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Diaphragm Flexibility

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INTRODUCTION

Diaphragms are essential to transfer lateral forces in the plane of the diaphragms to supporting shear walls underneath.

Diaphragms are essential to transfer lateral forces in the plane of the diaphragms to supporting shear walls underneath. As the distribution of lateral force to shear walls is dependent on the relative stiffness/flexibility of diaphragm to the shear walls, it is critical to know the stiffness of both diaphragm and shear walls, so that appropriate lateral force applied on shear walls can be assigned.

In design, diaphragms can be treated as flexible, rigid or semi-rigid. For a diaphragm that is designated as flexible, the in-plane forces can be assumed to be distributed to the shear walls according to the tributary areas associated with each shear wall. For a diaphragm that is designated as rigid, the loads are assumed to be distributed according to the relative stiffness of the shear walls, with consideration of additional shear force due to torsion for seismic design. In reality, diaphragm is neither purely flexible nor completely rigid, and is more realistically to be treated as semi-rigid. In this case, computer analysis using either plate or diagonal strut elements can be used and the load-deflection properties of the diaphragm will result in force distribution somewhere between the flexible and rigid models. However, alternatively envelope approach which takes the highest forces from rigid and flexible assumptions can be used as a conservative estimation in lieu of computer analysis.

According to ASCE 7 (2010), diaphragms constructed of wood structural panels are permitted to be idealized as flexible if any of the following conditions exist:

1. In structures where the vertical elements are steel braced frames, steel and concrete composite braced frames or concrete, masonry, steel, or steel and concrete composite shear walls.
2. In one- and two-family dwellings.
3. In structures of light-frame construction where topping of concrete or similar materials is not placed over wood structural panel diaphragms except for non-structural topping no greater than 38 mm (1-1/2 in.) thick.

Diaphragms not satisfying the above conditions are permitted to be idealized as flexible where the computed maximum in-plane deflection of the diaphragm under lateral load is more than two times the average story drift of adjoining vertical elements of the lateral force resisting system of the associated story under equivalent tributary lateral load, as shown in Fig. 1.

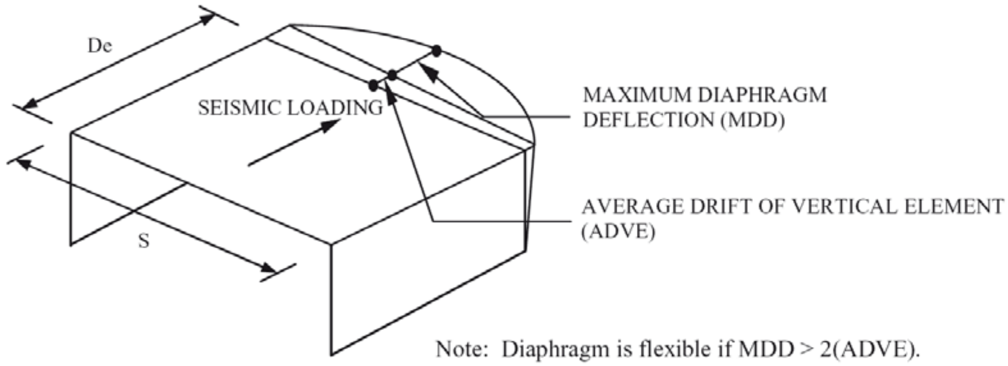

Figure 1 Flexible diaphragm

In accordance with ASCE 41-06, diaphragms shall be classified as rigid where the maximum lateral deformation of the diaphragm is less than half the average story drift of the vertical lateral-force-resisting elements of the associated storey. Diaphragms that are neither flexible nor rigid shall be classified as semi-rigid.

In design, engineer need to use sound engineering judgement regarding whether to use flexible or rigid diaphragm analysis or envelope approach to determine distribution of lateral forces to shear walls.

Deflection of wood diaphragms and supporting lateral force-resisting systems

Formulae for determining the deflections of diaphragms and shear walls are provided in CSA O86 (2009). The deflection at mid-span of a simply supported blocked diaphragm can be determined as follows:

$$\Delta_d = \frac{5vL^2}{96EAL_D} + \frac{vL}{4B_v} + 0.000614Le_n + \frac{\sum(\Delta_c x)}{2L_D}$$

where

v = maximum shear due to specified loads in the direction under consideration, N/mm

E = elastic modulus of the chord member (member at diaphragm boundary), N/mm^2

A = cross-sectional area of the chord member, mm^2

L_D = dimension of diaphragm parallel to direction of load, mm

L = dimension of diaphragm perpendicular to direction of load, mm

B_v = shear through-thickness-rigidity of the sheathing, N/mm (Tables 7.3A, 7.3 B and 7.3C of CSA O86)

e_n = nail deformation, mm (Clause A.9.7 of CSA O86)

$\Sigma(\Delta_c x)$ = sum of the individual chord-splice slip, Δc, on both sides of the diaphragm, each multiplied by its distance x to the nearest support

The derivation of the above equations is provided in ATC 7 (1981). The same method can be used to estimate deflections of diaphragms spanning multiple supports.

The deflection of a single storey blocked wood shear wall can be determined as follows:

$$\Delta_{sw} = \frac{2vH_s^{\,2}}{3EAL_s} + \frac{vH_s}{B_v} + 0.0025H_s e_n + \frac{H_s}{L_s} d_a$$

where

v = maximum shear due to specified loads at the top of the wall, N/mm

H_s = height of shearwall segment, mm

E = elastic modulus of boundary element (vertical member at shearwall segment boundary), N/mm^2

A = cross-sectional area of the boundary member, mm^2

L_s = length of shearwall segment, mm

B_v = shear-through-thickness rigidity of the sheathing, N/mm (Tables 7.3A, 7.3 B and 7.3C of CSA O86)

e_n = nail deformation, mm (Clause A.9.7 of CSA O86)

d_a = total vertical elongation of the wall anchorage system (including fastener slip, device elongation, anchor or rod elongation, etc.) at the induced shear load

The deflection of non-wood lateral force-resisting systems can be determined using the respective material codes.

Diaphragm supported on wood shear walls

For one- and two-family dwellings, diaphragms constructed of wood structural panels with non-structural topping no greater than 38 mm (1-1/2 in.) thick can be idealized as flexible.

For multi-storey wood frame buildings, flexible diaphragm assumptions are traditionally used for determining distribution of storey shears to shear walls. However, the application of the definition of diaphragm flexibility in Fig. 1 often indicates that rigid diaphragm assumption should be used for distribution of storey shears to shear walls. In reality, wood diaphragms likely fall somewhere between the flexible and rigid behaviour, causing the force distribution to shear walls somewhere between rigid and flexible diaphragm solutions. As a good practice guide, it is recommended that envelope approach be used in design for multi-storey wood frame buildings (3-storey or higher).

For a diaphragm which is supported by shear walls on three sides, it can be designated as rigid if the dimensions of the diaphragm meet the following restrictions:

- Depth of the diaphragm normal to the open wall does not exceed 7.5 m.
- Depth-to-width ratio is not greater than 1:1 for one-storey buildings and 1:1.5 for buildings over one-storey in height. However, the depth-to-width ratio may be increased to 2:1 for plywood, waferboard or strandboard diaphragms where calculations show that deflections can be tolerated.

Diaphragm supported on other types of wood lateral force-resisting system (LFRS)

For buildings where diaphragms constructed of wood structural panels are supported on wood-based LFRS other than shearwalls sheathed with wood-based panels, the diaphragm flexibility should be determined based on Figure 1. In cases where it is difficult to estimate relative stiffness of diaphragm and the lateral force-resisting system, it is recommended that envelop approach be used in design.

Diaphragm supported on non-wood lateral force-resisting system

In general, diaphragms constructed of wood structural panels with non-structural topping no greater than 38 mm (1-1/2 in.) thick are permitted to be designated as flexible in buildings where vertical elements of the lateral force-resisting system are concrete, masonry, or composite shear walls. Where wood diaphragms are used in combination with concrete or masonry LFRS, unblocked wood diaphragms should not be used. Where the vertical lateral force-resisting system is steel braced frame, the diaphragm flexibility should be determined based on Figure 1.

Torsional load

In addition to the lateral seismic forces experienced by the structure, lateral forces caused by torsional effects due to eccentricity between the centres of mass and resistance and accidental eccentricities need to be considered. For structures with rigid diaphragms, torsion moments shall be taken into account by using a minimum eccentricity of 10% of the plan dimension of the building perpendicular to the direction of seismic load being considered, in addition to the eccentricity between the centre of mass and the centre of resistance. For structures with flexible diaphragms, accidental torsion should be taken into account by moving the centre of mass by 5% of the plan building dimension perpendicular to the seismic load and using the largest of the seismic loads for the design of each vertical element.

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