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AISI Newly Developed Standard AISI S310-13, North American Standard for the Design of Profiled Steel Diaphragm Panels

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By John Mattingly[1] and Helen Chen[2],

Abstract

AISI S310, *North American Standard for the Design of Profiled Steel Diaphragm Panels,* has been approved by AISI consensus committee and approved by American National Standard Institute (ANSI) as American National Standard (ANS). This standard determines the resistance and stiffness of steel panels with or without concrete-fills, and the resistance and stiffness of connections in a diaphragm. Both analytical and test methods are provided in the standard. In this paper, a brief review of the background information and design provisions is provided.

1. Background of the Development of AISI S310

Two test based analytical approaches are commonly used in the U. S. to determine the strength and stiffness of diaphragms that are used in buildings as floors, roofs or walls:

- Analytical approach that is presented in the Steel Deck Institute (SDI) *Diaphragm Design Manual*, and
- Analytical approach in accordance with the *Technical Manual* (also commonly called *Tri-Service Manual*), developed by the U.S. Department of Army, the Navy and the Air force (NAVFAC, 1982).

The SDI *Diaphragm Design Manual* is based on the research work by Dr. Luttrell (1967 et al), and the first edition of the *Diaphragm Design Manual* was published in 1981.

The *Tri-Service Manual* was initially developed by S. B. Barnes and Association, and the first edition of this Manual was published in 1966.

Testing is always allowed in lieu of an analytical approach.

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Both testing and analytical design approaches have been widely used and well recognized by the industry.
In 2006, AISI was asked by the industry to develop a consensus standard for diaphragm design. A subcommittee formed by the representatives from the industry determined that the SDI analytical and AISI or ASTM testing methods should be the bases for this standard.

2. Scope and Applicability of AISI S310

A diaphragm can be used as a roof or floor in buildings to resist gravity loads and transfer the lateral loads to a lateral force resisting system, or can be a shear wall to resist the lateral loads. The diaphragm, therefore, needs to possess sufficient in-plane strength and rigidity in order to transfer the lateral loads or to function as a lateral force resisting system. AISI S310 can be used to evaluate the strength and stiffness of diaphragms that are covered with profiled steel panels, including acoustic panels, cellular deck, and composite deck filled with concrete. The diaphragm may be installed with or without insulation between the panels and supports, and may be supported by materials made of steel, wood or concrete. Insulation can be installed above deck but this contribution is neglected in the analytical approach.

3. Determine Diaphragm Strength and Stiffness Analytically

3a. Application Limits

Since the analytical approach for determining the diaphragm strength and stiffness provided in AISI S310 is based on the research work (Luttrell, 1967 et al), and was verified by tests that are summarized in SDI *Diaphragm Design Manual* (SDI, 1981), the analytical approach should be only applied within the limits established by the research and tests.

(1) For fluted panels or deck diaphragm systems, the following limits should apply:
   (a) 0.5 in. (12 mm) ≤ panel or deck depth ≤ 7.5 in. (191 mm),
   (b) 0.014 in. (0.35 mm) ≤ base panel or deck thickness ≤ 0.075 in. (1.91 mm) for depth less than or equal to 3.0 in. (76.2 mm),

0.034 in. (0.85 mm) ≤ base panel or deck thickness ≤ 0.075 in. (1.91 mm) for depth greater than 3.0 in. (76 mm),

(c) 33 ksi (230 MPa) ≤ specified F_y of panel or deck ≤ 80 ksi (550 MPa), 45 ksi (310 MPa) ≤ specified F_u of panel or deck ≤ 82 ksi (565 MPa), and

(d) Panel or deck pitch ≤ 12 in. (305 mm).

(2) For fluted panel diaphragm systems when insulation is installed between the panels and supports, the following limits should apply:

(a) 0.50 in. (12 mm) ≤ panel depth ≤ 4 in. (102 mm);

(b) 0.014 in. (0.356 mm) ≤ base steel thickness of panel ≤ 0.075 in. (1.91 mm);

(c) 33 ksi (230 MPa) ≤ specified F_y of panel ≤ 80 ksi (550 MPa);

45 ksi (310 MPa) ≤ specified F_u of panel ≤ 82 ksi (565 MPa);

(d) Support types are steel or wood;

(e) Insulation types are fiberglass with a nominal thickness not exceeding 6 in. (15.2 mm) (R-19), or polyisocyanurate or polystyrene boards with a nominal thickness not exceeding 3 ¼ in. (82.6 mm); and

(f) Deck or panel pitch ≤ 12 in. (305 mm).

(3) For cellular deck diaphragm systems, the following limits should apply:

(a) 0.5 in. (12.7 mm) ≤ cellular deck depth ≤ 7.5 in. (191 mm),

(b) 0.034 in. (0.864 mm) ≤ bottom plate base steel thickness ≤ 0.064 in. (1.63 mm),

(c) 0.034 in. (0.864 mm) ≤ top deck base steel thickness ≤ 0.064 in. (1.63 mm),

(d) Support fastener types are welds, screws, or power-actuated fasteners,

(e) No insulation beneath the cellular deck at the support,

(f) Fastener edge dimensions satisfy requirements specified in AISI S100, and

(g) Deck pitch ≤ 12 in. (305 mm).

For diaphragms outside the above limits, the test approach should be considered.

3b. Diaphragm Strength and Stiffness

To ensure that a diaphragm is capable to collect and transfer the lateral forces to the lateral force resisting system, the panel in-plane strength plus the connection strengths between the panels (side-lap connections), and between panels and supports (support connections) should be considered.

The diaphragm strength is the lower value obtained from the limit states controlled by either connection strength or panel out-of-plane buckling strength, i.e.,

For Allowable Strength Design (ASD),

$$S_a = \frac{S_n}{\Omega} = \min\left(\frac{S_{nf}}{\Omega_{df}}, \frac{S_{nb}}{\Omega_{db}}\right) \quad (3b\text{-}1)$$

For Load and Resistance Design (LRFD) or Limit States Design (LSD),

$$S_a = \phi S_n = \min(\phi_{df} S_{nf}, \phi_{db} S_{nb}) \quad (3b\text{-}2)$$

where

S_a = Available shear strength per unit length of diaphragm system

S_n = Nominal shear strength per unit length of diaphragm system

S_{nf} = Nominal shear strength per unit length of diaphragm system controlled by connections, as discussed in 3c

S_{nb} = Nominal shear strength per unit length of diaphragm system controlled by panel out-of-plane buckling, as discussed in 3d

Ω, ϕ = Safety and resistance factors for diaphragm strength, respectively, provided in Table 1

Ω_{db}, ϕ_{db} = Safety and resistance factors controlled by connections, respectively, provided in Table 1

Ω_{df}, ϕ_{df} = Safety and resistance factors controlled by panel out-of-plane buckling, respectively, provided in Table 1

Table 1, Safety Factors and Resistance Factors for Diaphragms

Load Type or Combinations Including	Connection Type	Limit State					
		Connection Related			Panel Out-of-Plane Buckling		
		Ω_d (*ASD*)	ϕ_d (*LRFD*)	ϕ_d (*LSD*)	Ω_d (*ASD*)	ϕ_d (*LRFD*)	ϕ_d (*LSD*)
Earthquake	Welds	3.00	0.55	0.50	2.00	0.80	0.75
	Screws	2.50	0.65	0.60			
Wind	Welds	2.35	0.70	0.65			
	Screws						
All Others	Welds	2.65	0.60	0.55			
	Screws	2.50	0.65	0.60			

The diaphragm stiffness for fluted panels without perforation is determined as follows:

$$G' = \left(\frac{Et}{2(1+\mu)\frac{s}{d} + \gamma_c D_n + C} \right) K \quad \text{kip/in. (kN/m)} \tag{3b-3}$$

For concrete filled fluted deck, the stiffness is determined:

$$G' = \frac{Et}{2(1+\mu)\frac{s}{d} + C} + K_3 \tag{3b-4}$$

where

E = Modulus of elasticity of steel
= 29,500 ksi, (203,000 MPa)

t = Base steel thickness of panel, in. (mm)

K = Stiffness factor relating support and side-lap connection flexibilities
= 1 for steel panels with lap-down on steel supports
= S_f/S_s for steel panels with lap-up on steel supports
= 0.5 for steel panels on wood supports

S_f = Structural support connection flexibility, in./kip (mm/kN)

S_s = Side-lap connection flexibility, in./kip (mm/kN)

K_3 = Stiffness contribution of the structural concrete fill
= $3.5d_c(f'_c)^{0.7}$, kip/in. for U.S. Customary units (3b-5)

$$= 786 d_c (f_c')^{0.7}\text{, kN/m} \quad \text{for SI units} \quad (3b\text{-}6)$$

d_c = Structural concrete thickness above top of deck, in. (mm)

f_c' = Structural concrete compressive strength, psi (MPa)

3c. Diaphragm Strength Controlled by Connections, S_{nf}

The diaphragm strength, S_{nf}, controlled by connections is the minimum of the following limit states:

(a) Connections at interior and exterior supports and side-laps of panels, S_{ni}
(b) Corner connections of panel, S_{nc}, and
(c) Edge panels along shear walls, collection struts or lateral force resisting systems, S_{ne}.

$$S_{ni} = [2A(\lambda - 1) + \beta]\frac{P_{nf}}{L} \quad (3c\text{-}1)$$

$$S_{nc} = \left(\frac{N^2\beta^2}{L^2N^2 + \beta^2}\right)^{0.5} P_{nf} \quad (3c\text{-}2)$$

$$S_{ne} = \frac{(2\alpha_1 + n_p\alpha_2)P_{nf} + n_e P_{nfs}}{L} \quad (3c\text{-}3)$$

where

A = Number of exterior support connections per flute located at the side-lap at an interior panel or edge panel's end

λ = Connection strength reduction factor at corner fastener, unit-less

$$= 1 - \frac{D_d L_v}{240\sqrt{t}} \geq 0.7 \quad \text{for U.S. Customary units} \quad (3c\text{-}4a)$$

$$= 1 - \frac{D_d L_v}{369\sqrt{t}} \geq 0.7 \quad \text{for SI units} \quad (3c\text{-}4b)$$

D_d = Depth of panel, in. (mm)

L_v = Span of panel between supports with fasteners, ft (m)

t = Base metal thickness of the panel, in. (mm)

β = Factor defining connection contribution and interaction to diaphragm shear strength per unit length

$= \quad n_s \alpha_s + 2 n_p \alpha_p^2 + 4 \alpha_e^2$ (3c-5)

n_s = Number of side-lap connections along a total panel length, L, and not into supports

$\alpha_s = \dfrac{P_{ns}}{P_{nf}}$ (3c-6)

P_{nf} = Nominal shear strength [resistance] of a support connection per fastener

P_{ns} = Nominal shear strength [resistance] of a side-lap connection per fastener

n_p = Number of interior supports along a total panel length, L

α_p^2 = Analogous section modulus of panel interior support connection group in an interior or edge panel

$= \left(\dfrac{1}{w^2}\right) \sum x_p^2$ (3c-7)

w = Panel cover width

x_p = Distance from panel center line to an interior support structural connection in a panel

α_e^2 = Analogous section modulus of panel exterior support fastener group in an interior or edge panel

$= \left(\dfrac{1}{w^2}\right) \sum x_e^2$ (3c-8)

x_e = Distance from panel center line to an exterior support structural connection in a panel

L = Total panel length

$= (n_p + 1) L_v$ for equal spans (3c-9)

N = Number of support fasteners per unit width at an interior or edge panel's end

α_1 = Measure of exterior support fastener group distribution across a panel width, w_e, at an edge panel

$= \dfrac{\sum x_{ee}}{w_e}$ (3c-10)

x_{ee} = Distance from panel center line to an exterior support structural connection in an edge panel

w_e = Panel cover width at the edge panel

α_2 = Measure of interior support fastener group distribution across a panel width, w_e, at an edge panel

$$= \frac{\sum x_{pe}}{w_e} \qquad (3c\text{-}11)$$

x_{pe} = Distance from panel center line to an interior support structural connection in an edge panel

n_e = Number of edge support connections between transverse supports and along an edge panel length, L

P_{nfs}= Nominal shear strength [resistance] of an edge support connection installed parallel with an edge panel span and between transverse supports

See Figure 1 for an illustration of the parameters in this section.

To apply Equations (3c-1) to (3c-3), in addition to the geometric parameters, P_{nf}, P_{ns}, and P_{nfs} should be determined in accordance with the connection type. The standard provides design provisions for the following connection conditions:

(1) Support connections in fluted deck or panels with weld, screw, power actuated fasteners (PAF) or nails depending on the supporting materials (steel, wood or concrete).
(2) Side-lap connections in fluted deck or panel with fillet welds, flare grooved welds, top arc seam side-lap welds, non-piercing button punch side-lap welds or side-lap screw connections.
(3) Support connections with insulation in fluted panels.
(4) Support and side-lap connections in fluted acoustic panels, cellular deck, standing seam panels, and double-skinned panels.

Detailed provisions for determining P_{nf}, P_{ns}, and P_{nfs} can be found in AISI S310.

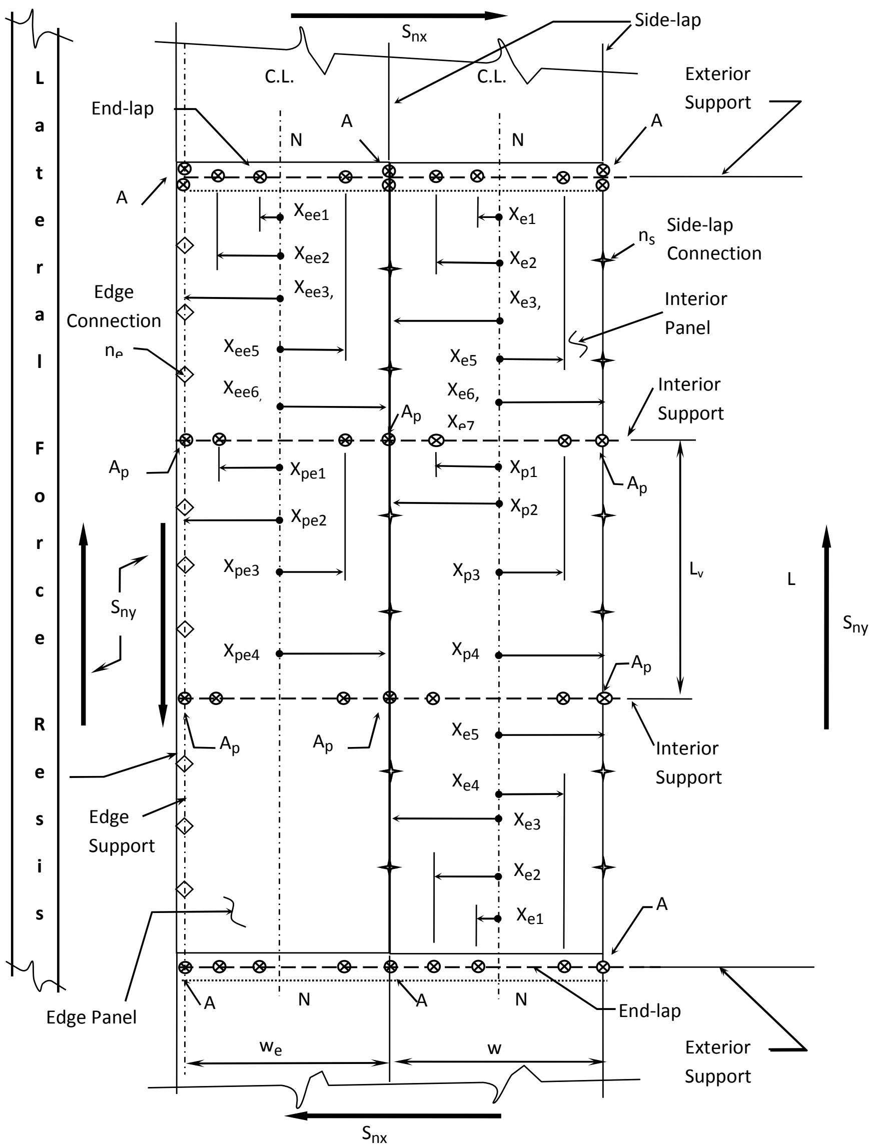


Figure 1 Schematic Illustration of Section 3a Parameters

3d. Diaphragm Strength Controlled by Out-of-Plane Buckling, S_{nb}

For fluted panels, the nominal shear strength controlled by the out-of-plane buckling can be determined by the following equation:

$$S_{nb} = \frac{7890}{\alpha L_v^{2}}\left(\frac{I_{xg}^{3} t^{3} d}{s}\right)^{0.25} \qquad (3d\text{-}1)$$

where

S_{nb} = Nominal diaphragm shear strength [resistance] per unit length controlled by panel out-of-plane buckling, kip/ft (kN/m)

α = Conversion factor for units
= 1 for U.S. customary units
= 1879 for SI units

L_v = Span of panel between supports with fasteners, ft (m)

I_{xg} = Moment of inertia of fully effective panel per unit width, in.^{4}/ft (mm^4/mm)

t = Base steel thickness of panel, in. (mm)

d = Panel corrugation pitch, in. (mm)

s = Developed flute width per pitch, in. (mm)
= 2(e + w) + f (3d-2)

- e = One-half the bottom flat width of panel measured between points of intercept, in. (mm)
- w = Web flat width of panel measured between points of intercept, in. (mm)
- f = Top flat width of panel measured between points of intercept, in. (mm)

For acoustic panels or cellular deck, modifications are required as provided in AISI S310.

4. Determine Diaphragm Strength and Stiffness Through Testing

Even though tests can be used to determine the diaphragm strength under any conditions, considering the expensive cost of diaphragm tests, tests should be minimized, if possible.

AISI S310 requires that a large-scale diaphragm test should be performed in accordance with AISI S907 (AISI, 2013a), and small scale tests for determining diaphragm connection strengths and stiffness should be performed in accordance with AISI S905 (AISI, 2013b).
Five test objectives are outlined in the standard, which describe the scenarios where tests are needed:

(1) To determine the connection nominal strengths or flexibilities that are not listed in the existing analytical approach for a diaphragm system that otherwise conforms to the analytical approach's specified limits;
(2) To refine the nominal connection strength equations provided in the existing analytical approach;
(3) To establish analytical equations for diaphragm systems that are not within the limits of the existing analytical approach;
(4) To establish analytical equations for strength and stiffness of diaphragm systems or components based on an existing test-based analytical model other than the analytical model presented in Chapter D of S310; and
(5) To establish the contribution of an accessory or detail.

4a. Test Calibration

The diaphragm nominal strength should be determined in accordance with AISI S907 if large-scale tests are performed; the nominal connection strength should be determined in accordance with AISI S905 if small-scale tests are performed.

Tests for developing an analytical equation that are used to determine the strength or stiffness of a diaphragm system, or tests for developing an analytical equation used for determining the connection strength of a diaphragm system should conform with Section F1.1(b) of AISI S100.

The safety and resistance factors should be determined in accordance with Section F1.1 of AISI S100 with the modification shown below. The calculated safety factor should not exceed the one provided in Table 1 for the same condition, and the calculated resistance factor should not be less than the one provided in Table 1 for the same condition.

The following modification should be made for determining the resistance factor in accordance with AISI S100 Section F1.1:

C_ϕ = Calibration coefficient
= 1.6 for *LRFD*
= 1.5 for *LSD*

P_m = Mean value of professional factor, P, for tested component

$$= \frac{\sum_{i=1}^{n} \frac{R_{t,i}}{R_{n,i}}}{n} \qquad (4a\text{-}1)$$

where

i = Index of tests
= 1 to n

n = Total number of tests

$R_{t,i}$ = Tested connection strength [resistance] of test i, or
= Tested nominal diaphragm shear strength [resistance] per unit length, $S_{ni\ test}$, of test i

$R_{n,i}$ = Calculated connection strength [resistance] of test i per rational engineering analysis model, or
= Calculated nominal diaphragm shear strength [resistance] per unit length, $S_{ni\ theory}$, of test i per diaphragm system model

V_Q = Coefficient of variation of load effect
= 0.25 for LRFD and LSD

V_P = Coefficient of variation of test results determined in accordance with AISI S100 Eq. F1.1-6, but not less than 0.065

C_P = Correction factor, determined in accordance with AISI S100 Eq. F1.1-4

β_o = Target reliability index, determined in accordance with Table 2

F_m = Mean value of fabrication factor, F, determined in accordance with Table 2

M_m = Mean value of material factor, M, determined in accordance with Table 2

V_F = Coefficient of variation of fabrication factor determined in accordance with Table 2

V_M = Coefficient of variation of material factor determined in accordance with Table 2

Table 2 Calibration Parameters β_o, F_m, M_m, V_F, V_M[1]

Diaphragm Conditions	β_o[2, 3]	F_m	M_m	V_F	V_M
Steel support	3.5 for LRFD 4.0 for LSD	AISI S100 Section F1.1(b)			
Structural concrete support or fill	3.5 for LRFD 4.0 for LSD	0.90	1.10	0.10	0.10
Insulating concrete fill	3.5 for LRFD 4.0 for LSD	AISI S100 Section F1.1(b)			
Wood support	4.0 for LRFD 4.5 for LSD	1.0	1.10	0.15	0.15

Note:

1. The most severe factors should be used where fastener type or support varies in the diaphragm.
2. β_o = 2.5 is permitted in LRFD and by extension in ASD for wind load on diaphragms with steel supports and without structural or insulating concrete fill provided the limits of Table 1 in Section 3b are met.
3. β_o = 3.5 for all load effects in LRFD and by extension in ASD, and 4.0 for all load effects in LSD are permitted with wood supports provided bearing of the panel against the fastener controls the connection shear strength and the bearing strength controlled by wood is at least 25% greater than the steel bearing strength.

5. Additional Information and Design Aids

This paper has only reviewed a very limited amount of design provisions in AISI S310. Readers should review the standard for more detailed and complete information. AISI S310 can be freely downloaded from AISI website (www.steel.org). To help readers better understand the standard, an AISI Diaphragm Design Task Group is developing design examples to illustrate the applications of the design provisions. In addition, SDI also will publish the fourth edition of the *Diaphragm Design Manual*, which provides load tables and design examples developed in accordance with AISI S310. In Appendices 1 and 2 of this paper, flowcharts are provided for assisting users to allocate the design provisions in AISI S310.

6. References

American Iron and Steel Institute (2012), AISI S100, *North American Specification for the Design of Cold-Formed Steel Structural Members*, 2012.

American Iron and Steel Institute (2013a), AISI S907, *Test Standard for Cantilever Test Method for Cold-Formed Steel Diaphragms*, 2013.

American Iron and Steel Institute (2013a), AISI S905, *Test Standard for Cold-Formed Steel Connections*, 2013.

Luttrell, L.D. (1967), "Strength and Behavior of Light-Gage Steel Shear Diaphragms," Cornell Engineering Research Bulletin, 1967

NAVFAC (1982), Technical Manual TM 5-809-10/NAVFAC P-335/AFM88-3, Department of the Army, the Navy, and Air Force Seismic Design for Buildings, 1982

Steel Deck Institute (1981), Diaphragm Design Manual, First Edition, Steel Deck Institute, January, 1981.

Appendix 1: Strength Determination with Analytical Approach for Diaphragms with Fluted Deck and Panels With or Without Concrete Fills or Insulations

Parameter Limits:
(1) Without insulation and Concrete Fill – Chapter D;
(2) With insulation between panel and support– D1.3
(3) With concrete fill – D4

S_{nf} = min(S_{ni}, S_{nc}, S_{ne}):
(1) Without insulation and concrete fill – D1;
(2) With insulation –D1 modified with D1.3;
(3) With concrete fill – D4.2 or D4.3

S_{nb}:
(1) Fluted deck or panels– D2.1;

P_{nf} and P_{nfs} at supports:
- Arc sport or seam welds: D1.1.1
- Screws into steel supports:
  - o Through panel bottom flat:
    - Without insulation: D1.1.2
    - With insulation:
      - (a) Interior flute: D1.3 (P_{nf} = 0)
      - (b) Side-lap flute: D1.3.2 (D1.1.2)
  - o Through panel top flat:
    - Interior flute: D1.3 (P_{nf} = 0)
    - Side-lap flute: D1.3.1
- PAF into steel support: D1.1.3
- Screws or nails into wood support: D1.1.4
  - o Through panel bottom flat:
    - Without insulation: D1.1.4.2
    - With insulation:
      - o Interior flute: D1.3 (P_{nf} = 0)
      - o Side-lap flute: D1.3.2 (D1.1.4.2)
  - o Through panel top flat:
    - Interior flute: D1.3 (P_{nf} = 0)
    - Side-lap flute: D1.3.1 (D1.1.4.3)

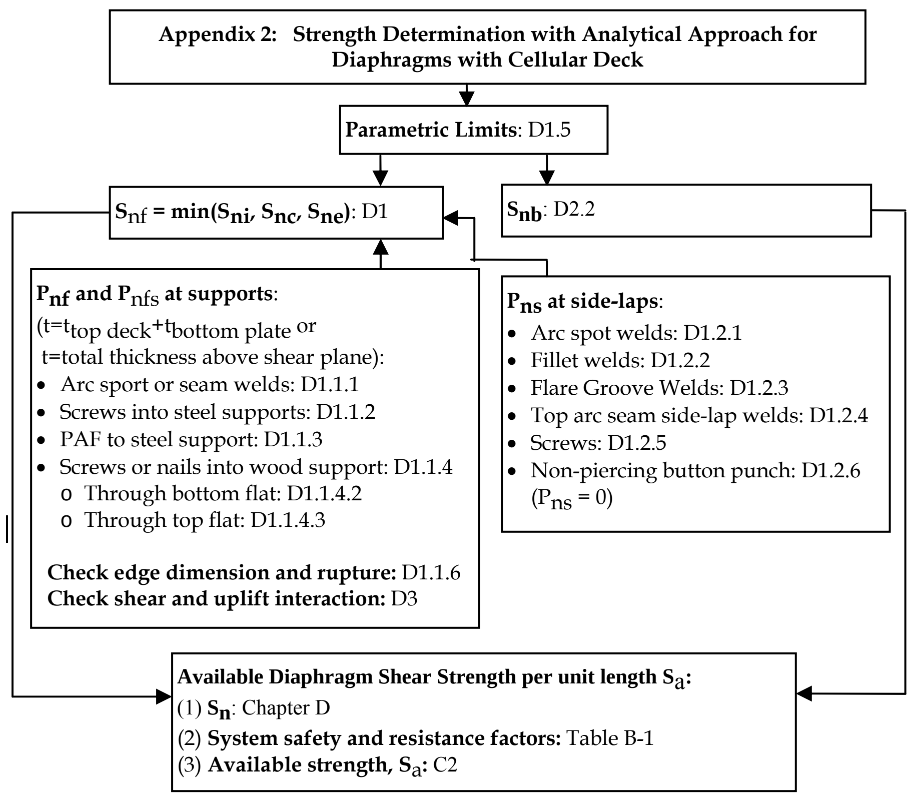
Determine P_{nf}, P_{nfs} at edge (for S_{ne}): D1.3

Check edge dimension and rupture: D1.1.6
Check shear and uplift interaction: D3

P_{ns} at side-laps:
- Arc spot welds: D1.2.1
- Fillet welds: D1.2.2
- Flare Groove Welds: D1.2.3
- Top arc seam side-lap welds: D1.2.4
- Screws: D1.2.5
- Non-piercing button punch: D1.2.6

Available Diaphragm Shear Strength per unit length S_a:
(1) **S_n**:
- Fluted deck or panels without concrete: Chapter D
- With structural concrete fill: D4.2
- With light-weight insulating concrete fill: D4.3

(2) **System safety and resistance factors:** Table B-1
(3) **Available strength, S_a:** C2


Appendix 2: Strength Determination with Analytical Approach for Diaphragms with Cellular Deck
Parametric Limits: D1.5
S_{nf} = min(S_{ni}, S_{nc}, S_{ne}): D1
S_{nb}: D2.2
P_{nf} and P_{nfs} at supports:
($t = t_{top\ deck} + t_{bottom\ plate}$ or
t=total thickness above shear plane):
• Arc sport or seam welds: D1.1.1
• Screws into steel supports: D1.1.2
• PAF to steel support: D1.1.3
• Screws or nails into wood support: D1.1.4
o Through bottom flat: D1.1.4.2
o Through top flat: D1.1.4.3
Check edge dimension and rupture: D1.1.6
Check shear and uplift interaction: D3
P_{ns} at side-laps:
• Arc spot welds: D1.2.1
• Fillet welds: D1.2.2
• Flare Groove Welds: D1.2.3
• Top arc seam side-lap welds: D1.2.4
• Screws: D1.2.5
• Non-piercing button punch: D1.2.6 (P_{ns} = 0)
Available Diaphragm Shear Strength per unit length S_a:
(1) S_n: Chapter D
(2) System safety and resistance factors: Table B-1
(3) Available strength, S_a: C2