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ROOF DIAPHRAGM STRENGTH and STIFFNESS

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Abstract

Five full-scale cantilever diaphragm tests were conducted at the Structures and Materials Research Laboratory of Virginia Polytechnic Institute and State University, Blacksburg, Virginia. The tests were sponsored by the Metal Construction Association (MCA) and were conducted to evaluate the applicability of the *Primer on Diaphragm Design*, published by the MCA, for aluminum panel assemblies over a wider range of panel depth, thickness and profile than is currently recognized. The tests were conducted in accordance with the AISI "Cantilever Test Method for Cold-Formed Steel Diaphragms."

The diaphragm shear stiffness development parallels that shown in the Steel Deck Institute *Diaphragm Design Manual* but with one modification, the introduction of a modified panel edge term, K. Most SDI diaphragms have their stiffness controlled by structural connectors along panel sidelaps with stitch fastener contribution added in through a ratio of fastener stiffness. Panel edge conditions dictate both strength and stiffness. The general stiffness formula is modified by a term, K=2/3 for aluminum panels when using the MCA Primer on Diaphragm Design. The use of K = 2/3 is supported by the test data.

The results show remarkably narrow scatter in tested-to-theoretical strength ratios. Similarly, tested-to-theoretical stiffness ratios compare well supporting the proposed use of K = 2/3 for Eq. 6. Page 22 of the *MCA Diaphragm Primer* has a *Case 3- Fasteners Through Aluminum Panels to Steel Supports.* The listed

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case indicates that, the recommendations apply to panels with a maximum thickness of 0.021 inches. That recommended 0.021 in. maximum thickness represented the upper thickness limit tested during development of the MCA Primer. The current studies indicate that the upper thickness limit can be raised safely to 0.050 inches. The test data further indicate that the MCA strength and stiffness formulations work well for panels with depths through 4 inches.

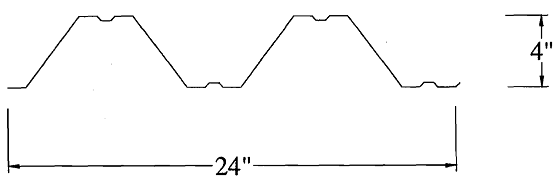
Introduction

Five cantilever diaphragm tests were conducted to evaluate the diaphragm strength and stiffness of Deep-Rib (0.04 in.), Hefti-Rib (0.032 in., 0.040 in. and 0.050 in.) and Strong-Rib (0.018 in.) aluminum panel assemblies. Deep-Rib and Hefti-Rib panels were HS35-H36 aluminum whereas Strong-Rib panels were HS35-H38 aluminum. The panel cross sections are illustrated in Figure 1. The tests were conducted in accordance with the AISI "Cantilever Test Method for Cold-Formed Steel Diaphragms".

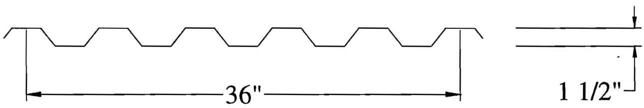
Experimental Study

The cantilever diaphragm test frame, as shown in Figures 2 and 3, was constructed of seven H-shaped sections. Four W10x30 sections were used as perimeter members. Three W10x20 sections were used as filler members except the Deep-Rib assembly for which only one filler beam was used.

Deep-Rib Panel (0.040 in)



Hefti-Rib Panel (0.032 in, 0.040 in and 0.050 in)



Strong-Rib Panel (0.018 in)

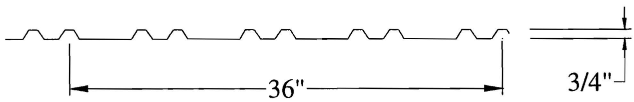


Figure 1- Deep-Rib, Hefti-Rib and Strong-Rib Panel Profiles

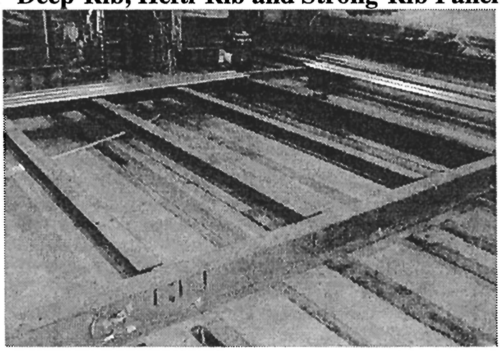


Figure 2- Bare Diaphragm Test Frame

Nominal plan dimensions were 16 ft by 16 ft. The perimeter members were connected with a single-angle at corner B, a double angle at corner C, and a T-section at corner D. A pin was used to connect the frame members at corner A. Member CD was attached to the reaction floor by using pinned base assemblies at locations C and D. The web was braced at points C and D to minimize rolling of the member, as illustrated in Figure 3. Member AB was supported by rollers at locations A and B. An additional roller assembly was positioned at A on the bottom flange to resist uplift of the member.

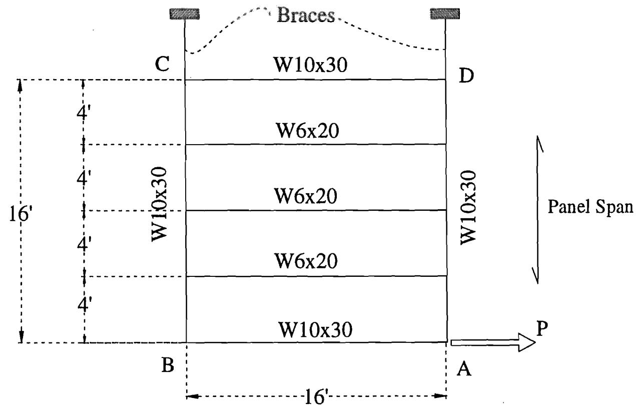


Figure 3- Diaphragm Test Setup- Plan View

The deck panels were connected to the frame (*structural connectors*) using ¼-14x1 in. screws and the panel-to-panel connectors (*stitch connectors*) were made with 14-10x3/4 in. screws. The panel profiles and connection details are illustrated in Figures 4-6.

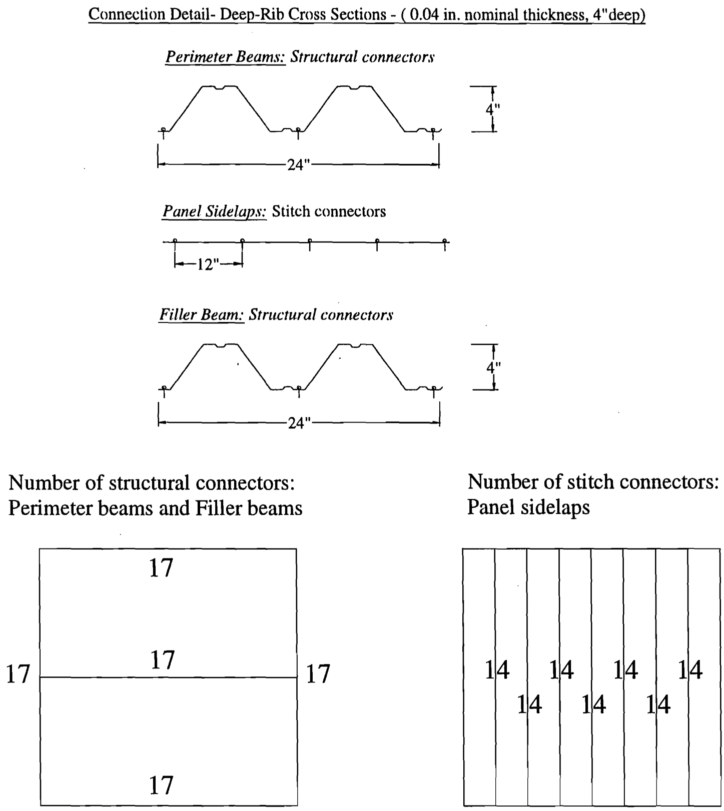
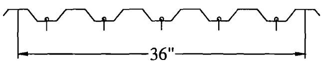


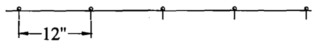
Figure 4- Deep-Rib Cross Section- Connection Details

Connection Detail- Hefti-Rib Cross Sections - 1 1/2"deep
(Same connector orientation for 0.032, 0.040, 0.050 in nominal thicknesses)

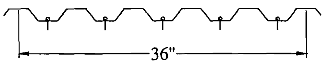
Perimeter Beams: Structural connectors



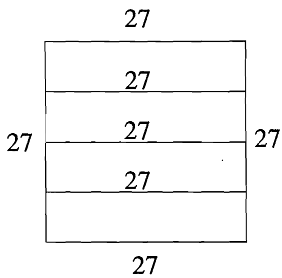
Panel Sidelaps: Stitch connectors



Filler Beams: Structural connectors



Number of structural connectors:
Perimeter beams and Filler beams



Number of stitch connectors:
Panel sidelaps

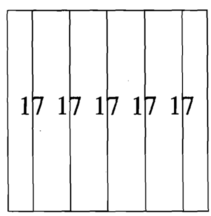


Figure 5- Hefti-Rib Cross Sections- Connection Details

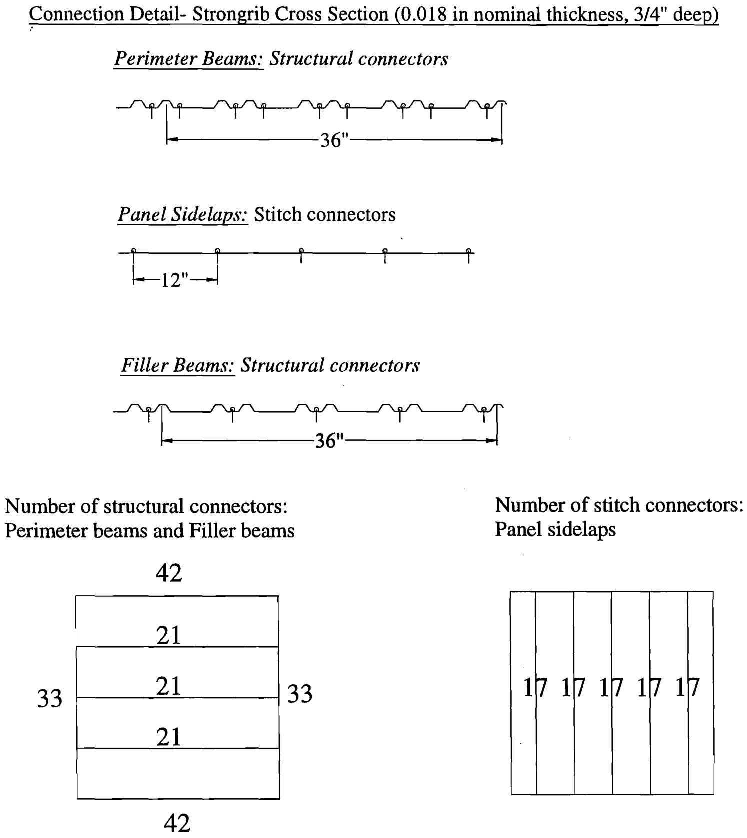


Figure 6- Strong-Rib Cross Section- Connection Details

The load was applied to the test setup at corner A using a hydraulic actuator attached to the reaction floor. The load was measured with a 20 kip load cell, which connected the frame to the hydraulic ram.

The stiffness of the bare test frame and additional roller assembly was found to be negligible.

Frame displacements were measured during each test by displacement transducers. Transducer locations are shown in Figure 7 and are identical in designation to the AISI cantilever diaphragm method. The load and all displacements were recorded for each test at various points using a Measurements Group System 5000 Data Acquisition System.

In accordance with the "Cantilever Test Method for Cold-Formed Steel Diaphragms," transverse and parallel deflections were combined to arrive at a net shear and corrected deflection that accounts for movement of the frame supports. Corrected deflection, Δ_f, was computed by:

$$\Delta_f = \Delta_3 - [\Delta_2 + (a/b)(\Delta_1 + \Delta_4)] \qquad (1)$$

where a and b are the dimensions of the diaphragm are both 16 feet.

The preload level for each test was between 10 and 20 percent of the maximum load. The loading sequence consisted of loading at 300-400 lbs per load increment. The system was then loaded to failure, which was determined when the load dropped significantly on the measured load vs. displacement curve.

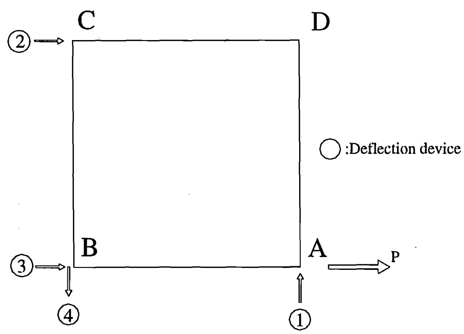


Figure 7- Displacement Transducer Locations

The results from the tests are summarized in Figures 8-12. Values are calculated for diaphragm shear strength and shear stiffness based on equations given in the AISI "Cantilever Test Method for Cold-Formed Steel Diaphragms." The maximum diaphragm shear strength, S_n, was calculated as:

$$S_n = \frac{P_n}{b} \qquad (2)$$

where P_n is the maximum applied force and b = 16 ft. The shear stiffness, G', was calculated for each test as:

$$G' = \left(\frac{P}{\Delta}\right)_{0.4Pn} \left(\frac{a}{b}\right) \quad (3)$$

where $P = 0.4P_n$, Δ=corrected deflection at P, a = b = 16 ft for the tests.
A comparison between test and theoretical information is also shown in Figs 8-12. The inclined dashed line from the origin represents the theoretical stiffness and the horizontal dashed line represents the theoretical strength as found from the MCA aluminum formulas.

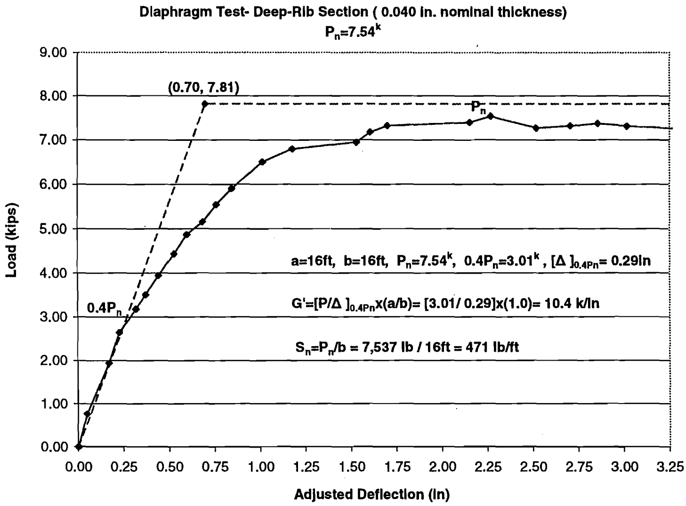


Figure 8- Load vs. Adjusted Def. for Deep-Rib (0.040 in) Section

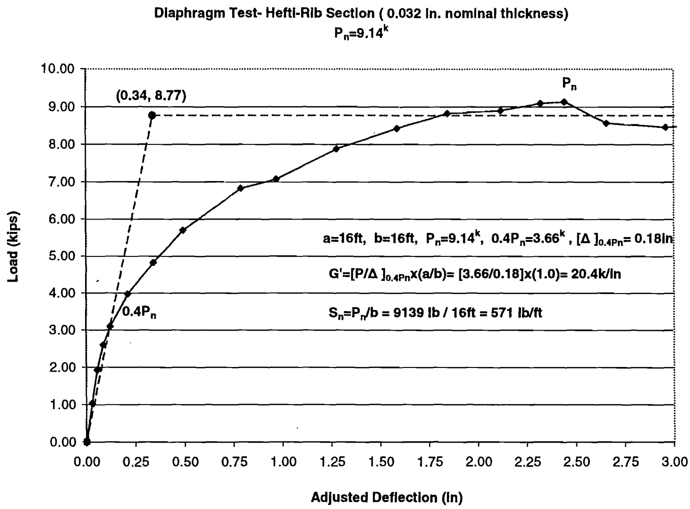


Figure 9- Load vs. Adjusted Def. for Hefti-Rib (0.032 in) Section

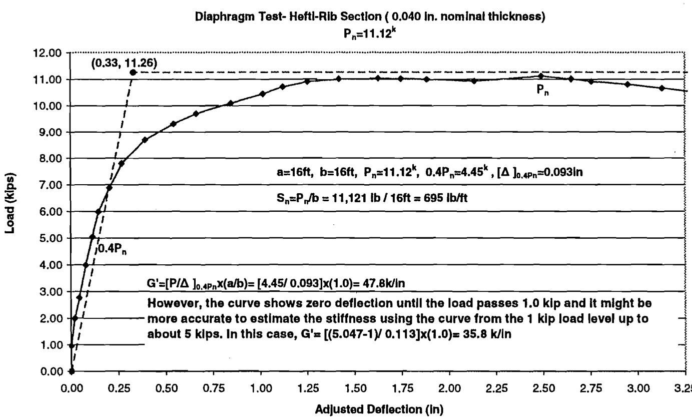


Figure 10- Load vs. Adjusted Def. for Hefti-Rib(0.040 in) Section

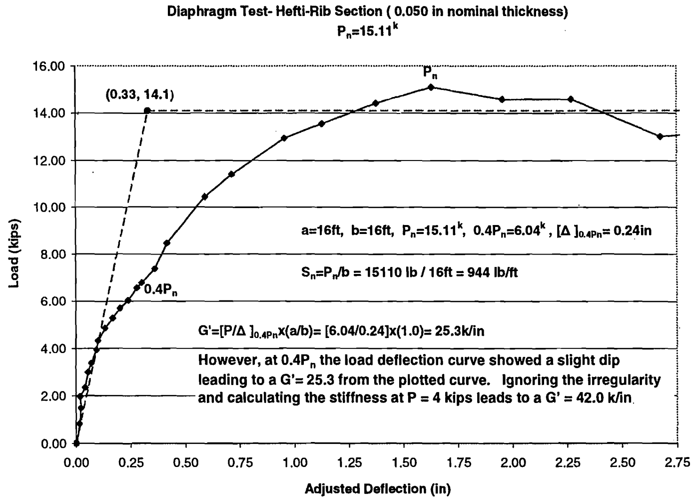


Figure 11- Load vs. Adjusted Def. for Hefti-Rib(0.050 in) Section

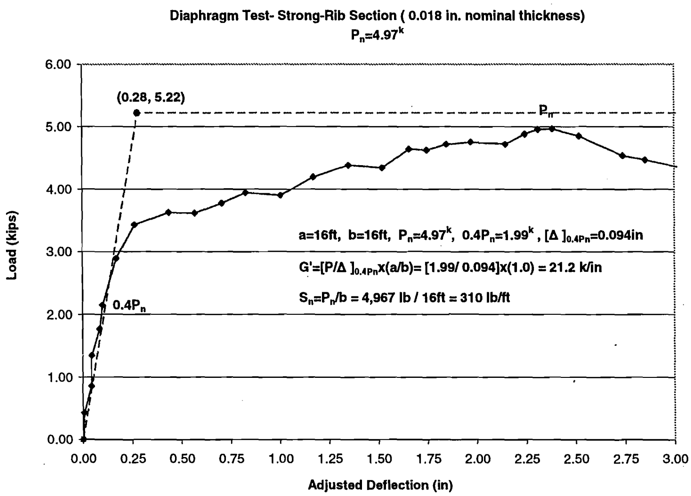


Figure 12-Load vs. Adjusted Def. for Strong-Rib (0.018 in) Section

The observed modes of failure are shown in Figs 13-15.

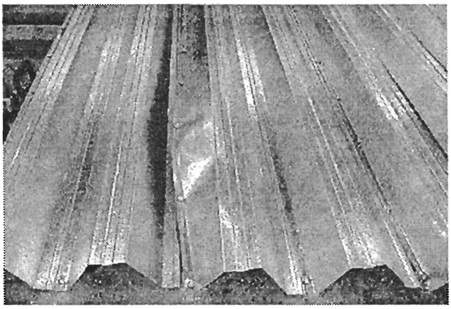


Figure 13- Deep-Rib (0.040 in) Panel at Failure

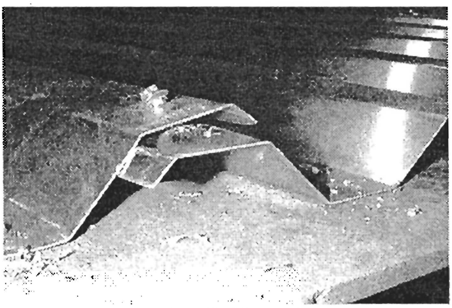


Figure 14- Hefti-Rib (0.050 in) Panel at Failure

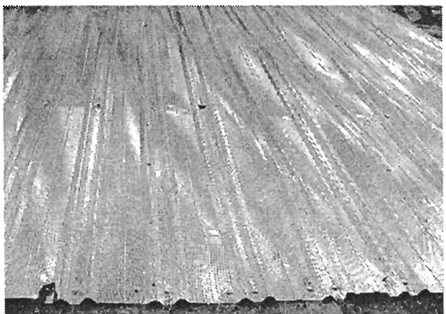


Figure 15- Strong-Rib (0.018 in) Panel at Failure

Analytical Study

The diaphragms tested in this program have been evaluated according to design formulas and principals contained in the *Primer on Diaphragm Design*, published by the MCA. A partial summary of applicable formulas is presented below and followed by the data evaluations. The *MCA Diaphragm Primer* contains a series of example problems that may make interpretation of this report easier and it is presumed that the MCA Primer is available to the reviewer.

Diaphragm shear strength typically is controlled by one of three limiting conditions with two being in the field of diaphragm and the third being shear transfer limits on longitudinal edges. In this test series, longitudinal edge connections were spaced at the same distance as fasteners at sidelaps. Edge fasteners were stronger than average fasteners on sidelaps and the longitudinal edge condition did not control in the tests. Limits are detailed in Section 5 of the primer. Equation 9 from the *MCA Primer* is given by:

$$S_u = \frac{P_u}{L} = B\frac{Q_f}{L} \qquad (4)$$

where $B = n_s \alpha_s + 2 n_p \sum \frac{x_p^2}{w^2} + 4 \sum \frac{x_e^2}{w^2}$

x_p = any purlin fastener position relative to panel centerline
x_e = any end fastener position relative to panel centerline
w = panel width, in.
L = panel length, ft
$Q_f = 1.818\ d\ F_{by}\ t$ (limiting at cross supports)
$Q_f = 1.282\ d\ F_{bu}\ t$
$Q_s = 4.2\ F_{tu}\ (t^3\ d)^{0.5}$
$\alpha_s = Q_s/Q_f$, ratio of stitch fastener strength to structural fastener strength.
P_u = diaphragm strength

A second strength limiting condition involves those structural fasteners on panel corners. The MCA Primer indicates that panel corner fasteners will experience perpendicular shear components with one developing across the panel width and the other in the panel spanning direction. The resultant may limit field strength as follows:

$$S_u = Q_f \sqrt{\frac{N^2 B^2}{L^2 N^2 + B^2}} \qquad (5)$$

N = average number of structural fasteners per foot across panel ends.
The diaphragm shear stiffness development parallels that shown in the *Steel Deck Institute Diaphragm Design Manual* but with one modification, the

introduction of a modified panel edge term, K. Most SDI diaphragms have their stiffness controlled by structural connectors along panel sidelaps with stitch fastener contribution added in through a ratio of fastener stiffness. Panel edge conditions dictate both strength and stiffness. For aluminum panel diaphragms, the general stiffness formula is modified by a term, K=2/3, which is supported by the test data in this chapter.

$$G' = \left[\frac{E\,t}{2.6\,(s/p) + D_n + C} \right] K \tag{6}$$

where: E = Young's modulus, 10,100 ksi for aluminum
t = panel base metal thickness, in.
K = 2/3 for diaphragms with aluminum panels
s = developed sheet width per pitch, in.
p = rib pitch, in.
D_n = panel warping term developed by Eq. 8 below.

$$C = \frac{E\,t}{w} S_f \left(\frac{24\,L}{2\alpha_e + n_p\alpha_p + 2n_s(S_f/S_s)} \right) \tag{7}$$

with: w = panel cover width, in.
S_f = structural fastener stiffness, in./kip.
L = panel length, ft.
n_p = number of interior purlins per L. (Panel end supports counted elsewhere.)
α_e = fastener position factor at panel ends.
α_p = fastener position factor on interior purlins.
S_f/S_s = unity for aluminum panels

With connections of various spacing across panel ends, the *MCA Diaphragm Primer* defines the warping term as:

$$D_n = [0.94(p/w_t)][V^2][d_d w_t^2/25L][1/t]^{1.5} \quad \text{For } 1 < V \le 4 \tag{8}$$

where: d_d = depth of panel profile
w_t = width of top flat element in corrugation

When end fasteners are in every valley, V = 1, Eq. 8 simplifies to

$$D_{n1} = [d_d w_t^2/25L][1/t]^{1.5} \tag{9}$$

Results from the test series are summarized in Table 1 below:

Table 1- Test Summaries

Test No.	Test S_0 (k/ft)	Theoretical S_u (k/ft)	Test/ Th. S_0/S_u	Test G_0' (k/in)	Theoretical G' (k/in)	Test/ Th. G_0'/G'
Deep-Rib (0.040 in)	0.471	0.488	0.97	10.4	11.22	0.93
Hefti-Rib (0.032 in)	0.571	0.548	1.04	20.4	26.04	0.78
Hefti-Rib (0.040 in)	0.695	0.704	0.99	35.8	33.87	1.06
Hefti-Rib (0.050 in.)	0.944	0.881	1.07	42.0	42.88	0.98
Strong-Rib (0.018 in)	0.310	0.326	0.95	21.2	18.68	1.13
		Avg.	1.00		Avg.	0.98

Conclusions

The results of Table 1 show remarkably narrow scatter in tested-to-theoretical strength ratios. The tested-to-theoretical stiffness ratios of the last column compare well, thus supporting the proposed use of K = 2/3 for Eq. 6. *Case 3- Fasteners Through Aluminum Panels to Steel Supports* of the *MCA Diaphragm Primer* (page 22) indicates that the recommendations apply to panels with a maximum thickness of 0.021 inches. The recommended 0.021 in. maximum thickness represents the upper thickness limit tested during development of the MCA Primer. The current studies indicate that the upper thickness limit can be raised safely to 0.050 inches. The test data also indicate that the MCA strength and stiffness formulations work well for panels with depths through 4 inches.

References

AISI (1996). "Specification for the Design of Cold-Formed Steel Structural Members", American Iron and Steel Institute, Washington, D.C.

Luttrell, L. D. and Mattingly, J. A., "A Primer on Diaphragm Design", Metal Construction Association.