Two-Way Joist (Waffle) Slab Design Approach and Methodology

Two-way joist slab often called two-way ribbed slab or waffle slab is an economical floor system when the spans are long and/or loads are high.

Waffle slab analysis and design is similar to the procedure used with flat plates except that special considerations need to be taken into account to reduce the complexity of calculations needed when using exact geometry of the two-way joists.

The following summarizes all the relevant analysis and design provisions in accordance with the Equivalent Frame Method (EFM). Also, included are detailed illustration of the reference provisions in applicable standards.

Rib Dimensions:

The ACI code requires that joist dimensions should be limited to the following:

1) Width of ribs shall be at least 4 in. at any location along the depth.   *ACI 318-14 (9.8.1.2)*

2) Overall depth of ribs shall not exceed 3.5 times the minimum width.   *ACI 318-14 (9.8.1.3)*

3) Clear spacing between ribs shall not exceed 30 in.   *ACI 318-14 (9.8.1.4)*

4) Slab thickness (with removable forms) shall be at least the greater of: *ACI 318-14 (8.8.3.1)*

     a) 1/12 clear distance between ribs

     b) 2 in.
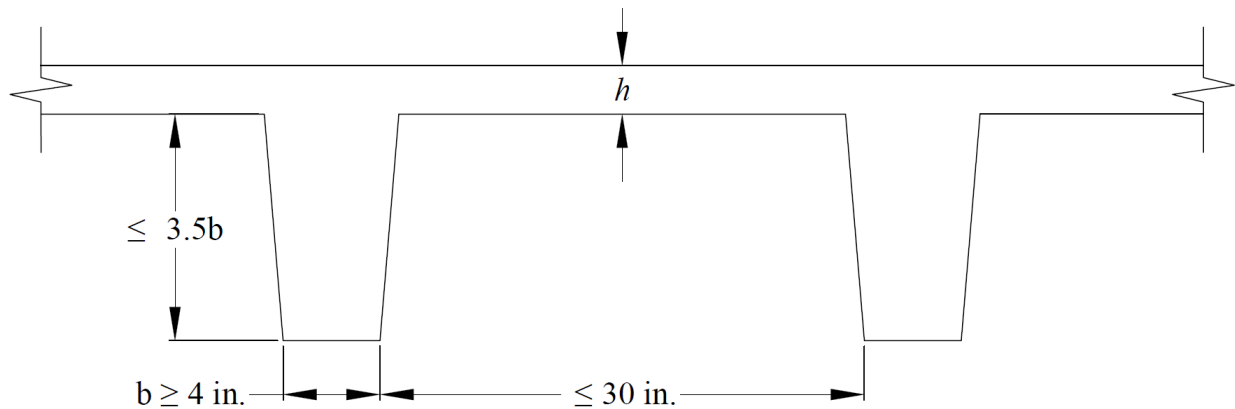
Valid Rib Dimensions

Minimum Thickness:

The minimum slab thickness allowed for joist slabs is one-twelfth the clear rib spacing or 1.5 in. for ACI code.

ACI 318-14 (8.8.2.1.1)

Drop Panels (Drop Heads):

In waffle slabs a drop panel is automatically invoked to guarantee adequate two-way (punching) shear resistance at column supports. The drop panel dimensions are limited by the ACI code as follows:

1) The drop panel shall project below the slab at least one-fourth of the adjacent slab thickness.

ACI 318-14 (8.2.4(a))

Drop panel depth is also controlled by the rib depth (the soffit of both at the same plane).

The total thickness includes the actual slab plus the drop panel thickness

2) The drop panel shall extend in each direction from the centerline of support a distance not less than one-sixth the span length measured from center-to-center of supports in that direction.

ACI 318-14 (8.2.4(b))

Equivalent Solid Slab Thicknesses:

For the purposes of analysis and design, the ribbed slab can be replaced with a solid slab of equivalent moment of inertia, weight, punching shear capacity, and one-way shear capacity.

The equivalent thickness based on moment of inertia is used to find slab stiffness considering the ribs in the direction of the analysis only. The ribs spanning in the transverse direction are not considered in the stiffness computations. This thickness is given by:

$$h_{MI} = \left(\frac{12 \times I_{rib}}{b_{rib}} \right)^{1/3}$$

spSlab Software Manual (Eq. 2-11)

where:

I_{rib} = Moment of inertia of one joist section between centerlines of ribs.

b_{rib} = The center-to-center distance of two ribs (clear rib spacing plus rib width).

Find system self-weight using the equivalent thickness based on the weight of individual components (see the following figure). This thickness is given by:
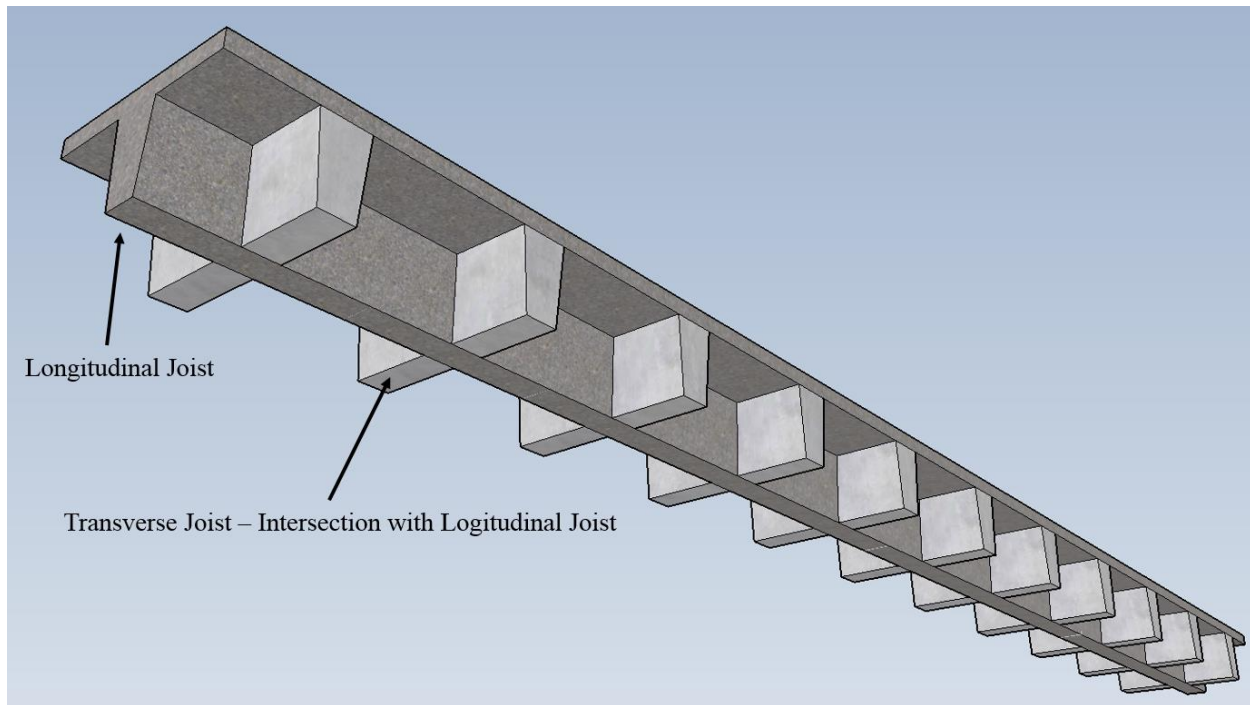
$$h_w = \frac{V_{mod}}{A_{mod}}$$

spSlab Software Manual (Eq. 2-10)

where:

V_{mod} = The volume of one joist module.

$V_{mod} = V_{\text{Longitudinal Joist}} + V_{\text{Transverse Joists}} - V_{\text{Intersection between Joists}}$

A_{mod} = The plan area of one joist module.

Equivalent Thickness Based on the Weight of Individual Components

One-Way (Beam Action) and Two-Way (Punching) Shear Considerations:

For two way joist slab, it is necessary to check shear at multiple sections as defined in the **_ACI 318-14_**. The critical sections shall be located with respect to:

      1) Edges or corners of columns.   **_ACI 318-14 (22.6.4.1(a))_**

      2) Changes in slab thickness, such as edges of drop panels.   **_ACI 318-14 (22.6.4.1(b))_**

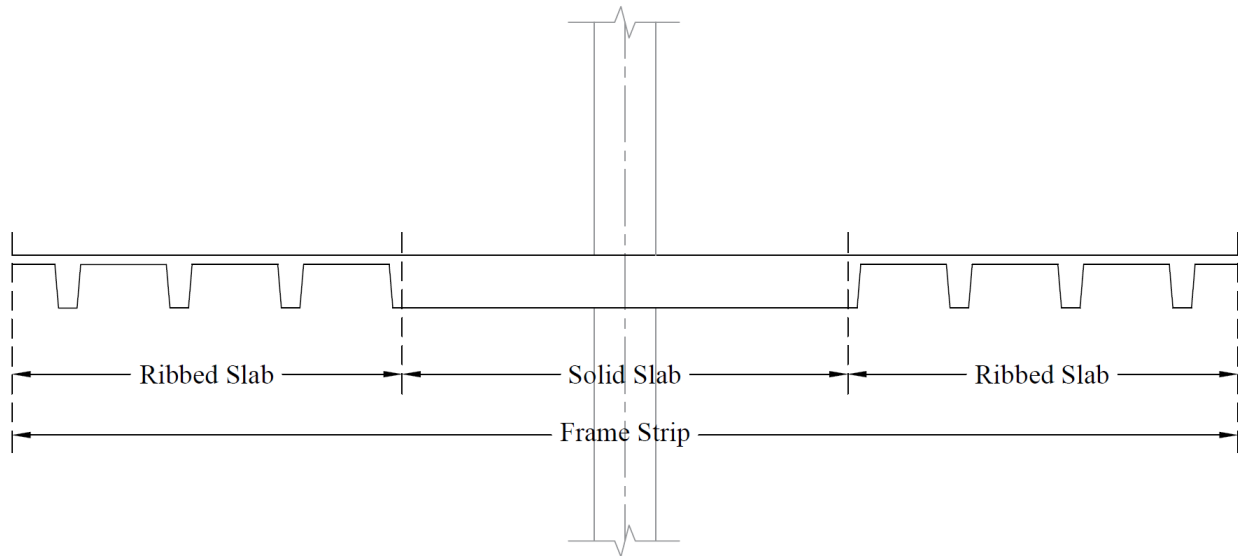One-way shear check at distance d from the supporting column:

One way shear capacity is calculated assuming the shear cross section area consisting of ribs and the portion of slab above, decreased by the concrete cover. And the equivalent shear width of single rib is calculated as follows:

$$b_v = b + \frac{d}{12}$$

Where:

b = rib width.

d = distance from extreme compression fiber to tension reinforcement centroid.
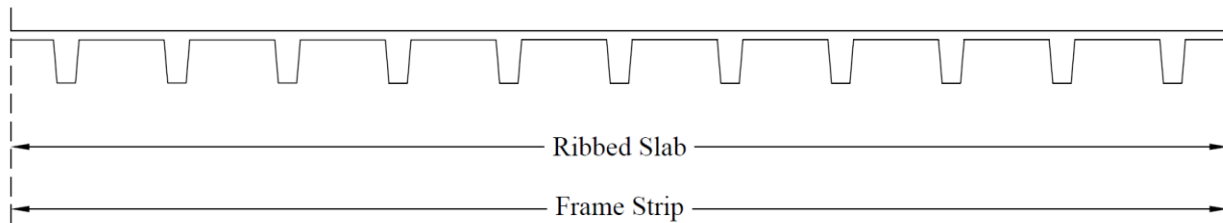
Frame strip cross section (at distance *d* from the face of the supporting column)

The one-way shear capacity for the ribbed slab portions shown is permitted to be increased by 10%.

ACI 318-14 (9.8.1.5)

$$\varphi V_c = \left(\varphi V_c\right)_{\text{Solid Slab}} + 1.10 \ \left(\varphi V_c\right)_{\text{Ribbed Slab}}$$

One-way shear check at the face of drop panel:

Frame strip cross section (at distance *d* from the face of the supporting column)

The one-way shear capacity for the ribbed slab portions shown is permitted to be increased by 10%.

ACI 318-14 (9.8.1.5)

$$\varphi V_c = 1.10 \ \left(\varphi V_c\right)_{\text{Ribbed Slab}}$$

Two-way shear check around drop panels:

Two-way shear is critical on a rectangular section located at *d*/2 away from the face of the drop panel.

The equivalent thickness based on shear area is used to compute the area of concrete section resisting punching shear transfer (A_c) around drop panels in two way joist (waffle) systems. The equivalent slab thickness used to compute A_c is calculated as follows:
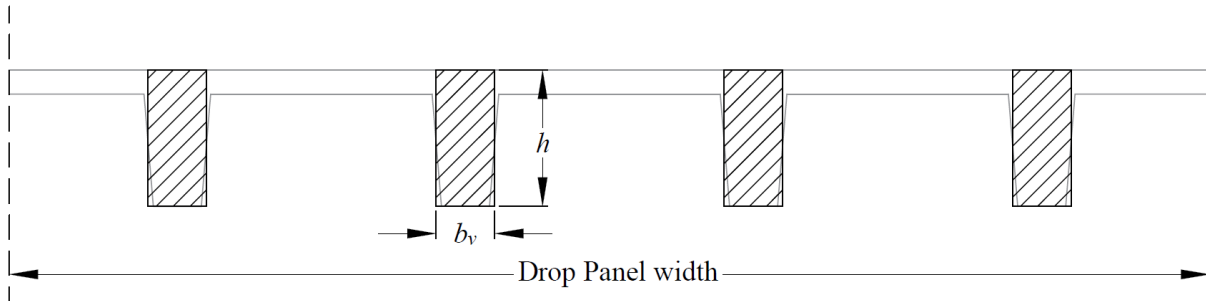
$$h_v = \frac{A_{rib}}{b_{rib}} + d_{reinf}$$

__spSlab Software Manual (Eq. 2-14)__

Where:

b = rib width.

d = distance from extreme compression fiber to tension reinforcement centroid.

Equivalent thickness based on shear area calculation

In waffle slab design where the drop panels create a large critical shear perimeter, the factor (b_o/d) has limited contribution and is traditionally neglected for simplicity and conservatism.

__spSlab software manual (Eq. 2-46)__

The two-way shear capacity for the ribbed slab is permitted to be increased by 10%. *__ACI 318-14 (9.8.1.5)__*
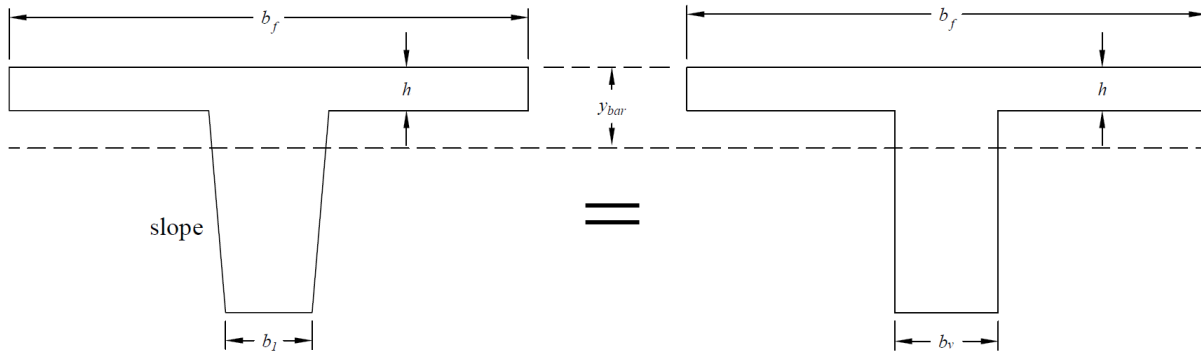
Immediate Deflection Considerations:

For positive moment (midspan) section:

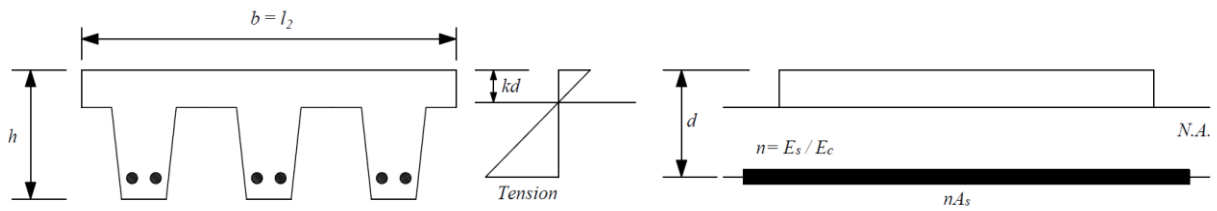I_g = Moment of inertia of the gross uncracked concrete section.

$$I_g = I_{g/rib} \times \# \ of \ ribs$$

y_t = Distance from centroidal axis of gross section, neglecting reinforcement, to tension face, in.
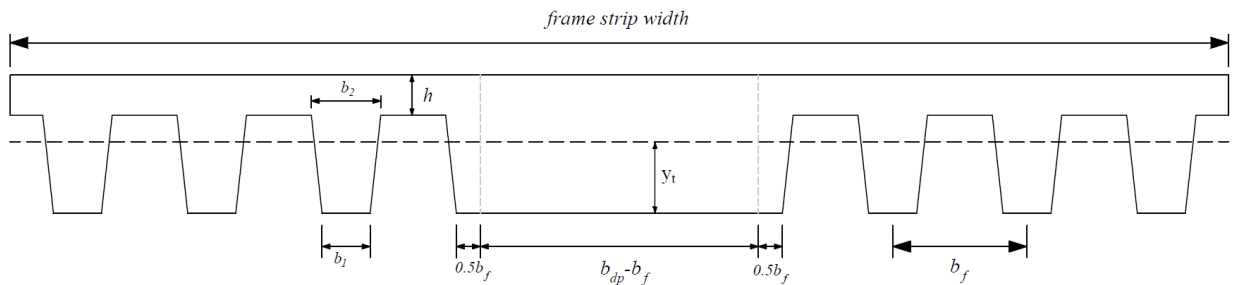
$$y_t = h_{rib} - y_{bar}$$

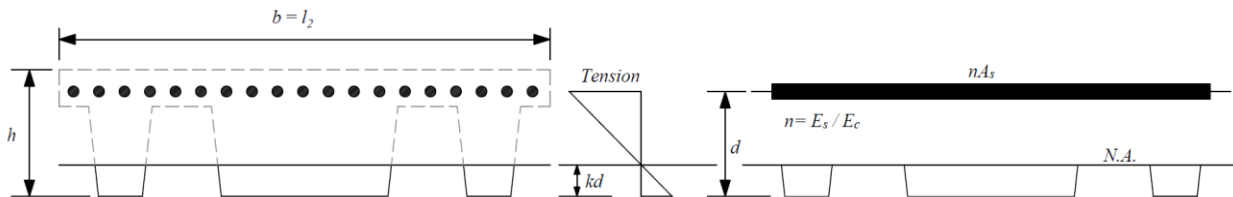Equivalent gross section for one rib - positive moment section

Cracked Transformed Section - positive moment section

For negative moment section (near the interior support of the end span):

Gross section – negative moment section

Cracked transformed section - negative moment section

For averaged effective moment of inertia:

Since midspan stiffness (including the effect of cracking) has a dominant effect on deflections, midspan section is heavily represented in calculation of I_e and this is considered satisfactory in approximate deflection calculations. Both the midspan stiffness ($I_e{}^+$) and averaged span stiffness ($I_{e,avg}$) can be used in the calculation of immediate (instantaneous) deflection.

The averaged effective moment of inertia ($I_{e,avg}$) is given by:

$$I_{e,avg} = 0.70\ I_e^+ + 0.15\left(I_{e,l}^- + I_{e,r}^-\right) \text{ for interior span}$$ *PCA Notes on ACI 318-11 (9.5.2.4(2))*

$$I_{e,avg} = 0.85\ I_e^+ + 0.15\ I_e^- \text{ for end span}$$ *PCA Notes on ACI 318-11 (9.5.2.4(1))*

However, the waffle slab is considered as non-prismatic members and the following expressions are recommended according to ACI 318-89:

$$I_{e,avg} = 0.50\ I_e^+ + 0.25\left(I_{e,l}^- + I_{e,r}^-\right) \text{ for interior span}$$ *ACI 435R-95 (2.14)*

$$I_{e,avg} = 0.50\ I_e^+ + 0.50\ I_e^- \text{ for end span}$$ *ACI 435R-95 (2.14)*