector elements must be capable of transferring the seismic or wind forces originating in other portions of the structure to the elements providing resistance to those forces.

Two key definitions relative to establishing complete load paths and the analysis and design of complex diaphragms and shear walls are:

- *Diaphragm boundary*: In light-frame construction, a location where shear is transferred into or out of the diaphragm sheathing. Transfer is to either a boundary element or to another force-resisting element.

- *Drag strut; collector*: A diaphragm or shear wall element parallel and in line with the applied load that collects and transfers diaphragm shear forces to the vertical elements of the lateral force-resisting system and/or distributes forces within the diaphragm.

All of these components of the load path, including connections, help to ensure effective performance during a significant wind or seismic loading event.

For the purpose of clarification on the use within this paper, drag struts and collectors function in the same manner and are therefore the same thing, collector elements. It is the author's preference to designate a collector element that receives shears from one side as a "drag strut." A collector element that receives shears from both sides is designated as a "collector."

FIGURE 1
Simple Rectangular Diaphragms
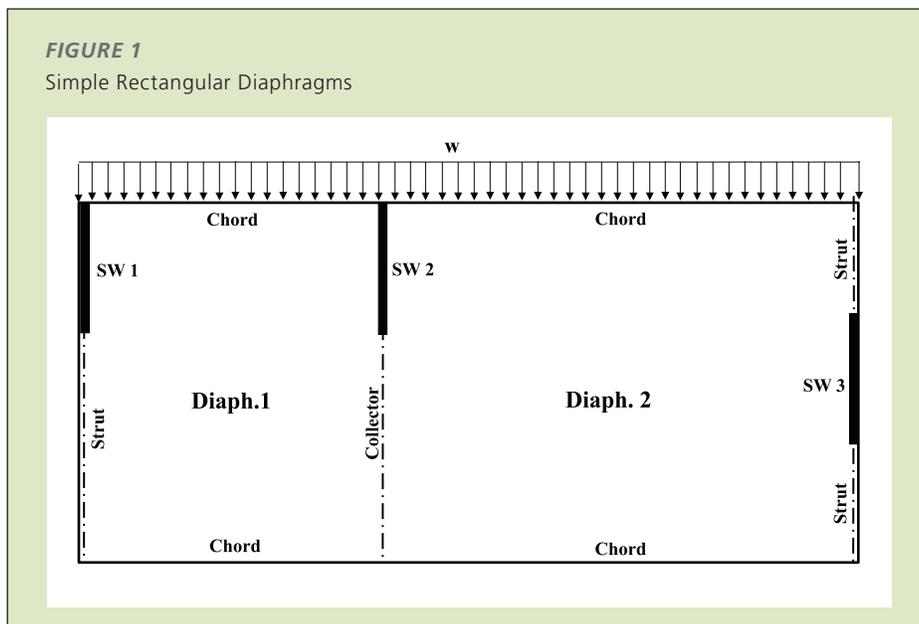
Discontinuities and Irregularities

Discontinuities in diaphragms are often created when a portion of an exterior wall line is offset from the main wall line, causing a disruption in the diaphragm chord or strut. When this occurs, the disrupted chord or strut force must be transferred across the discontinuity through an alternate load path. It is important to remember that, at diaphragm discontinuities such as offsets, openings or re-entrant corners, the design must assure that the dissipation or transfer of edge (chord) forces combined with other forces in the diaphragm is within the shear and tension capacity of the diaphragm. All irregularities and/or discontinuities within a system of diaphragms and shear walls must be addressed. The term "combined with other forces" is frequently misunderstood. The main diaphragm is already under shear force from the applied loads. Additional shear force is applied at the transfer area from the discontinuous member force. These shears must be combined with the basic diaphragm shear to be in compliance with code.

FIGURE 2
Typical Commercial Type
Diaphragm Discontinuities
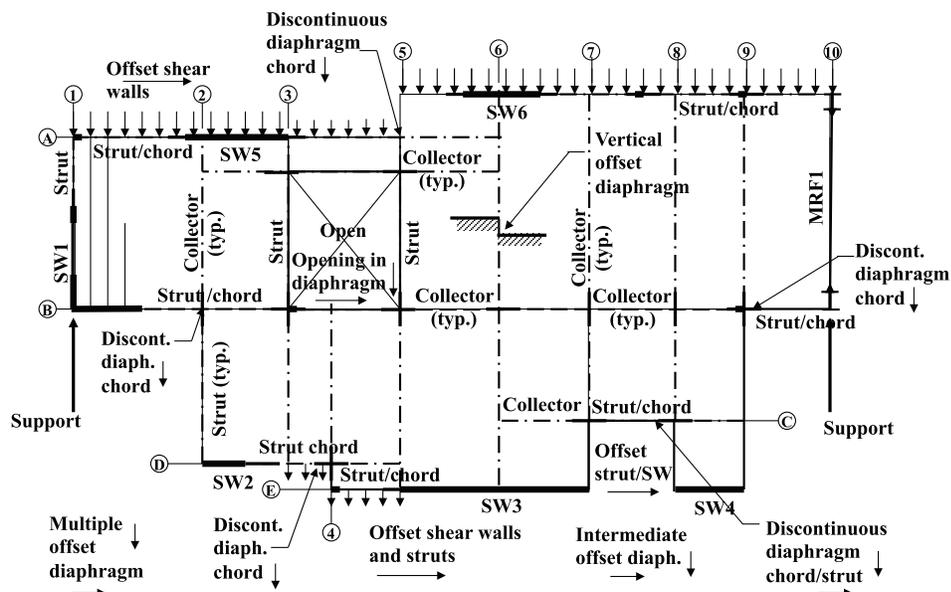
- **ASCE 7-10 section 12.10.1 – At diaphragm discontinuities such as openings and re-entrant corners, the design shall assure that the dissipation or transfer of edge (chord) forces <u>combined</u> with other forces in the diaphragm is within shear and tension capacity of the diaphragm.**

The example diaphragm shown in Figure 2 contains many discontinuities and irregularities commonly seen in modern designs. When highly irregular diaphragms are viewed as a whole, a rational design of the lateral force-resisting paths may seem daunting; however, when approached one section at a time, keeping in mind the statics approach outlined below, a robust design can be developed.

Method of Analysis

For practical purposes and ease of demonstrating the method, the simple diaphragm shown in Figure 3 will be reviewed. For those same reasons, the orientation of the main framing members must also be ignored. Diaphragm dimensions and loading are provided in the figure along with a complete set of calculations at the end of this paper so the reader can follow along. The diaphragm shown has a single horizontal (end) offset at the left support. The offset causes a discontinuity in the diaphragm chord.

In order to successfully transfer forces through areas of discontinuity, it is important to understand how shears are distributed into and out of a diaphragm. The discontinuous chord shown at grid line B/2 is typically extended into the main

body of the diaphragm with the use of a continuous light-gauge steel strap and flat blocking between the framing members. The intent is to overlap and transfer the disrupted chord force into the main chord at grid line C. The strap is lapped onto the discontinuous chord, and is then applied over the sheathing and blocking within the main diaphragm. The distance the strap is extended into the diaphragm will depend on the results of the calculations (discussed below), practicality and engineering judgment.

When the chord along line C is under tension, the transfer area lying between grid lines B/2 and C/3, shown as a dashed rectangle in Figure 3, could rotate if there is no means to resolve the rotational movement from the chord forces. Framing members at grid lines 2 and 3 can be designed to oppose the rotating couple forces. Local over-stressing and deformation in this area of the diaphragm can occur if resolution of the rotational forces is omitted. The free-body diagram at the right of the figure illustrates a simple method that not only eliminates rotational problems but also provides a complete load path that complies with code requirements.

Briefly, the method utilizes a portion of the diaphragm to the right of the discontinuity as a sub-diaphragm, or transfer diaphragm (TD), which receives the disrupted chord force and

FIGURE 3
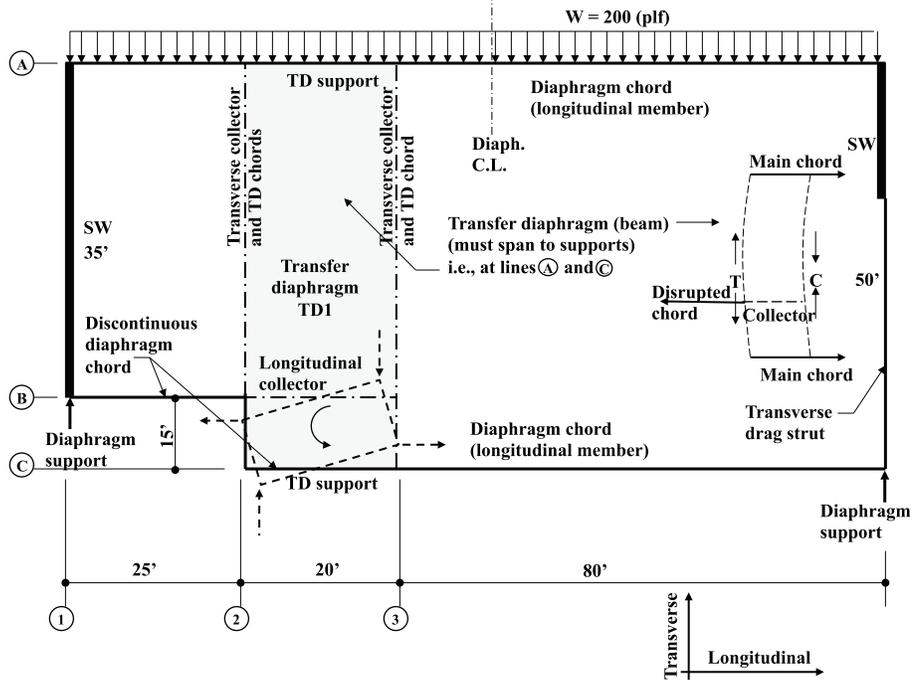
FIGURE 4
Basic Procedure
Method by Edward F. Diekmann
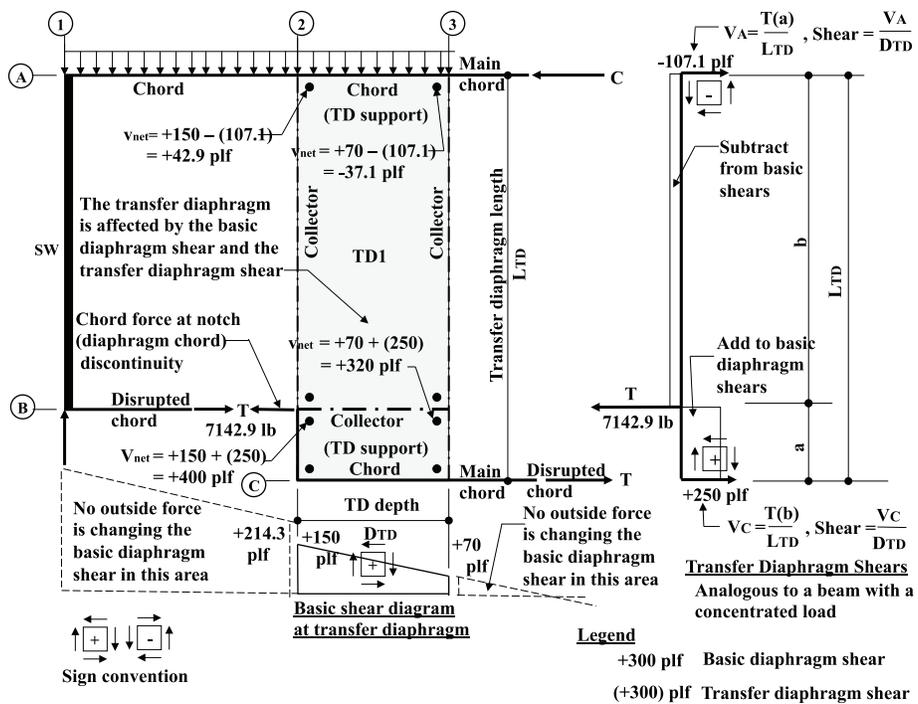
distributes it out to the main diaphragm chords at grid lines A and C by beam action. The transfer diaphragm acts like a beam with a concentrated load applied as depicted by the inset diagram. This method of analyzing diaphragms with offsets and openings was developed in the 1980s.[2]

Figure 4 provides an overview of the method of analysis. Typical symbols for 1 foot x 1 foot pieces of sheathing called "sheathing element symbols" are shown on the lower left. The directions of the shears applied at each edge of the elements indicate whether the shears are positive or negative. The basic shear diagram, expressed in pounds per linear foot (plf), is plotted below the diaphragm. The diaphragm unit shears (plf) at grid lines 1, 2 and 3 are determined and designated as positive or negative by placing the appropriate sheathing element symbols on the basic shear diagram as shown in the figure.

The main diaphragm and transfer diaphragm area are already under shear from the uniform load, as calculated in the basic shear diagram. Additional transfer diaphragm shears are created by the disrupted chord force. The transfer diaphragm shears must be added to or subtracted from the basic diaphragm shears to accurately account for the combined localized effects within the transfer diaphragm, resulting in net shears occurring within the transfer diaphragm area. This is what is intended by the ASCE 7[2] requirement of "combined with other forces." The transfer diaphragm is the only area affected by combined shears. The unit shears in the areas outside the transfer diaphragm remain unchanged.

The transfer diaphragm shears are determined by analyzing the transfer diaphragm as a simple span beam with a concentrated load. Since the disrupted chord force acts to the left, the reactions of the analogous beam will act to the right as shown on the right side of the figure. The unit shears in the transfer diaphragm caused by the disrupted chord force are equal to the calculated reactions divided by the depth of the transfer diaphragm (DTD). The key in determining if the shears in the transfer diaphragm are positive or negative is to understand that the unit shears just determined and the direction of the arrows are acting on the edge of the sheathing element and not on the outer diaphragm chords. Placing the sheathing element symbols next to the unit shears at the transfer diaphragm reaction area and completing the direction of the shears acting on the other edges of the sheathing element symbol will determine whether the shears are positive or negative.

The final transfer diaphragm shears are determined by adding or subtracting the transfer diaphragm shears from the basic diaphragm shears. The calculated basic diaphragm unit shear just to the right of grid line 2 is equal to +150 plf, the transfer diaphragm unit shear above the collector located at grid line B is equal to -107.1 plf, and the transfer diaphragm unit shear below the collector is equal to +250 plf. The net shears in the transfer diaphragm to the right of grid line 2 then become:

Below the collector at grid line 2, from B to C

$v2 = +150 + (250) = +400$ plf

Above the collector at grid line 2, from A to B

$v2 = +150 - (107.1) = -42.9$ plf

Herrington Recovery Center

Designed to blend with its lakefront setting, the 21,000-square-foot treatment facility has a complex diaphragm with vertical and horizontal offsets.

STRUCTURAL ENGINEER:
Pujara Wirth Torke, Inc.

Photo: Curtis Walz

FIGURE 5
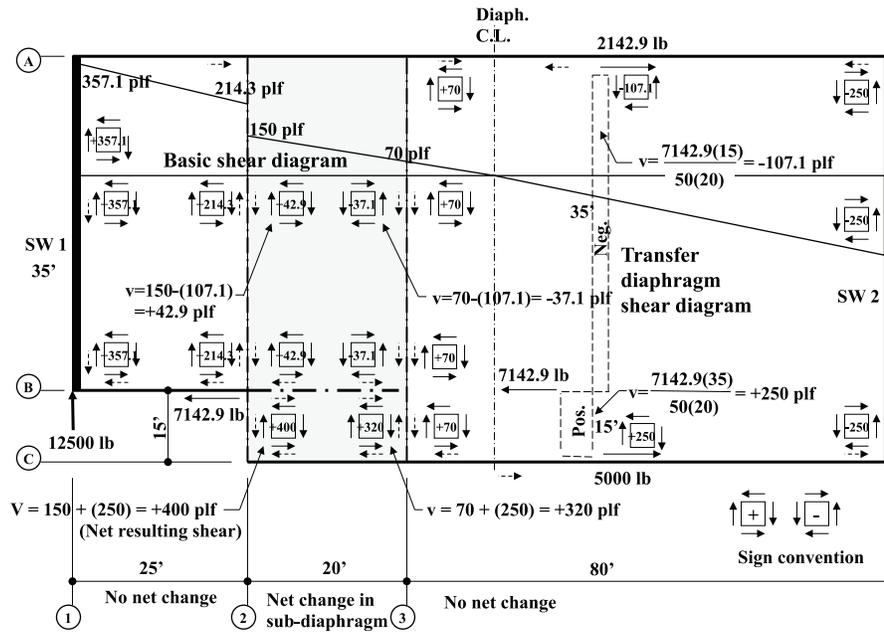
Figure 5
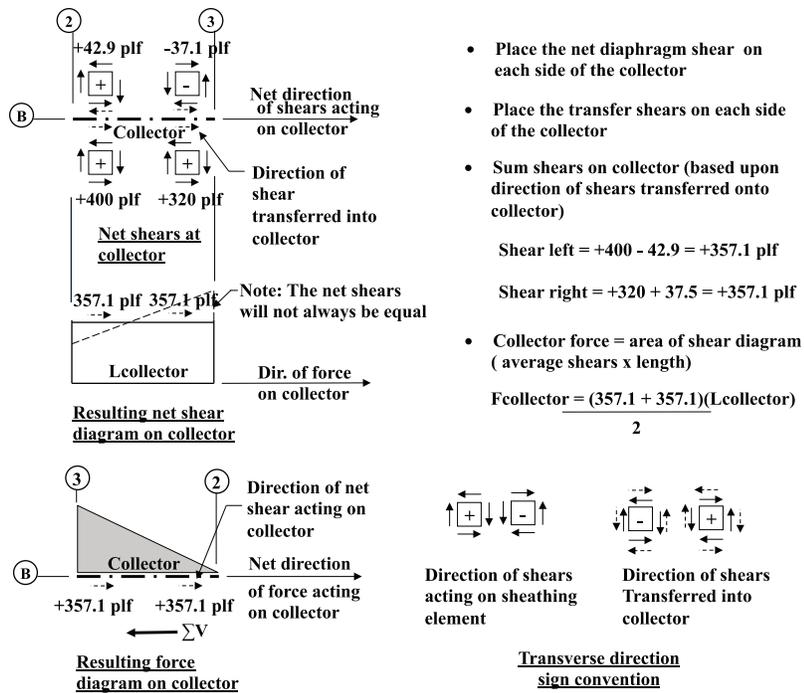
FIGURE 6

Figure 6

The process is repeated at the left side of grid line 3. Once all of the net transfer diaphragm shears are determined, the sheathing element symbols and their magnitude are placed on the plan for visual reference, as shown in Figure 5. It is important to remember that the shears shown at each edge of the sheathing elements are acting on the sheathing. The shears that are transferred into the collectors and chords from the sheathing elements are of the same magnitude but act in the opposite direction, as designated by the dashed line arrows. The transfer shears, shown by dashed lines, should also be placed on the plan. All chord, strut and collector forces can now be determined.

Observing the collector at grid line B from 2 to 3, it can be seen that the collector receives shears from both sides, which must once again be combined to produce a net shear acting along the collector. If the transfer shears acting on each side of the collector are acting in the same direction, they must be added together. If the transfer shears are acting in opposite directions, they must be subtracted. The procedure for determining the chord, strut or collector force is summarized in Figure 6.

Finally, the force on the collector is equal to the average net shears acting on the collector times its length, or in other words, the area of the shear diagram. All of the force diagrams for the chords, collectors and struts should be calculated and drawn on the plan. This is recommended as a check to confirm that the overall analysis is correct. If any of the force diagrams do not close to zero, then an error exists and the analysis must be adjusted.

Summary of Procedure

1. Solve for the diaphragm reactions.

2. Construct the basic shear diagram (unit shears - plf or klf).

3. Find the shear values at critical locations on the basic shear diagram (at all collector locations and areas of discontinuities).

4. Find the chord force at the discontinuity (offset at 2B).

5. Determine the additional shear applied to the transfer diaphragm from the transfer of the disrupted chord force (transfer diaphragm shears).

6. Determine the net diaphragm shears in the transfer diaphragm area by adding or subtracting the transfer diaphragm shears from the basic diaphragm shears. See Table 1.

7. Place all of the sheathing elements and the direction of the shears being transferred into all of the chords, struts and collectors on the plan.

8. Determine ALL of the strut, collector and chord forces. The force is equal to the area of the shear diagram. Sum the forces along the length of the collectors or line of lateral-force-resistance. The force diagrams must close to zero or an error exists.

9. Determine the diaphragm nailing requirements.

10. Design all struts, collectors, chords and connections, applying the over-strength factor as required by code.

Complete Example Calculations

Diaphragm reaction and unit shears:

$$R_1 = R_4 = \frac{wL}{2} = \frac{200(125)}{2} = 12{,}500 \text{ lb}$$

$$v_1 = \frac{R_1}{D} = \frac{12{,}500}{35} = +357.1 \text{ plf unit shear}$$

$$V_2 = R_1 - wx = 12500 - 200(25)$$

$$= 7{,}500 \text{ lb shear at grid line 2.}$$

$$v_{2L} = \frac{V_2}{D_{left}} = \frac{7{,}500}{35} = +214.3 \text{ plf (left)}$$

$$v_{2R} = \frac{V_2}{D_{Right}} = \frac{7{,}500}{50} = +150 \text{ plf (right)}$$

$$V_3 = 12{,}500 - 200(45) = 3{,}500 \text{ lb}$$

$$v_3 = \frac{3{,}500}{50} = +70 \text{ plf}$$

$$v_4 = \frac{-12{,}500}{50} = -250 \text{ plf}$$

The chord force at grid line B/2

$$M_{B2} = R_1x - \frac{wx^2}{2}$$

$$= 12,500(25) - \frac{200(25)^2}{2}$$

$$= 250,000 \text{ ft} - \text{lb}$$

$$F_{B2} = \frac{M_{B2}}{D} = \frac{250,000}{35} = 7142.9 \text{ lb}$$

Determination of transfer diaphragm shears

$$V_A = \frac{7,142.9(15)}{50} = 2,142.9 \text{ lb at line A}$$

$$V_A = \frac{V_A}{D_{TD}} = \frac{2,142.9}{20} = -107.1 \text{ plf unit shear in the transfer diaphragm at line A based on sheathing element symbol}$$

$$V_C = \frac{7142.9(35)}{50} = 5,000 \text{ lb}$$

$$V_C = \frac{5,000}{20} = +250 \text{ plf}$$

Determination net transfer diaphragm shears

TABLE 1 • Net transfer diaphragm shears

Location (grid line)	Net Shear
1 from A to B	v = +357.1 plf
2 from A to B (left)	v = +214.3 plf
2 from A to B (right)	v = +150 − (107.1) = +42.9 plf
2 from B to C (right)	v = +150 + (250) = +400 plf
3 from A to B (left)	v = +70 − (107.1) =-37.1 plf
3 from B to C (left)	v = +70 + (250) = +320 plf
3 from A to C (right)	v = +70 plf

Determine the chord/collector forces

(see sample calculation, Figure 6)

The chord force to the right of grid line B/2 is equal to:

$$V_A = \frac{(400\text{-}42.9)+(320+37.1)}{2}(20)$$

$$= 7,142 \text{ lb tension}$$

This is equal to the disrupted chord force; therefore, the force diagram closes to zero. All of the forces acting on the remaining chords, struts and collectors should be calculated in a similar manner.

Conclusion

The method outlined in this paper can be used to solve most of the complex diaphragm layouts experienced today. The example addressed discontinuous diaphragm chords; however, this method can also be used for resolving discontinuous struts and collectors, complex shear walls, offset shear walls and vertical offsets in the diaphragm. Today's complex structures require careful attention to how the loads are distributed through the structure, how these forces are transferred across discontinuities, and the details necessary to allow the transfer of those forces. Most of the problems and challenges presented by these structures can be resolved by using simple statics.

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Based on: *The Analysis of Irregular Shaped Structures:*
Diaphragms and Shear Walls [4]

References

[1] *International Building Code, 2012,* International Code Council

[2] Diekmann, E.F., *Design of Wood Diaphragms*, Journal of Materials Education, 8:1-2, 1986, Fourth Clark C. Heritage Memorial Workshop, Wood Engineering Design Concepts, University of Wisconsin

[3] ASCE 7-10, American Society of Civil Engineers

[4] Malone, R.T., Rice, R.W., *The Analysis of Irregular Shaped Structures: Diaphragms and Shear Walls*, McGraw-Hill and International Code Council publishers, 2012