STEEL DECK INSTITUTE

Technical Note - No. 17

DEEPER STEEL DECK AND CELLULAR DIAPHRAGMS

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DEEPER STEEL DECK AND CELLULAR DIAPHRAGMS

Introduction

This paper supplements the paper, *Deeper Steel Deck and Cellular Diaphragms,* Luttrell (2005) (4), which includes a method to calculate diaphragm stiffness for cellular deck at Eq. 5. That analytical method was compared with existing tests. The 2005 paper fills a gap that exists in the *Diaphragm Design Manual, Third Edition*, Luttrell (2004) (3), since cellular and deep decks had not been included in this and previous editions. Bagwell (2008) (1) performed additional tests sponsored by the Steel Deck Institute (SDI) and the American Iron and Steel Institute (AISI) to reinforce the results presented in the 2005 paper and to verify the method.

Deeper and cellular deck testing has existed for years but the majority of earlier testing was: a) sponsored by industry, b) empirical, or c) proprietary. An analytical design method based on proprietary work was presented in *Seismic Design for Buildings* (commonly called the Tri Service Manual) (7), which was first published in 1966. Many manufactures used this earlier manual to develop load tables for cellular deck prior to 2005.

This paper focuses on load sharing between the cellular deck elements and the general warping term in the diaphragm stiffness equation, which here is found to be several orders of magnitude smaller than is the warping in open corrugated diaphragms. This supplement does four things:

a. Includes the impact of perforations in cellular deck,
b. Modifies the stiffness equation for cellular deck and provides a unified transition between solid and perforated cellular deck,
c. Includes appendices, which compare tests with the revised theory and provides examples, and
d. Provides the limits of applicability.

The strength methods for deeper and cellular deck, and the stiffness method for deeper decks are unchanged. The paper, *Perforated Metal Deck Diaphragm Design*, Luttrell (2011) (5), provides a method to calculate the impact of perforations over the acceptable range of fluted profiles for non-cellular diaphragms. The paper, *Perforated Metal Deck Design with Commentary*, Luttrell (2011) (6), provides a method to calculate the impact of perforations over the acceptable range of fluted and cellular profiles for other structural applications.

Cellular Deck Stiffness

Among other influences, cellular deck diaphragm shear stiffness will depend on what fraction of the total diaphragm shear force travels through the flat plate. The hat-shaped element has a greater shear width than the portion of flat plate immediately below it meaning the flat plate is the stiffer of the two when they are of equal thickness. Furthermore, the hat-shape will have some tendency to warp and roll over in shear if there are no transverse end closures. With flexibility in the hat-shape and with shear warping, the bottom closure plate tends to resist even more of the applied shear. The *Diaphragm Design Manual* (3) shear stiffness Equation 3.3-3 was developed for open corrugated diaphragms in the form:

$$G' = \frac{Et}{A_A + \phi D_n + C} \quad (1)$$

Where:

A_A = 2.6 (s/p)
s = developed corrugated shear width per pitch
p = corrugation or cell width
φ = purlin factor, 1 for single & dual spans; 0.9 for three spans; See DDM (3) Section 3.2.
D_n = warping factor = D/ℓ for non-cellular decks
D = warping characteristic of deck profile and fastener pattern, adjusted for units
ℓ = panel length
C = slip coefficient
t = top element (hat) base metal thickness
E = modulus of elasticity

A decrease in magnitude of any denominator term will increase the stiffness, G'. The stiffness is expressed in terms of the hat thickness, but the pan effect is present. D_n measures the torsion warping relaxation of the open corrugated hat. Corrugated panels and flat sheets can be used to form a cellular deck profile. The units are welded to each other along the lower flange of the hat section forming cells with high torsional stiffness. The warping effect is dramatically reduced leading to a great increase in shear stiffness for the panel. The C-term in Equation 1 is a measure of fastener relaxation, which depends on the panel thickness. Side lap connection properties depend on the element thickness at the fastener, which most often is that of the bottom panel.

When perforations are introduced in a flat element having a thickness, t, shear introduces a displacement across a width, W, that is $\delta = (\tau/G)W$. G is the shear modulus and τ is the shear stress. A band of perforations in the element will lower the shear stiffness in proportion to the reduction to the solid area as caused by the perforations. The area reduction effect is easier to reflect through a modified or effective width approach. Detailed treatments of perforation effects are given in *Perforated Metal Deck Diaphragm Design*, Luttrell (5).

$$\delta=\left[W+W_p\left(\frac{1}{k}-1\right)\right]\frac{\tau}{G} \quad (2)$$

Where:

k = perforation reduction factor

W_p = perforation strip width within W

Figure 1 is used to illustrate the effects of a shear load, P, where the resistance to that load is from more than one element. The a-side at the left is different in width from the b-side at the right. The b-side contains a perforated band of width, b_p, extending fully across the depth, L.

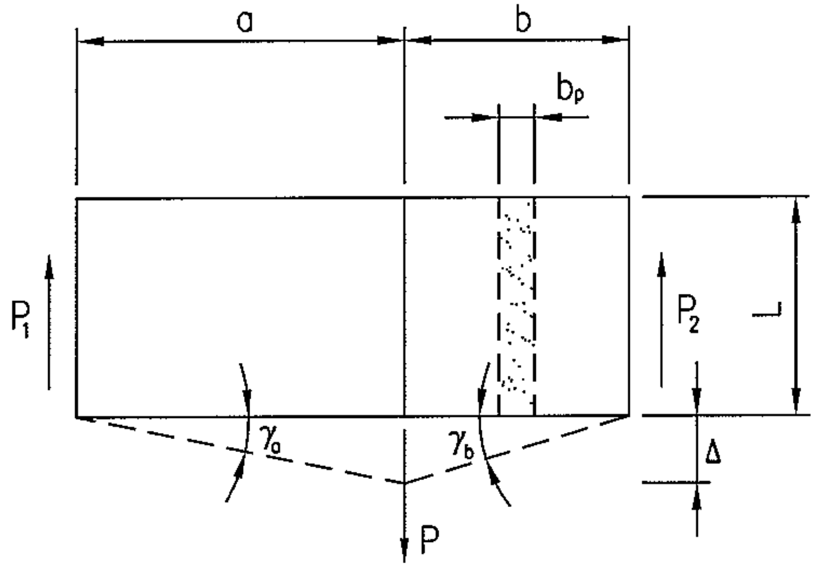

FIGURE 1
Shear distribution within non-symmetric systems

From equilibrium considerations, the end reactions are determined as follows.

$$P_1=\frac{b}{a+b}P \quad (3)$$

$$P_2=\frac{a}{a+b}P \quad (4)$$

The b_p wide dotted strip represents a band of perforations. These perforations reduce the shear stiffness on the right and the shear strain line will not have a uniform slope along the γ_b line. From the right end, an equivalent width, S_{eb}, is introduced to account for the perforations. The shear strain is τ/G outside the perforated zone and is $\tau/(kG)$ inside the perforated zone. k is a perforation factor. The deflection, Δ, can be established from either side as follows:

From the left:
$$\Delta = \frac{\tau}{G} a = \frac{P_1}{G\,Lt} a \qquad (5)$$

From the right:
$$\Delta = \frac{P_2}{GLt_b}\left[b + b_p\left(\frac{1}{k} - 1\right)\right] \qquad (6)$$

Where:
- t is the thickness over the a-width
- t_b is the thickness over the b-width

Note: Δ is independent of the location of b_p within b.

Define S_{eb} as the effective width of the b-wide unit with a b_p wide perforated strip:

$$S_{eb} = b + b_p\left(\frac{1}{k} - 1\right) \qquad (7)$$

S_e is a similar term for the left side. Though no left-side perforated strip is indicated in Figure 1, such is not excluded. The left-side effective width is as follows and equal to a when a_p =0.

$$S_e = a + a_p\left(\frac{1}{k} - 1\right) \qquad (8)$$

After substituting S_e or S_{eb}, Equation 5 and Equation 6 are used to find the P_1 value as a fraction of the total shear load, P.

$$P_2 = P_1 \frac{t_b}{t}\frac{S_e}{S_{eb}} \qquad (9)$$

The total applied load is:

$$P = P_1 + P_2 = P_1\left(1 + \frac{t_b}{t}\frac{S_e}{S_{eb}}\right) \qquad (10)$$

And the fraction of the load acting across the a-side is:

$$P_1 = \frac{P}{\left(1 + \frac{t_b}{t}\frac{S_e}{S_{eb}}\right)} \qquad (11)$$

Rearranging terms leads to:

$$\frac{P_1}{P} = \frac{tS_{eb}}{tS_{eb} + t_b S_e} = \frac{1}{1 + \frac{t_b S_e}{tS_{eb}}} \qquad (12)$$

Some numerical boundary checks are:

1. With $S_e = S_{eb} = 1$ and with equal thicknesses, $t_b = t$, a symmetric system is described. With $P_1 = P/2$ and this is OK.
2. With $S_e = S_{eb} = 1$ and $t_b = 2$ t, $P_1 = P/(1+2) = P/3$. The b-side is stiffer. OK
3. With $S_{eb} = 2S_e$ and $t_b = t$, $P_1 = P/(1+0.5) = 0.67P$. OK

The D_n warping term of Equation 1 represents an open corrugated tube or hat-shaped tube with low torsional resistance relative to a similar closed tube unit. Consider a closed thin-wall tube having a radius at mid-wall thickness of R with properties listed in Figure 2.

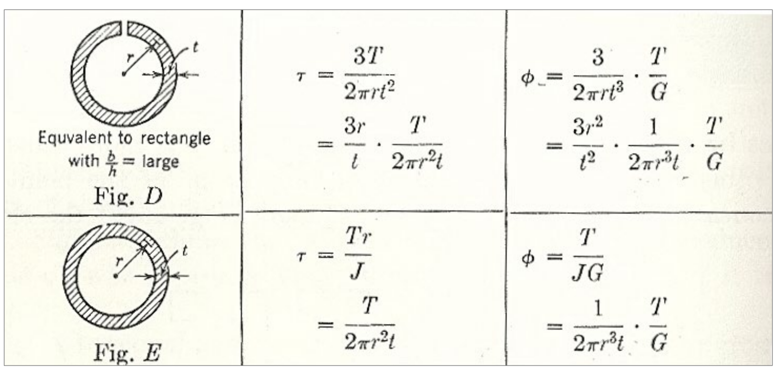

FIGURE 2

Torsional properties of Tubes from Advanced *Mechanics of Materials*, Seely & Smith, 2^{nd} Ed 1952

The ϕ term is the twist per unit length developing from the torque, T. Figure 2 E is for a closed tube with an inverse polar moment of inertia coefficient, $1/(2\pi r^3 t)$. For the open tube in Fig. D of Figure 2, there is a multiplier, $3r^2/t^2$. Suppose t = 0.03" and r = 3" the multiplier becomes 30,000 meaning that the open tube is 30,000 times more flexible in this specific case. The same general argument holds for open or closed rectangular tubes and open or closed corrugated deck panels. Closed deck cells will exhibit no discernable twist and the D_n term in Equation 1 will vanish for cellular deck as shown in Equation 13.

Note that the Figure 1 solution is for systems in shear and that other alignment forces exist to maintain the P-force in a vertical path. Indeed, the above is a model of the system in Figure 3.

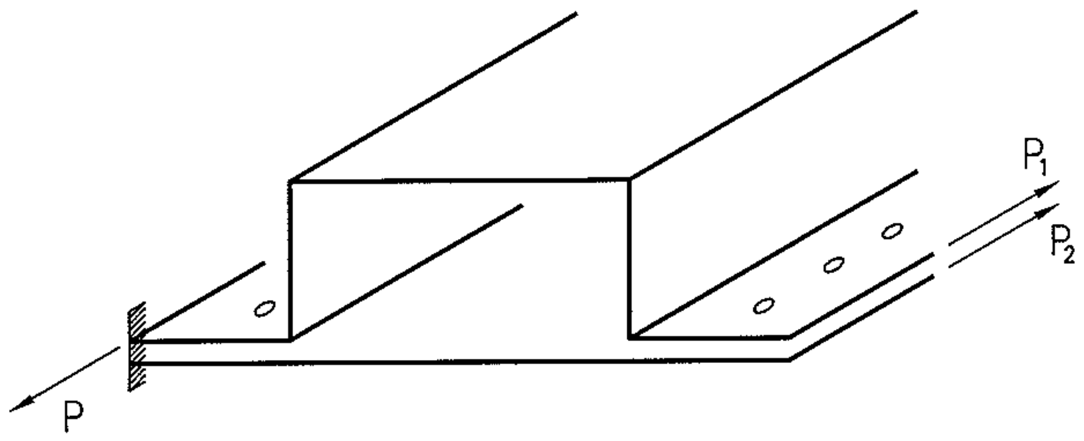

FIGURE 3
Cellular Deck Model

Figure 3 represents a hat-shaped top unit affixed to a lower flat plate by spot welds along each lower flat of the cell such that both units exhibit exactly the same shear deflection along the right side. The total P-shear is then shared between the two elements according to their shear stiffness.

Note that, if this unit were mathematically opened up about a left side hinge and the hat unit flattened out, the conditions would be modeled by Figure 1 where $a = W_b + 2\ W_w + W_t$. W_b, W_w, and W_t represent the bottom, web, and top dimensions of the hat.

The fraction, P_1 of the total load, P, is described in Equation 12 and it can have a major impact on the stiffness as described in the modification of Equation 1 shown below.

$$G' = \frac{Et}{A_A + C} \qquad (13)$$

The A_A term is related to shear strain in the top unit as if all the shear moves through the hat. Obviously, it does not. Of the total shear applied, represented by P, only that part described by Equation 12, goes through the hat. In the original paper, *Deeper Steel Deck and Cellular Diaphragms*, Luttrell (4), the case for a 2 in. deep roof deck with an 8 in. pitch was presented where the A_A term was 2.6 (s/p) = 3.90. The paper's modifications reduced that to 1.56 representing the plate's effect when the plate and hat had the same thickness. The current consideration of using a proportioned load, Equation 12, has S_e = 12 in. and S_{eb} = 8 in., which leads to $P_1 = 0.40P$ and $A_A = 3.90\ (0.40) = 1.56$, the same value as the original paper for a non-perforated application. But the current approach has the advantage of having the perforation influence built into the formulas.

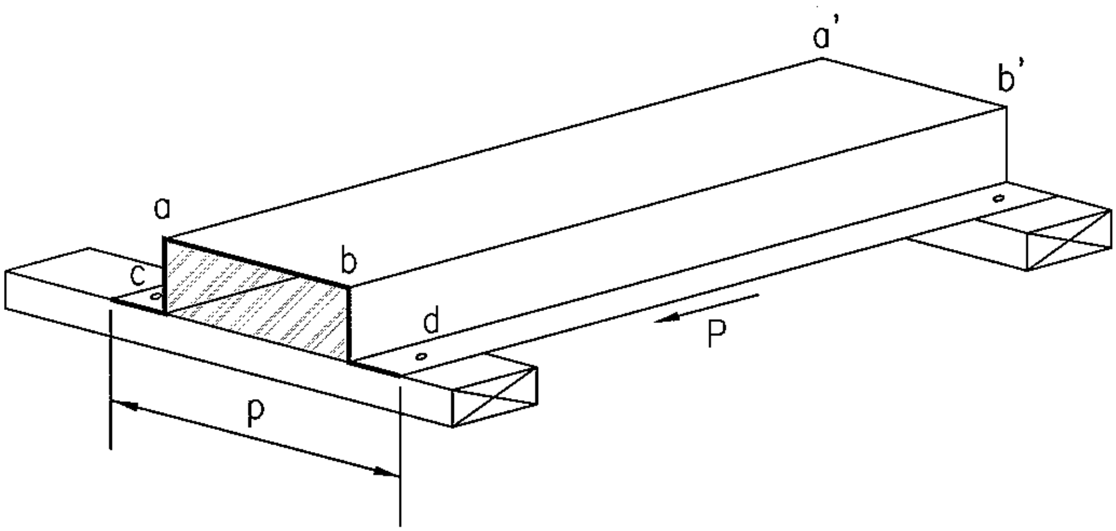

FIGURE 4
Fluted unit with end closures

A fluted element is shown in Figure 4 where the top part is flat and defines a rectangle a-b wide and a-a' long. This rectangle is part of a thin-wall assembly that has vertical web elements, running the full length of the system and connecting to narrow flat elements at the bottom. With p-dimension being the corrugation width and distance between welds in deck bottoms, Figure 4 can represent part of a steel roof deck panel where an end view may lead to the description, hat shaped. Finally, the ends are closed with transverse diaphragms as indicated by the hash-marked trapezoid below the a-b line.

The Figure 4 assembly is attached to structural support members that deliver a shear force, P, to the edge of the hat shaped unit. The force produces a shear stress $\tau = P/Lt$ where L is the length and t is the assembly wall thickness. An opposing parallel force, P, acts at the far side of the unit leading to a couple. End shear forces at the base of the transverse diaphragms stabilize the assembly. The P-load produces only shear stresses in the hat.

The sum of the panel element widths per corrugation width, p, is the sum of five parts: $S_e = W_t + 2W_w + 2E$ representing the top, webs, and bottom elements respectively. P then produces a shear deflection requiring shear stiffness developed as follows.

$$G' = Gt = \frac{\tau t}{\gamma} \qquad (14)$$

With diaphragm of width a, the shear strain is defined as $\gamma = \Delta_S/a$ leading to $G' = (Pa/L)/\Delta_S$. Since $G = E/(2(1+\upsilon))$, the pure shear deflection per width, a, adjusted for the shear path through the hat is:

$$\Delta_S = \frac{Pa}{L} \frac{2(1+\upsilon)}{Et} \frac{S_e}{p} \qquad (15)$$

The S_e/p multiplier indicates the developed shear width per corrugation pitch, p. Equation 8 will define S_e when perforations are present but perforations in cellular deck top hat units are not typical.

If the transverse end diaphragms were removed while maintaining the shear load, the Figure 4 a-b line would shift to the left and line a'-b' to the right resulting in a small increase in the shear displacement.

$$\Delta = \Delta_S + \Delta_w \qquad (16)$$

The Figure 4 assembly can be made into a cellular unit by attaching a flat closure plate below the bottom flanges. The upper and lower components will then share the shear load, P, as was illustrated in Figure 3. The free body of Figure 5 shows the webs and top flat element of a cellular assembly where external loads have produced a shear force, τt. A similar opposing shear exists at the far side. The P' and H forces are internal and shown for illustrative purposes. For a top flat element of width, W_t, and length, L, equilibrium requires $H = P'(L/W_t)$.

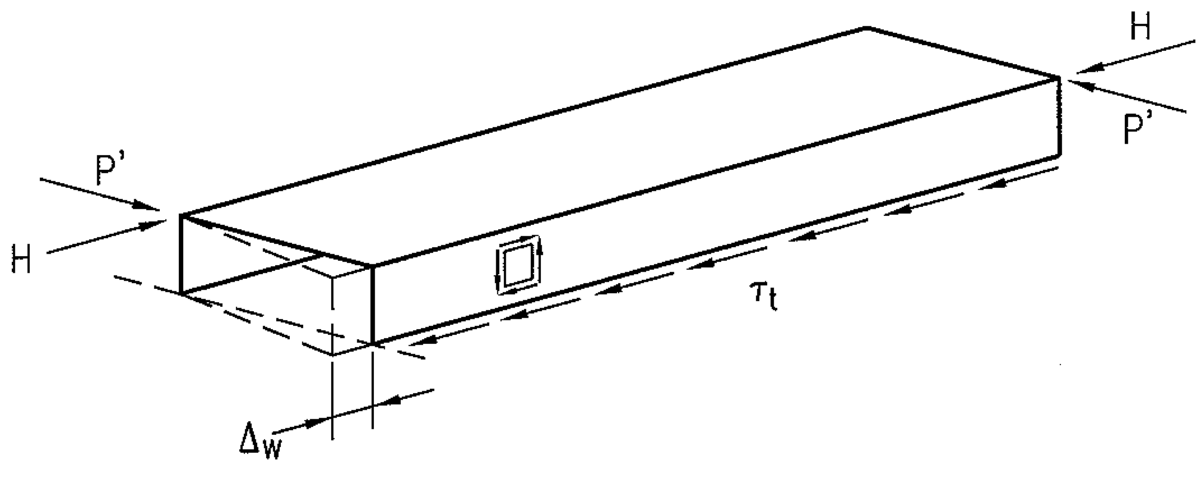

FIGURE 5
Upper free body

Removal of the end closures places both P' and H at zero permitting small increases in the deflection, Δ_W. This increase is limited by shear deflections in the bottom plate already contained in the A_A term of Equation 1.

Two views of warping influences are contained in Figures 6 and 7 from Virginia Tech Studies, Bagwell (2008) (1). The first shows an open corrugated deck diaphragm under advanced shear loading. It is clear that adjacent flange elements have significant relative movement associated with panel end warping and imposed shear forces. The second view is for a cellular diaphragm at maximum load where the lower flat plate has limited diaphragm shear deflection and rendered the warping effect invisible.

FIGURE 6
View of end warping in open corrugated section

FIGURE 7
Negligible end warping in deep cellular section. at ultimate shear

Recommendations

Based on the above discussions and on observations from cellular diaphragm tests, it is found that the warping term in the Equation 1 denominator is substantially zero. Therefore, it is recommended that Equation 1 be reformed as follows:

$$G' = \frac{Et}{A_A + C} \tag{17}$$

With consideration of the shear sharing between the top element and bottom plate, the t term in the numerator of Equation 17 is the top element thickness and the A_A term in the denominator is:

$$A_A = \frac{2.6\left(s/p \right)}{1 + \left(s/w_d \right)\frac{t_b}{t}} \tag{18}$$

Where:

The terms are defined below Equation 1 with the following refinements

- s = developed width of the cell top hat adjusted for perforations in accordance with the method of Equation 8
- p = corrugation or cell top hat pitch
- w_d = width of the cell measured between the fastener lines in the cellular deck adjusted for perforations in the bottom plate in accordance with the method of Equation 8
- t = thickness of cell top hat
- t_b = thickness of bottom plate

Appendix 2 evaluates the ratio, G'_{test}/G'_{theory}, using Equation (17) and provides an average value of 0.96 for 32 tests. The tests covered a broad range of profile depths, spans, thickness combinations, connection types, and number of connections. The average and scatter for these tests are consistent with Equation 1 as reported in *Steel Deck Institute Diaphragm Design Manual*, *First Edition* Luttrell (1981) (2) however the cellular deck outliers were greater than those reported in 1981.

Application Limits

The limits of applicability in *Diaphragm Design Manual, Third Edition*, Luttrell (2004) (3), apply to cellular deck with the following additional limitations:

1. Cellular deck depth less than or equal to 7.5 in.
2. Combined top and bottom deck thickness less than or equal to 0.155 in.
3. Thickness of each element greater than or equal to 0.035 in.
4. Top element pitch less than or equal to 12 in.
5. Bottom element that is nominally a flat plate with or without stiffeners

This does not preclude application of the theory to products outside of these limits in designs, which are verified by tests.

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2. Luttrell, L.D., *Diaphragm Design Manual*, First Edition, Steel Deck Institute, St. Louis MO, 1981.
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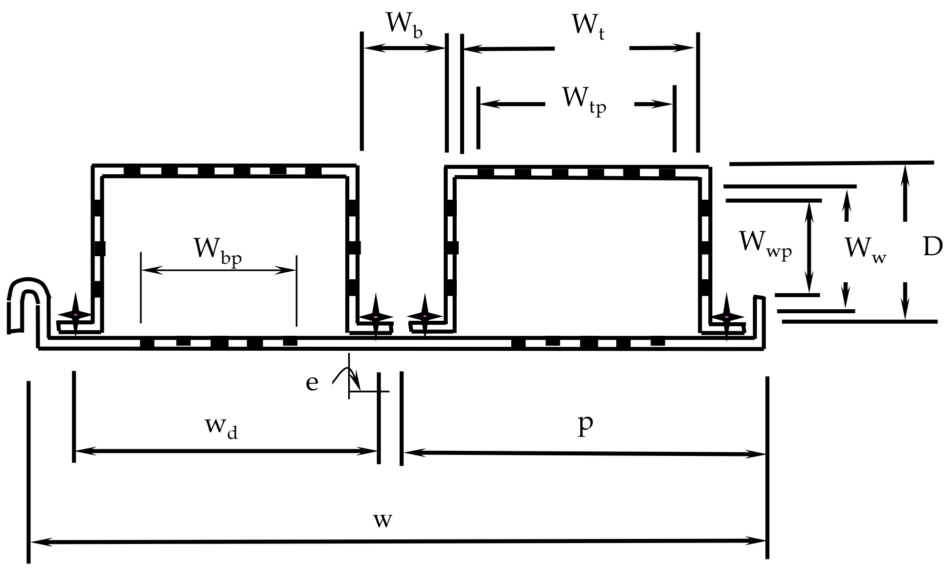
APPENDIX 1

EXAMPLE 1

Calculate the Stiffness of Cellular Deck

Figure shows perforations in all flats. This is possible but is not requisite and is not the norm. Perforations are far more common in the bottom plate only.



$$G' = \frac{Et}{A_A + C}$$

G' = Stiffness kips/in
E = 29500 ksi

$$A_A = \frac{2.6\, s_{et}/p}{1 + \left(s_{et}/s_{eb}\right)\left(t_b/t\right)}$$

$$C = \left(\frac{Et}{w}\right)\left(\frac{2L}{2\alpha_1 + n_p\alpha_2 + 2n_s \, S_f/S_s}\right)S_f$$

DATA						NOTES
Material	F_y (ksi) =	40	p_o =	0.20		p_o = Perf. area percentage within band as decimal
Hat Thickness	t =	0.0474	W_t =	8.50		Band widths are arbitrary to illustrate the method
Bottom Thickness	t_b =	0.0598	W_{tp} =	8.00		
Hat Depth	D =	6	W_b =	3.03		
Inside Radius	R_i =	0.1875	W_{bp} =	7.50		All elements - same hole pattern
Cover Width	w =	24	W_w =	5.58		Perf. centered in flat element
Pitch	p =	12	W_{wp} =	5.00		No perforations at corners

$k_e = 1 - 2.175p_o$ for $p_o < 0.2$ — Perforation Zone Efficiency

$k_e = 0.9 + p_o^2 + 1.875p_o$ for $0.2 \leq p_o \leq 0.58$ — $k_e = 0.565$

EXAMPLE 1 (continued)

Determine the contribution of shear strain in the material to diaphragm deflection considering shear sharing between the top and bottom elements -- A_A

s_{et} = Developed width of top element adjusted for perforations.

s_{eb} = Width of bott. plate between cellular deck connections adjusted for perfs.

$$s_{eb} = \left(1 + \frac{W_{bp}}{w_d}\left(\frac{1}{k} - 1\right)\right) w_d \qquad w_d = p - w_b + 1.5$$

w_d = 10.470 in.

s_{eb} = 16.244 in.

s_{et} = 37.170 in.

$$s_{et} = \left(1 + \frac{W_{tp}}{W_t}\left(\frac{1}{k} - 1\right)\right)\left(W_t + 2R_i + t\right) + 2\left(1 + \frac{W_{wp}}{W_w}\left(\frac{1}{k} - 1\right)\right) D + 1.5$$

Note: 1.5" is an allowance for total distance from webs to cellular deck connections.
The shear strain in the bott. plate between conectors is partly covered by the ratio: s_{et}/p

A_A = 2.072

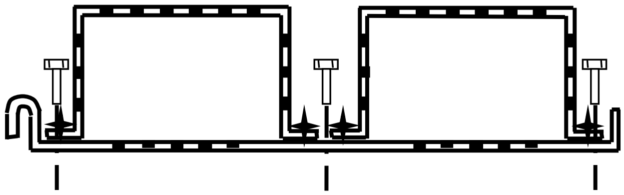
If there are no perforations in the top hat or bottom plate, A_A = 1.312 Ratio: 0.63

Determine the contribution of side lap slippage to diaphragm deflection -- C

Consider the following diaphragm construction to define a particular C:

Shear Span, L_v, (ft) = 16 Number spans = 2

Total panel length, L, (ft) = 32



Fastener Schedule

SUPPORT

Type = # 12 screws

Pattern = 24/3

SIDE LAP

Type = Button Punch

Spacing = 24 in.

Over Supports = Yes

See DDM03 for definitions and tabulation (page AIV-7): α_1, α_2, S_f, S_s, n_p and n_s

α_1 = 1 α_2 = 1 If want more precise determination:

$$\alpha_1 = \frac{\sum x_1}{w}$$

α_1 = (2*11.25+ 0)/24 = 0.9375

α_2 = (2*11.25+ 0)/24 = 0.9375

Use in Calcs

Fastener Flexibilities:

Although it is possible that screw will only be through t_b at the center, use the total thickness ($t + t_b$) to determine S_f.

$$S_f = 1.3/\left(1000\sqrt{t + t_b}\right)$$

$$S_s = 30/\left(1000\sqrt{t_b}\right)$$

S_f = 0.0040 in./kip

S_s = 0.1227 in./kip

Fasteners are not in perforated zone

Number of side lap fasteners along panel length, L. n_s = 17 n_p = 1

C = 45.404 Note: C is unitless so L has to be converted to inches.
Slip (C) dominates stiffness and deflection.

Perf: G' = 29.5 kips/in

If no perfs in top hat or in bott. plate:

G' = 29.9 kips/in Ratio: 0.985

Results: Not much difference in this case since slippage (C) dominates. C>>A_A

EXAMPLE 2

Calculate the Stiffness of Cellular Deck

Do the same problem as Example 1 but revise the fastener schedule so side lap slippage does not totally dominate -- use welds at side lap and supports.

Fastener Schedule

SUPPORT	SIDE LAP
Type = 3/4 " ϕ arc spot	Type L_w (in.)= 1.50 arc seam weld
Pattern = 24/3 weld	Spacing = 24 in. o. c.
	Over Supports = Yes

A_A = 2.072 $\alpha_1 = 0.9375$ $n_s = 17$

$\alpha_2 = 0.9375$ $n_p = 1$

Total panel length, L, (ft) = 32

$$S_f = 1.15/\left(1000\sqrt{t + t_b}\right)$$

$S_f = 0.0035$ in./kip

$$S_s = \left(\frac{1.12}{1000\sqrt{t_b}}\right)\left(\frac{L_w}{1.5}\right)^{0.25}$$

$S_s = 0.0046$ in./kip

See Nunna[8].

$$C = \left(\frac{Et}{w}\right)\left(\frac{2L}{2\alpha_1 + n_p\alpha_2 + 2n_s \frac{S_f}{S_s}}\right)S_f$$

C = 5.441

$$G' = \frac{Et}{A_A + C}$$

With Perforations in Top and Bottom

G' = 186.1 kips/in

No Perforations in Top and Bottom

A_A = 1.312 **C = 5.441** **G' = 207.1** kips/in

$\Delta G'$ = 207.1-186.1 = 21.0

Results: In this case with A_a/ C = 0.24, the perforations reduce the stiffness by 10%. This is an unusual case with perforations over most of the width of all elements. This impact is relatively minor.

Do the same problem as Example 2 but with no perforations in the top hat while perforations are in the bottom plate. This application is quite common.

No Perforations in Top and Perforations in Bottom

A_A = 1.772 **C = 5.441** **G' = 193.9** kips/in

s_{et} = 22.422 in. $\Delta G'$ = 207.1-193.9 = 13.2

Results: In this case with A_A/ C = 0.33, the bottom perforations reduce the stiffness by 6.4%. The impact is relatively minor.

APPENDIX 2

TABLE A2-1 Summary of Luttrell 2005 Report Data

Test Number	Source	Elements - in. top	depth	pitch	bottom	Cover	Fastener Schedule Support		Side-lap			Flexibility - in/kip t + t_b	t_b	**G'** $_{test}$	**Span** ft
		t	D	d	t_b	w	weld	pattern	type	spacing	n_s	S_f	S_s	kip/in.	L_v
10	D Cellular	0.0478	3	12	0.0598	24	1 in.	24/3	1.5 TS	18	9	0.00351	0.00458	230	12
57-2	Table1	0.0478	3	12	0.0598	24	1 in.	24/3	1.5 TS	18	9	0.00351	0.00458	322	12
58-8		0.0478	4.5	12	0.0598	24	1 in.	24/3	1.5 TS	18	16	0.00351	0.00458	189	22
58-5		0.0478	6	12	0.0598	24	1 in.	24/3	1.5 TS	18	21	0.00351	0.00458	276	30
58-6		0.0478	6	12	0.0598	24	1 in.	24/3	1.5 TS	18	21	0.00351	0.00458	247	30
59-4		0.0478	3	12	0.0598	24	1 in.	24/3	1.5 TS	18	11	0.00351	0.00458	150	15
58-4		0.0478	6	12	0.0598	24	1 in.	24/3	1.5 TS	18	21	0.00351	0.00458	205	30
58-2		0.0478	7.5	12	0.0598	24	1 in.	24/3	1.5 TS	18	21	0.00351	0.00458	191	30
58-2a		0.0478	7.5	12	0.0598	24	1 in.	24/3	1.5 TS	18	21	0.00351	0.00458	218	30
9		0.0478	3	12	0.0478	24	1 in.	24/3	1.5 TS	18	9	0.00372	0.00512	176	12
59-2		0.0478	4.5	12	0.0478	24	1 in.	24/3	1.5 TS	18	16	0.00372	0.00512	167	22
2a	Nilson 56	0.0598	3	12	0.0598	24	1 in.	24/3	BP	24	7	0.00333	0.12268	83	12
57-3	D Cellular	0.0478	3	12	0.0598	24	1 in.	24/3	BP	24	7	0.00351	0.12268	118	12
57.5	Table 2	0.0478	3	12	0.0598	24	1 in.	24/3	BP	24	7	0.00351	0.12268	109	12
5	Nilson 56	0.0598	3	12	0.0598	24	1 in.	24/3	BP	24	6	0.00333	0.12268	84	10
58-3		0.0478	6	12	0.0598	24	1 in.	24/3	BP	24	16	0.00351	0.12268	35	30
11		0.0478	3	12	0.0478	24	1 in.	24/3	BP	24	7	0.00372	0.13722	64	12
59-5		0.0478	3	12	0.0478	24	1 in.	24/3	BP	24	9	0.00372	0.13722	49	15
58-7		0.0478	4.5	12	0.0478	24	1 in.	24/3	BP	24	12	0.00372	0.13722	25	22
SBB2	M2SR -18/16	0.0478	7.5	12	0.0598	24	5/8 in.	24/3	BP	24	16	0.00351	0.12268	21	30
Corn 69-1		0.0478	3	12	0.0747	24	1 In. +	24/5	2.5+TS	9	65	0.00329	0.00466	430	48
Corn 69 2		0.0478	7.5	12	0.1045	24	1 in. +	24/5	3.5+ TS	9	65	0.00295	0.00428	720	48

Note: Shaded Results are repeat tests. **TS** = Top Seam Weld **BP** = Button Punch

S_s for TS welds is based on Nunna (2012)[8]. Other flexibilities are taken from DDM03, Luttrell (2004)[3].

Calibration of Cellular Deck Stiffness Equation Using Luttrell Report Data Listed in Table A2-1

TABLE A2-2 Calibration

Total Tests = n = 22

All test = single span $n_p = 0$, $\alpha_2 = 0$

Test Number	Side lap Type	s	w_d	α_1	A_A	C	G'_{theory} kip/in.	R_i	Average	$(R_i-R_m)^2$
10	TS	16.5	10.5	0.938	1.205	3.790	282	0.815	0.840	0.092
57-2		16.5	10.5	0.938	1.205	3.790	282	1.141		0.000
58-8		19.5	10.5	0.938	1.271	4.124	261	0.723		0.156
58-5		22.5	10.5	0.938	1.324	4.359	248	1.112		0.000
58-6		22.5	10.5	0.938	1.324	4.359	248	0.996		0.015
59-4		16.5	10.5	0.938	1.205	3.962	273	0.550		0.323
58-4		22.5	10.5	0.938	1.324	4.359	248	0.826		0.085
58-2		25.5	10.5	0.938	1.368	4.359	246	0.776		0.117
58-2a		25.5	10.5	0.938	1.368	4.359	246	0.885		0.054
9		16.5	10.5	0.938	1.390	4.212	252	0.699		0.176
59-2		19.5	10.5	0.938	1.479	4.595	232	0.719		0.159
2a	BP	16.5	10.5	0.938	1.390	31.224	54	1.534	1.422	0.173
57-3		16.5	10.5	0.938	1.205	26.075	52	2.283		1.356
57.5		16.5	10.5	0.938	1.205	26.075	52	2.109		0.981
5		16.5	10.5	0.938	1.390	26.661	63	1.336		0.047
58-3		22.5	10.5	0.938	1.324	53.167	26	1.353		0.055
11		16.5	10.5	0.938	1.390	27.916	48	1.330		0.045
59-5		16.5	10.5	0.938	1.390	33.294	41	1.205		0.008
58-7		19.5	10.5	0.938	1.479	45.686	30	0.836		0.080
SBB2		25.5	10.5	0.938	1.368	53.167	26	0.812		0.094
Corn 69 1	TS	16.5	10.5	1.875	1.035	2.329	419	1.026	1.283	0.009
Corn 69 2		25.5	10.5	1.875	0.876	2.140	468	1.540		0.177
							R_m =	**1.118**	Σ =	4.203

$$R_i = \frac{G'_{i\,test}}{G'_{i\,theory}}$$

$$R_m = \frac{\sum R_i}{n}$$

$$G' = \frac{Et}{A_A + C}$$

$$A_A = \frac{2.6\left(s/p\right)}{1 + \left(s/w_d\right)\frac{t_b}{t}}$$

$$C = \left(\frac{Et}{w}\right)\left(\frac{2L}{2\alpha_1 + n_p\alpha_2 + 2n_s\frac{S_f}{S_s}}\right)S_f$$

V_p = 0.40 Coefficient of variation. See Commentary of AISI Specification Section F1.1.

Note: t in numerator of G' is top element thickness
Shaded areas are outliers that skew results.

Average of all TS is 0.908; average of all BP is 1.422. Each set has values either side of 1.0. Average of all is 1.118.
R_m is consistent with the results of identical tests - 322/230 = 1.4, 276/205 = 1.35, 218/191 = 1.14, and 119/109 = 1.09.

TABLE A2-3 Summary of Bagwell 2008 Report Data Based on Corner Deflections

Test	Source	Elements - in.					Fastener Schedule					Flexibility - in/kip			Span
		top	depth	pitch	bottom	Cover	Support		Side-lap			$t + t_b$	t_b	G'_{test}	ft
Number		t	D	d	t_b	w		pattern	type	spacing	n_s	S_f	S_s	kip/in.	L_v
2	USD 20/20	0.0359	4.5	12	0.0359	24	#12	24/3	#10	36	7	0.00586	0.01583	55.10	24
4	USD 18/18	0.0472	4.5	12	0.0475	24	#12	24/3	#10	36	7	0.00509	0.01376	33.15	24
5	USD 18/20	0.0475	7.5	12	0.0358	24	#12	24/3	#10	36	7	0.00569	0.01586	53.30	24
10	USD 18/20	0.0474	7.5	12	0.0358	24	Hilti	24/3	#10	36	7	0.00328	0.01586	34.34	24
11	USD 16/18	0.0597	7.5	12	0.0471	24	Hilti	24/3	#10	36	7	0.00288	0.01382	35.88	24
13	USD 20/20	0.0358	4.5	12	0.0355	24	3/4 weld	24/3	#10	12	23	0.00521	0.01592	52.21	24
15	VC 16/16	0.0592	3	8	0.0592	24	Hilti	24/4	BP	12	23	0.00218	0.12330	14.88	24
16	VC 20/20	0.0360	3	8	0.0360	24	Hilti	24/4	BP	12	23	0.00280	0.15811	11.47	24
18	VC 18/18	0.0464	3	8	0.0464	24	#12	24/4	#12	12	23	0.00427	0.01393	96.35	24
19	VC 20/20	0.0360	3	8	0.0360	24	#12	24/4	#12	12	23	0.00484	0.01581	72.25	24

Note: #12, #10 = Screw **Hilti =** X-ENP-19 L15 **BP** = Button Punch

Bagwell report has apparent discrepancy at Tests 16, 19; the reported thickness does not agree with nomenclature and connection strength back calculation. The thickness in calibration is most probable answer.

USD side lap is unique. S_f should be based on the average of t_b and $t + t_b$, and S_s on t_b. VC S_f is based on $t+t_b$ and S_s on t_b.

Calibration of Cellular Deck Stiffness Equation Using Bagwell Report Data Listed in Table A2-3

TABLE A2-4 Calibration

Total Tests = n = 10

All test = single span $n_p = 0$

$\alpha_2 = 0$

Test Number	Side lap Type	s	w_d	α_1	A_A	C	G'_{theory} kip/in.	R_i	Average	$(R_i\text{-}R_m)^2$
2	screw	19.5	10.5	1	1.479	20.737	48	1.156	0.744	0.281
4		19.5	10.5	1	1.473	23.706	55	0.599		0.001
5		25.5	10.5	1	1.952	27.239	48	1.110		0.235
10		25.5	10.5	1	1.949	22.487	57	0.600		0.001
11		25.5	10.5	1	1.895	24.742	66	0.543		0.007
13		19.5	10.5	1	1.487	7.743	114	0.456		0.029
15	BP	13.26	8	1.33	1.622	26.258	63	0.238	0.238	0.151
16		13.26	8	1.33	1.622	20.476	48	0.239		0.150
18	screw	13.26	8	1.33	1.622	8.364	137	0.703	0.657	0.006
19		13.26	8	1.33	1.622	7.367	118	0.612		0.000
							R_m =	0.626	Σ =	0.859
									V_p =	0.49

Shaded areas are outliers that skew results.

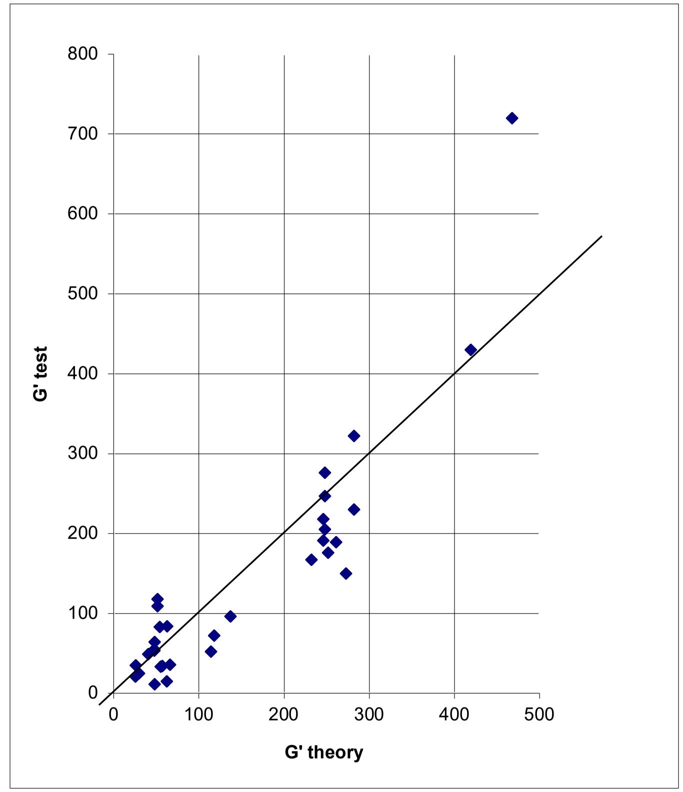
TABLE A2-5 Calibration of All Cellular Deck Stiffness Data

Total Number of Tests = n = 32

Test Number	Side lap Type	Data Source	G'_{test} kip/in.	G'_{theory} kip/in.	R_i	R_i Average	$(R_i-R_m)^2$
10	**TS**	Luttrell 2005 Report	230	282	0.815	0.908	0.022
57-2			322	282	1.141		0.031
58-8			189	261	0.723		0.058
58-5			276	248	1.112		0.022
58-6			247	248	0.996		0.001
59-4			150	273	0.550		0.172
58-4			205	248	0.826		0.019
58-2			191	246	0.776		0.036
58-2a			218	246	0.885		0.006
9			176	252	0.699		0.070
59-2			167	232	0.719		0.060
Corn 69 1			430	419	1.026		0.004
Corn 69 2			720	468	1.540		0.331
2a	**BP**	Luttrell 2005 Report	83	54	1.534	1.207	0.325
57-3			118	52	2.283		1.738
57.5			109	52	2.109		1.310
5			84	63	1.336		0.138
58-3			35	26	1.353		0.151
11			64	48	1.330		0.134
59-5			49	41	1.205		0.058
58-7			25	30	0.836		0.016
SBB2			21	26	0.812		0.023
15VC		Bagwell Report	15	63	0.238		0.528
16 VC			11	48	0.239		0.527
2	**Screw**	Bagwell Report	55	48	1.156	0.722	0.037
4			33	55	0.599		0.133
5			53	48	1.110		0.021
10			34	57	0.600		0.133
11			36	66	0.543		0.178
13			52	114	0.456		0.258
18			96	137	0.703		0.068
19			72	118	0.612		0.125

$R_m =$ **0.964** $\Sigma = 6.733$

$V_p = 0.483$



Shaded areas are outliers that skew results.

Cellular Deck Stiffness Data

Comments

Data covers a wide range of configurations varying: span, thickness combination, connection type, and number of side lap connections. Each side lap connection sub-set has data either side of 1.0. Greatest scatter occurs at BP but most BP tests are conservative - Test > Theory. The Bagwell tests generally are not conservative even with screws but Bagwell also measured diagonal readings, which is allowed by AISI S907.

When diagonal readings are used, the average of tests, Rm, changed from 0.63 to 1.92 for all and from 0.72 to 2.32 for screws. This confirms that accurate measurement of deflection is both difficult and essential. Historical testing used corner readings. The scatter of the cellular deck stiffness equation (84% > 0.6) is consistent with DDM01 Luttrell (1981), which ranged between 0.61 and 1.41.

The proposed stiffness method is reasonable.