

4.5 Procedures for Diaphragms

This section provides Tier 2 evaluation procedures that apply to diaphragms: general, wood, metal deck, concrete, precast concrete, horizontal bracing, and other diaphragms.

Commentary:

Diaphragms are horizontal elements that distribute seismic forces to vertical lateral force resisting elements. They also provide lateral support for walls and parapets. Diaphragm forces are derived from the self weight of the diaphragm and the weight of the elements and components that depend on the diaphragm for lateral support. Any roof, floor, or ceiling can participate in the distribution of lateral forces to vertical elements up to the limit of its strength. The degree to which it participates depends on relative stiffness and on connections. In order to function as a diaphragm, horizontal elements must be interconnected to transfer shear, with connections that have some degree of stiffness. An array of loose elements such as ceiling tiles, or metal-deck panels attached to beams with wind clips does not qualify.

4.5.1 General

Commentary:

It is customary to analyze diaphragms using a beam analogy. The floor, which is analogous to the web of a wide-flange beam, is assumed to carry the shear. The edge of the floor, which could be a spandrel or wall, is analogous to the flange, and is assumed to carry the flexural stress. A free-body diagram of these elements is shown in Figure 4-27. The diaphragm chord can be a line of edge beams that is connected to the floor, or reinforcing in the edge of a slab or in a spandrel. Examples of chords are shown in Figure 4-28.

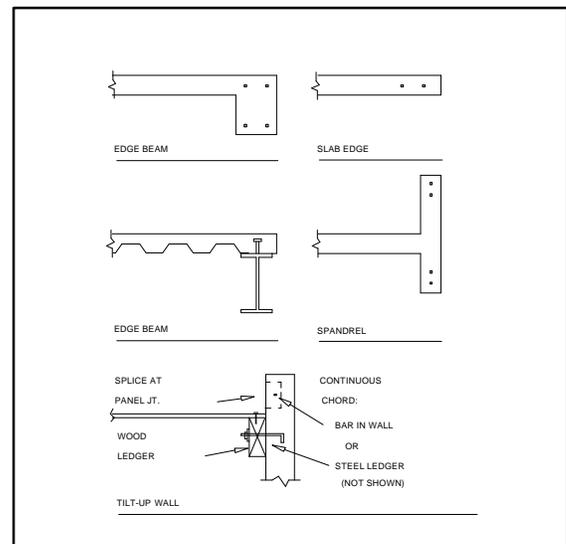
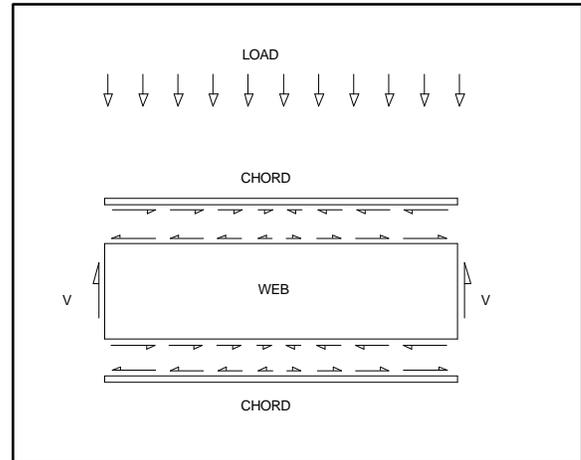


Figure 4-27. Diaphragm as a Beam

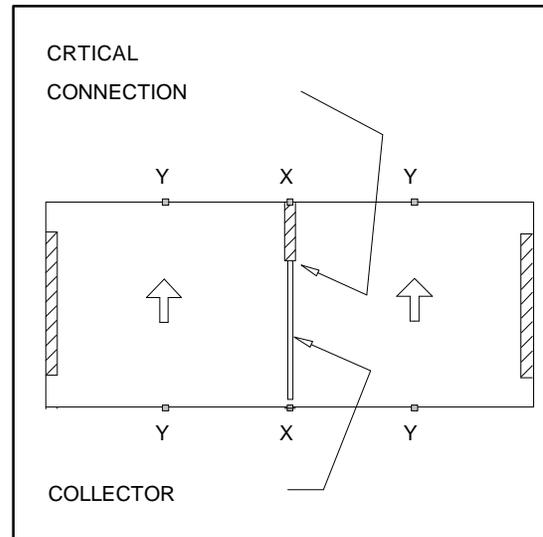
Figure 4-28. Chord Sections

Two essential requirements for the chord are continuity and connection with the slab. Almost any building with an edge beam has a potential diaphragm chord. Even if designed for vertical loads only, the beam end connections probably have some capacity to develop horizontal forces through the column.

The force in the chord is customarily determined by dividing the moment in the diaphragm by the depth of the diaphragm. This yields an upper bound on the chord force since it assumes elastic beam

behavior in the diaphragm and neglects bending resistance provided by any other components of the diaphragm. A lack of diaphragm damage in post-earthquake observations provides some evidence that certain diaphragms may not require specific chords as determined by the beam analogy. For the purpose of this Handbook, the absence of chords is regarded as a deficiency that warrants further evaluation. Consideration may be given to the available evidence regarding the suitability of the beam analogy and the need for defined chords in the building being evaluated.

Consistent with the beam analogy, a stair or skylight opening may weaken the diaphragm just as a web opening for a pipe may weaken a beam. An opening at the edge of a floor may weaken the diaphragm just as a notch in a flange weakens a beam.



4.5.1.1 DIAPHRAGM CONTINUITY: The

An important characteristic of diaphragms is flexibility, or its opposite, rigidity. In seismic design, rigidity means relative rigidity. Of importance is the in-plane rigidity of the diaphragm relative to the walls or frame elements that transmit the lateral forces to the ground (Figure 4-29). A concrete floor is relatively rigid compared to steel moment frames, whereas a metal deck roof is relatively flexible compared to concrete or masonry walls. Wood diaphragms are generally treated as flexible, but consideration must be given to rigidity of the vertical elements. Wood diaphragms may not be flexible compared to wood shear wall panels in a given building.

Another consideration is continuity over intermediate supports. In a three-bay building, for example, the diaphragm has three spans and four supports. If the diaphragm is relatively rigid, the chords should be continuous over the supports like flanges of a continuous beam over intermediate supports. If the diaphragm is flexible, it may be designed as a simple beam spanning between walls without consideration of continuity of the chords. In the latter case, the design professional should remember that the diaphragm is really continuous, and that this continuity is simply being neglected.

Figure 4-29. Rigid and Flexible Diaphragms

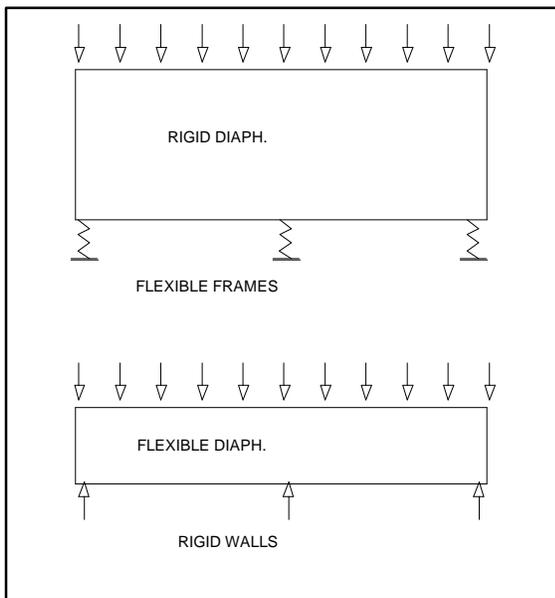


Figure 4-30. Collector

diaphragms shall not be composed of split-level

Figure 4-30 (on previous page) shows a diaphragm of two spans that may or may not be continuous over the intermediate support. If chord continuity is developed at the points marked X, these will be the locations of maximum chord force. If chord continuity is not provided at X, the spans will act as two simple beams. The maximum chord force will occur at the middle of each span, at the points marked Y. The end rotations of the two spans may cause local damage at points X.

Finally, there must be an adequate mechanism for the transfer of diaphragm shear forces to the vertical elements. This topic is addressed in detail in Section 4.6. An important element related to diaphragm force transfer is the collector, or drag strut. In Figure 4-31, a member is added to collect the diaphragm shear and drag it into the short intermediate shear wall. The presence of a collector avoids a concentration of stress in the diaphragm at the short shear wall. Collectors must be continuous across any interrupting elements such as perpendicular beams, and must be adequately connected to the shear wall to deliver forces into the wall.

In buildings of more than one story, the design professional must consider the effect of flexible diaphragms on walls perpendicular to the direction of seismic force under consideration.

floors. In wood buildings, the diaphragms shall not have expansion joints.

Tier 2 Evaluation Procedure: The load path around the discontinuity shall be identified. The diaphragm shall be analyzed for the forces in Section 4.2 and the adequacy of the elements in the load path shall be evaluated.

4.5.1.2 CROSS TIES: There shall be continuous cross ties between diaphragm chords.

Commentary:

Split level floors and roofs, or diaphragms interrupted by expansion joints, create discontinuities in the diaphragm. This condition is common in ramped parking structures. It is a problem unless special details are used, or lateral-force-resisting elements are provided at the vertical offset of the diaphragm or on both sides of the expansion joint. Such a discontinuity may cause the diaphragm to function as a cantilever element or three-sided diaphragm. If the diaphragm is not supported on at least three sides by lateral-force-resisting elements, torsional forces in the diaphragm may cause it to become unstable. In both the cantilever and three-sided cases, increased lateral deflection in the discontinuous diaphragm may cause increased damage to, or collapse of, the supporting elements.

If the load path is incomplete, mitigation with elements or connections required to complete the load path is necessary to achieve the selected performance level.

Tier 2 Evaluation Procedure: Out-of-plane forces in accordance with Section 4.2 shall be calculated. The adequacy of the existing connections, including development of the forces into the diaphragm, shall be evaluated.

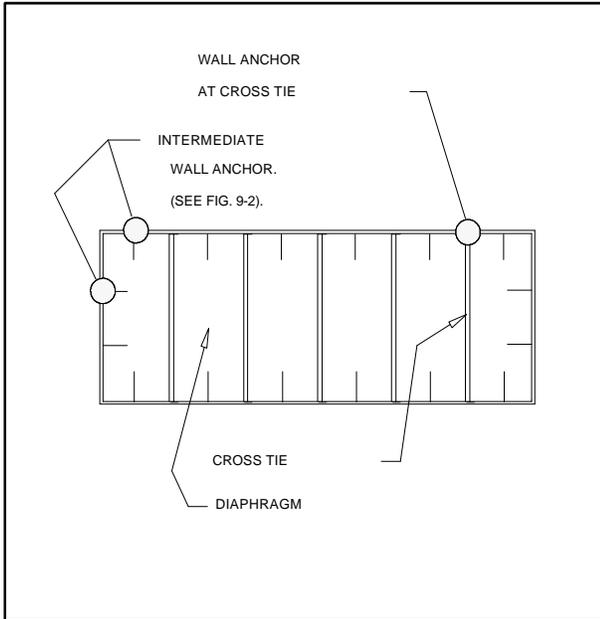
Figure 4-31. Cross Ties

Commentary:

Continuous crossties between diaphragm chords are needed to develop out-of-plane wall forces into the diaphragm (see Figure 4-31). The crossties should have a positive and direct connection to the walls to keep the walls from separating from the building. The connection of the crosstie to the wall, and connections within the crosstie, must be detailed so that cross-grain bending or cross-grain tension does not occur in any wood member (see Section 4.6.1.2).

Sub-diaphragms may be used between continuous cross-ties to reduce the required number of full length cross-ties.

4.5.1.3 ROOF CHORD CONTINUITY: All chord



elements shall be continuous, regardless of changes in roof elevation.

Tier 2 Evaluation Procedure: The load path around the discontinuity shall be identified. The diaphragm shall be analyzed for the forces in Section 4.2 and the adequacy of the elements in the load path shall be evaluated.

Figure 4-32. Roof Chord Continuity

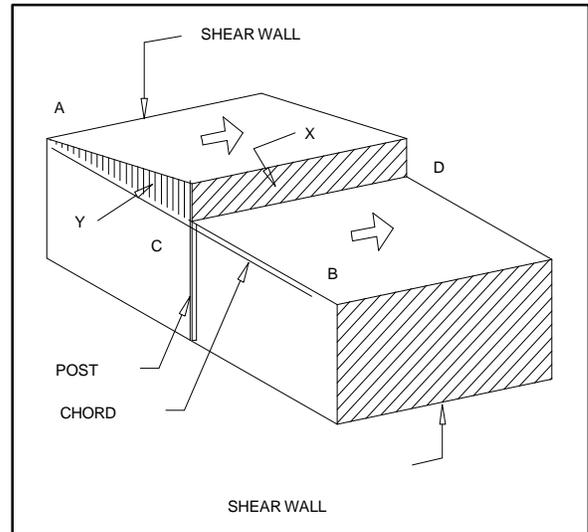
Commentary:

Diaphragms with discontinuous chords will be more flexible and will experience more damage around the perimeter than properly detailed diaphragms. Vertical offsets or elevation changes in a diaphragm often cause a chord discontinuity (see Figure 4-32). To provide continuity the following elements are required: a continuous chord element; plane X to connect the offset portions of the diaphragm; plane Y to develop the sloping diaphragm into the chord; and vertical

supports (posts) to resist overturning forces generated by plane X.

If the load path is incomplete, mitigation with elements or connections required to complete the load path is necessary to achieve the selected performance level.

4.5.1.4 OPENINGS AT SHEAR WALLS:



Diaphragm openings immediately adjacent to the shear walls shall be less than 25% of the wall length for Life Safety and 15% of the wall length for Immediate Occupancy.

Tier 2 Evaluation Procedure: The in-plane shear transfer demand at the wall shall be calculated. The adequacy of the diaphragm to transfer loads to the wall shall be evaluated considering the available length and the presence of any drag struts. The adequacy of the walls to span out-of-plane between points of anchorage shall be evaluated and the adequacy of the diaphragm connections to resist wall out-of-plane forces shall be evaluated.

Figure 4-33. Opening at Exterior Wall

Commentary:

Large openings at shear walls significantly limit the ability of the diaphragm to transfer lateral forces to the wall (see Figure 4-33). This can have a compounding effect if the opening is near one end of the wall and divides the diaphragm into small segments with limited stiffness that are ineffective in transferring shear to the wall. This might have the net effect of a much larger opening. Large openings may also limit the ability of the diaphragm to provide out-of-plane support for the wall.

The presence of drag struts developed into the diaphragm beyond the wall will help mitigate this effect.

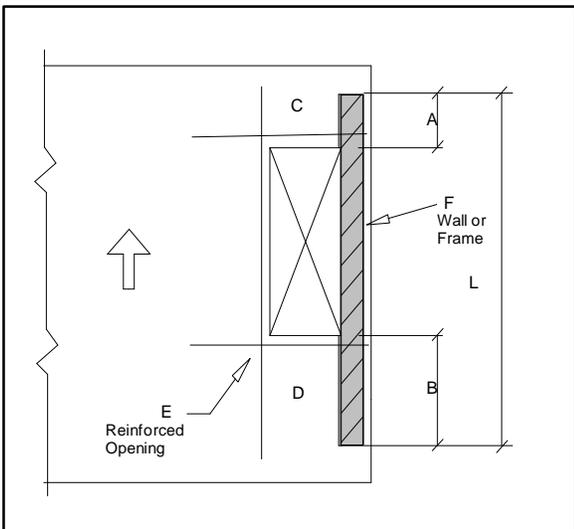
Commentary:

Large openings at braced frames significantly limit the ability of the diaphragm to transfer lateral forces to the frame. This can have a compounding effect if the opening is near one end of the frame and divides the diaphragm into small segments with limited stiffness that are ineffective in transferring shear to the frame. This might have the net effect of a much larger opening.

The presence of drag struts developed into the diaphragm beyond the frame will help mitigate this effect.

not be greater than 8 ft. long for Life Safety and 4 ft. long for Immediate Occupancy.

4.5.1.5 OPENINGS AT BRACED FRAMES:



Diaphragm openings immediately adjacent to the braced frames shall extend less than 25% of the frame length for Life Safety and 15% of the frame length for Immediate Occupancy.

Tier 2 Evaluation Procedure: The in-plane shear transfer demand at the frame shall be calculated. The adequacy of the diaphragm to transfer loads to the frame shall be evaluated considering the available length and the presence of any drag struts.

4.5.1.6 OPENINGS AT EXTERIOR MASONRY SHEAR WALLS: Diaphragm openings immediately adjacent to exterior masonry walls shall

Tier 2 Evaluation Procedure: The in-plane shear transfer demand at the wall shall be calculated. The adequacy of the diaphragm to transfer loads to the wall shall be evaluated considering the available length and the presence of any drag struts. The adequacy of the walls to span out-of-plane between points of anchorage shall be evaluated and the adequacy of the diaphragm connections to resist wall out-of-plane forces shall be evaluated.

Commentary:

Large openings at shear walls significantly limit the ability of the diaphragm to transfer lateral forces to the wall (see Figure 4-33). This can have a compounding effect if the opening is near one end of the wall and divides the diaphragm into small segments with limited stiffness that are ineffective in transferring shear to the wall. This might have the net effect of a much larger opening. Large openings may also limit the ability of the diaphragm to provide out-of-plane support for the wall.

The presence of drag struts developed into the diaphragm beyond the wall will help mitigate this effect.

4.5.1.7 PLAN IRREGULARITIES: There shall be tensile capacity to develop the strength of the diaphragm at re-entrant corners or other locations of plan irregularities. This statement shall apply to the Immediate Occupancy performance level only.

Tier 2 Evaluation Procedure: The chord and collector demands at locations of plan irregularities shall be calculated by analyzing the diaphragm for the forces in Section 4.2. Relative movement of the projecting wings of the structure shall be considered by applying the static base shear assuming each wing moves in the same direction, or each wing moves in opposing directions, whichever is more severe. The adequacy of all elements that can contribute to the tensile capacity at the location of the irregularity shall be evaluated.

Commentary:

Diaphragms with plan irregularities such as extending wings, plan insets, or E-, T-, X-, L-, or C-shaped configurations have re-entrant corners where large tensile and compressive forces can develop (see Figure 4-34). The diaphragm may not have sufficient strength at these re-entrant corners to resist these tensile forces. Local damage may occur (see Figure 4-35).

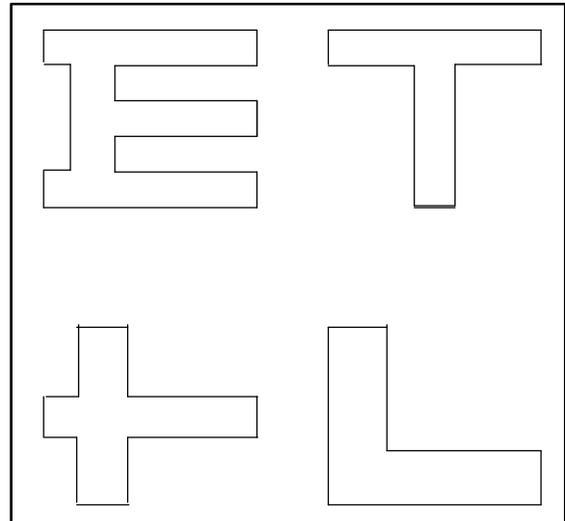


Figure 4-34. Plan Irregularities

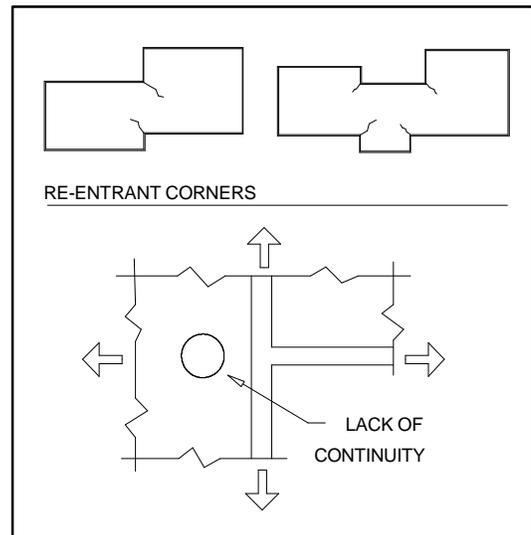


Figure 4-35. Re-entrant Corners

4.5.1.8 DIAPHRAGM REINFORCEMENT AT OPENINGS: There shall be reinforcing around all diaphragms openings larger than 50% of the building width in either major plan dimension This statement shall apply to the Immediate Occupancy performance level only.

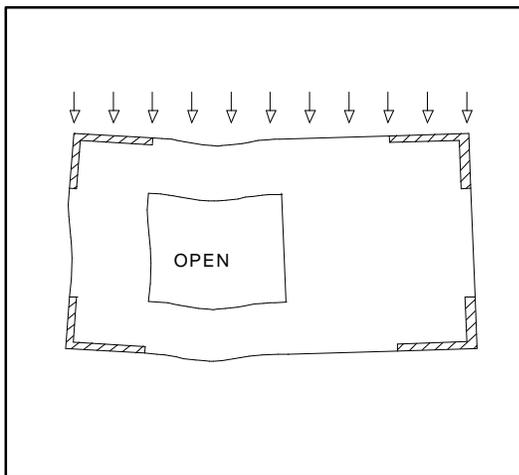
Tier 2 Evaluation Procedure: The diaphragm shall be analyzed for the forces in Section 4.2. The shear and flexural demands at major openings shall be calculated and the resulting chord forces shall be determined. The adequacy of the diaphragm elements to transfer forces around the opening shall be evaluated.

Figure 4-36. Diaphragm Opening

Commentary:

Openings in diaphragms increase shear stresses and induce secondary moments in the diaphragm segments adjacent to the opening. Tension and compression forces are generated along the edges of these segments by the secondary moments, and must be resisted by chord elements in the subdiaphragms around the openings.

Openings that are small relative to the diaphragm dimensions may have only a negligible impact. Openings that are large relative to the diaphragm dimensions can substantially reduce the stiffness of the diaphragm and induce large forces around the openings (see Figure 4-36).



4.5.2 Wood Diaphragms

4.5.2.1 STRAIGHT SHEATHING: All straight sheathed diaphragms shall have aspect ratios less than 2 to 1 for Life Safety and 1 to 1 for Immediate Occupancy in the direction being considered

Tier 2 Evaluation Procedure: An analysis in accordance with Section 4.2 shall be performed. The adequacy of the shear capacity of non-compliant diaphragms shall be evaluated.

Commentary:

Straight-sheathed diaphragms are flexible and weak relative to other types of wood diaphragms. Shear capacity is provided by a force couple between nails in the individual boards of the diaphragm and the supporting framing. Because of the limited strength and stiffness of these diaphragms, they are most suitable in applications with limited demand, such as in regions of low seismicity.

In regions of moderate and high seismicity, the span and aspect ratio of straight-sheathed diaphragms are limited to minimize shear demands. The aspect ratio (span/depth) must be calculated for the direction being considered.

Compliance can be achieved if the diaphragm has adequate capacity for the demands in the building being evaluated.

4.5.2.2 SPANS: All wood diaphragms with spans greater than 24 ft. for Life Safety and 12 ft. for Immediate Occupancy shall consist of wood structural panels or diagonal sheathing. Wood commercial and industrial buildings may have rod-braced systems.

Tier 2 Evaluation Procedure: An analysis in accordance with Section 4.2 shall be performed. The adequacy of the shear capacity of non-compliant diaphragms shall be evaluated. The diaphragm deflection shall be calculated, and the adequacy of the vertical-load carrying elements shall be evaluated at maximum diaphragm deflection, including p-delta effects.

Commentary:

Long span diaphragms will often experience large lateral deflections and diaphragm shear demands. Large deflections in the diaphragm can result in increased damage or collapse of elements laterally supported by the diaphragm. Excessive diaphragm shear demands will cause damage and reduced stiffness in the diaphragm.

Compliance can be demonstrated if the diaphragm and vertical load carrying elements can be shown to have adequate capacity at maximum deflection.

Wood commercial and industrial buildings may have rod-braced systems, in lieu of wood structural panels, and can be considered compliant.

4.5.2.3 UNBLOCKED DIAPHRAGMS: All unblocked wood panel diaphragms shall have horizontal spans less than 40 ft. for Life Safety and 25 ft. for Immediate Occupancy and shall have aspect ratios less than or equal to 4 to 1 for Life Safety and 3 to 1 for Immediate Occupancy.

Tier 2 Evaluation Procedure: An analysis in accordance with Section 4.2 shall be performed. The adequacy of the shear capacity of non-compliant diaphragms shall be evaluated.

Commentary:

Wood structural panel diaphragms may not have blocking below unsupported panel edges. The shear capacity of unblocked diaphragms is less than that of fully blocked diaphragms, due to the limited ability for direct shear transfer at unsupported panel edges. The span and aspect ratio of unblocked diaphragms are limited to minimize shear demands. The aspect ratio (span/depth) must be calculated for the direction being evaluated.

Compliance can be demonstrated if the unblocked diaphragm can be shown to have adequate capacity for the demands in the building being evaluated.

4.5.3 Metal Deck Diaphragms

Commentary:

Bare metal deck can be used as a roof diaphragm when the individual panels are adequately fastened to the supporting framing. The strength of the diaphragm depends on the profile and gage of the deck and the layout and size of the welds or fasteners. Allowable shear capacities for metal deck diaphragms are usually obtained from approved test data and analytical work developed by the industry.

Metal decks used in floors generally have concrete fill. In cases with structural concrete fill, the metal deck is considered to be a concrete form, and the diaphragm is treated as a reinforced concrete diaphragm. In some cases, however, the concrete fill is not structural. It may be a topping slab or an insulating layer that is used to encase conduits or provide a level wearing surface. This type of construction is considered to be an untopped metal deck diaphragm with a capacity determined by the metal deck alone. Non-structural topping, however, is somewhat beneficial and has a stiffening effect on the metal deck.

Metal deck diaphragm behavior is limited by buckling of the deck and by the attachment to the framing. Weld quality can be an issue because welding of light gage material requires special consideration. Care must be taken during construction to ensure the weld has proper fusion to the framing, but did not burn through the deck material.

Concrete-filled metal decks generally make excellent diaphragms and usually are not a problem as long as the basic requirements for

chords, collectors, and reinforcement around openings are met. However, the evaluating engineer should look for conditions that can weaken the diaphragm such as troughs, gutters, and slab depressions that can have the effect of short circuiting the system or of reducing the system to the bare deck.

4.5.3.1 NON-CONCRETE DIAPHRAGMS: Untopped metal deck diaphragms or metal deck diaphragms with fill other than concrete shall consist of horizontal spans of less than 40 ft. and shall have span/depth ratios less than 4 to 1. This statement shall apply to the Immediate Occupancy performance level only.

Tier 2 Evaluation Procedure: Non-compliant diaphragms shall be evaluated for the forces in Section 4.2. The adequacy of the shear capacity of the metal deck diaphragm shall be evaluated.

Commentary:

Untopped metal deck diaphragms have limited strength and stiffness. Long span diaphragms with large aspect ratios will often experience large lateral deflections and high diaphragm shear demands. This is especially true for aspect ratios greater than 4 to 1.

In regions of moderate and high seismicity, the span and aspect ratio of untopped metal deck diaphragms are limited to minimize shear demands. The aspect ratio (span/depth) must be calculated for the direction being considered.

Compliance can be achieved if the diaphragm has adequate capacity for the demands in the building being evaluated.

No evaluation statements or Tier 2 procedures specific to cast-in-place concrete diaphragms are included in this Handbook. Concrete diaphragms shall be evaluated for the general diaphragm evaluation statements and Tier 2 procedures in Section 4.5.1.

4.5.5 Precast Concrete Diaphragms

Commentary:

Concrete slab diaphragm systems have demonstrated good performance in past earthquakes. Building damage is rarely attributed to a failure of the concrete diaphragm itself, but rather failure in related elements in the load path such as collectors or connections between diaphragms and vertical elements. These issues are addressed elsewhere in this Handbook. The design professional should assess concrete diaphragms for general evaluation statements that will address configuration, irregularities, openings and load path. The design professional should also carefully assess pan joist systems and other systems that have thin slabs.

4.5.5.1 TOPPING SLAB: Precast concrete diaphragm elements shall be interconnected by a continuous reinforced concrete topping slab.

Commentary:

Precast concrete diaphragms consist of horizontal precast elements which may or may not have a cast-in-place topping slab. Precast elements may be precast planks laid on top of framing, or precast T-sections which consist of both the framing and the diaphragm surface cast in one piece.

Because of the brittle nature of the connections between precast elements, special attention should be paid to eccentricities, adequacy of welds, and length of embedded bars. If a topping slab is provided, it should be capable of taking all of the shear. Welded steel connections between precast elements, with low rigidity relative to the concrete topping, will not contribute significantly to the strength of the diaphragm when a topping slab is present.

4.5.4 Concrete Diaphragms

Tier 2 Evaluation Procedure: Non-compliant diaphragms shall be evaluated for the forces in Section 4.2. The adequacy of the slab element interconnection shall be evaluated. The adequacy of the shear capacity of the diaphragm shall be evaluated.

4.5.6 Horizontal Bracing

Commentary:

Precast concrete diaphragm elements may be interconnected with welded steel inserts. These connections are susceptible to sudden failure such as weld fracture, pull-out of the embedment, or spalling of the concrete. Precast concrete diaphragms without topping slabs may be susceptible to damage unless they were specifically detailed with connections capable of yielding or of developing the strength of the connected elements.

In precast construction, topping slabs may have been poured between elements without consideration for providing continuity. The topping slab may not be fully effective if it is interrupted at interior walls. The presence of dowels or continuous reinforcement is needed to provide continuity.

When the topping slab is not continuous, an evaluation considering the discontinuity is required to ensure a complete load path for shear transfer, collectors and chords.

No evaluation statements or Tier 2 procedures have been provided for horizontal bracing. Horizontal bracing shall be evaluated for the general diaphragm evaluation statements and Tier 2 procedures in Section 4.5.1.

4.5.7 Other Diaphragms

Commentary:

Horizontal bracing usually is found in industrial buildings. These buildings often have very little mass so that wind considerations govern over seismic considerations. The wind design is probably adequate if the building shows no signs of distress. If bracing is present, the design professional should look for a complete load path with the ability to collect all tributary forces and deliver them to the walls or frames.

4.5.7.1 OTHER DIAPHRAGMS: The diaphragm shall not consist of a system other than those described in Section 4.5.

Tier 2 Evaluation Procedure: Non-compliant diaphragms shall be evaluated for the forces in Section 4.2. The adequacy of the non-compliant diaphragms shall be evaluated using available reference standards for the capacity of diaphragms not covered by this Handbook.

Commentary:

In some codes and standards there are procedures and allowable diaphragm shear capacities for diaphragms not covered by this Handbook. Examples include thin planks and gypsum toppings, but these systems are brittle and have limited strength. As such, they may not be desirable elements in the lateral force resisting system.

The design professional should be watchful for systems that look like diaphragms but may not have the strength, stiffness, or interconnection between elements necessary to perform the intended function.