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UPDATE ON DIAPHRAGM DESIGN VALUE DETERMINATION

Using the Modified Metal Construction Association Procedure

Lateral loads are primarily resisted by roof diaphragms and shear walls in post-frame buildings. Although a variety of sheathing materials can be used, most often corrugated steel panels are fastened to the wood frame to form shear walls and diaphragms. The strength and stiffness of these diaphragm assemblies must be known if proper analysis and lateral design of the building are to be carried out; however, the design database is lacking.

Three methods are commonly used to determine steel-clad wood-framed (SCWF) diaphragm strength and stiffness: large-scale diaphragm tests, small-scale diaphragm tests and mathematical modeling. Large-scale diaphragms are an exact replica (in regard to both construction and size) of the diaphragm in the building being designed. Small-scale tests typically range in size from 9 x 12 foot cantilever tests to 24 x 12 foot simple beam tests and are equivalent in construction to the diaphragm in the building being designed. Design values are typically derived through small-scale tests conducted in accordance with American National Standards Institute/American Society of Agricultural Engineers Standard EP558 (American Society of Agricultural and Biological Engineers, 2004). Although most common, design values obtained from small-scale tests are limited because of their high cost and the considerable time required to perform tests. Furthermore, the structural responses of small-test diaphragms do not necessarily mimic the responses of larger test panels or actual full-size roof diaphragms.

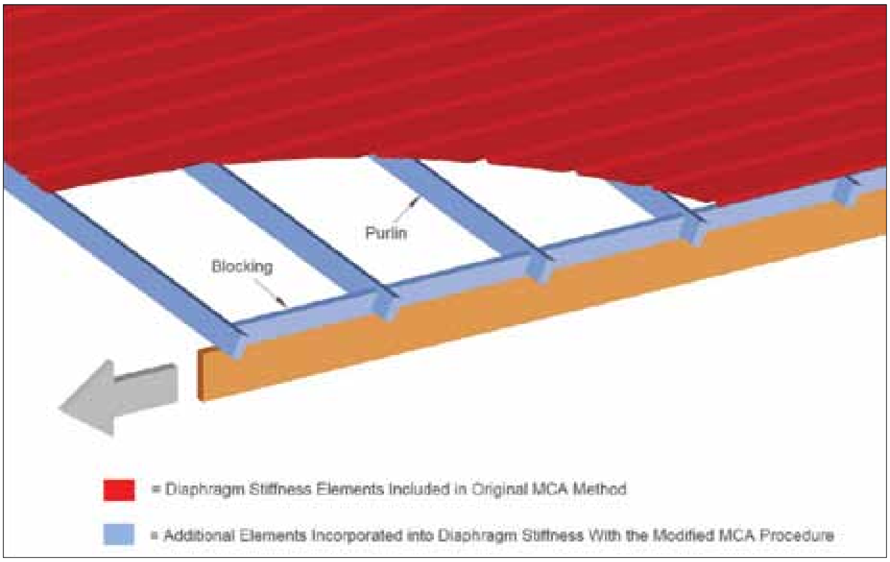

Figure 1. Deformation of out-of-plane elements when loaded (rotation of framing members amplified to demonstration deformed shape)

A mathematical method for determining strength and stiffness for steel-clad steel-framed (SCSF) diaphragms, *A Primer on Diaphragm Design*, was developed by Luttrell and Mattingly (2004) and published by the Metal Construction Association. The MCA method has been widely used by the steel building industry. Leflar (2008) and Anderson (2011) modified the MCA procedure to predict shear strength and stiffness of SCWF diaphragms. The model, referred to as the *modified MCA procedure*, allows design values to be predicted analytically with less reliance on expensive diaphragm testing (Anderson, 2011).

The modified MCA procedure is being considered as a tool for developing the standard design value database for the next revision of the ANSI/ASAE EP484.2 diaphragm design standard (ASABE, 2012). This article presents an overview of the modified MCA procedure, along with an independent validation of the modified MCA procedure using data obtained from recent diaphragm tests sponsored by the National Frame Building Association (Bender & Aguilera, 2013). In addition, our examination of the modified MCA procedure revealed potential issues with using design values obtained from small-scale diaphragm tests. The model predicts that diaphragm length can have impacts on strength and stiffness. Blocking, often used in small-scale diaphragm tests to eliminate premature purlin failure, can significantly increase stiffness values. However, in an actual building an unblocked diaphragm is commonly used, and the stiffness of a test panel may not be appropriate. **Figure 1** shows blocking in a diaphragm with purlins running on top of truss top chords. The modified MCA model can accommodate blocked, partially blocked and unblocked diaphragms. These issues are being considered in the next revision of the ASAE EP484.2 diaphragm design standard, with the end goal of safe and economical post-frame designs.

The Modified MCA Procedure

The modified MCA procedure is based on engineering mechanics and empirical formulas. A general outline of the model is shown in the flowchart in **Figure 2**. One significant contribution made by Leflar (2008) and Anderson (2011) is the incorporation of blocking to account for its effects on strength and stiffness. Screws placed into the blocking add strength to the diaphragm, while also adding considerable stiffness to the diaphragm assembly. The strength of the diaphragm is governed by the smallest value obtained from the three limit states of steel panel buckling, failure of panel corner fasteners and failure of fasteners in the field (Anderson, 2011). The stiffness of *out-of-plane elements*, namely the purlins and shear blocking, are incorporated into the diaphragm stiffness, yielding lower stiffness values than those computed from the original MCA procedure, and compare well with small-scale SCWF diaphragm test panels. Figure 1 depicts the additional layers and associated displacements accounted for by the modified MCA procedure.

In post-frame buildings, the distribution of loads is dependent on the stiffness of connected structural components that form the load path. The load path to the diaphragm is such that loads enter the building at frame locations and the load transfers from frames, through the purlin connections, to the diaphragm; *three* elements must be accounted for. Current design procedures in EP484.2 (ASABE, 2012) use a two-element spring analog for determining load distribution and require the stiffness of only *two* elements: the frame and the diaphragm. The purlin connection is neglected but must be accounted for in structural analysis because it forms the load path from frames to the diaphragm.

Traditionally, the purlin connection has been accounted for by incorporating purlins (and blocking if used) into the diaphragm stiffness for small test panels. The testing standard for SCWF diaphragms, ANSI/ASAE Standard EP558 (ASABE, 2004), specifically states that deflection measurements should be taken on loaded rafters, and in doing so the resulting stiffness will be one which incorporates purlins, and blocking if used, into the stiffness of the diaphragm. This diaphragm stiffness allows use of procedures in EP484.2 without additional consideration of the purlin or blocking stiffness. The modified MCA procedure takes the same approach by incorporating the stiffness of blocking and purlins into the diaphragm stiffness. Alternative methods may be used to deal with purlin and blocking connections, such as incorporating the stiffness of purlins into the frame stiffness or using a more complex three-element spring analog that requires the stiffness of all three elements to be known (Bohnhoff, Boor & Anderson, 1999).

Description of Diaphragms Used for Validation

Diaphragms were tested in accordance with ANSI/ASAE Standard EP558 (2004) using a simple beam configuration. Diaphragms were nominally 24 feet wide by 12 feet long with three 8-foot bays. Rafters were 2x8 Douglas fir (N) select structural lumber, and purlins were 2x4 Spruce Pine Fir 1650 Fb-1.5E lumber. All diaphragms were fully blocked, with purlins running on top of rafters, except diaphragm type 5, which used recessed purlins with hanger supports. All diaphragms used the field screw pattern shown in **Figure 3** with #10 x 1-inch structural screws used in the flat regions next to major corrugations. Seam screw type, seam screw spacing and steel cladding profile varied for each diaphragm; details are provided in **Table 1**.

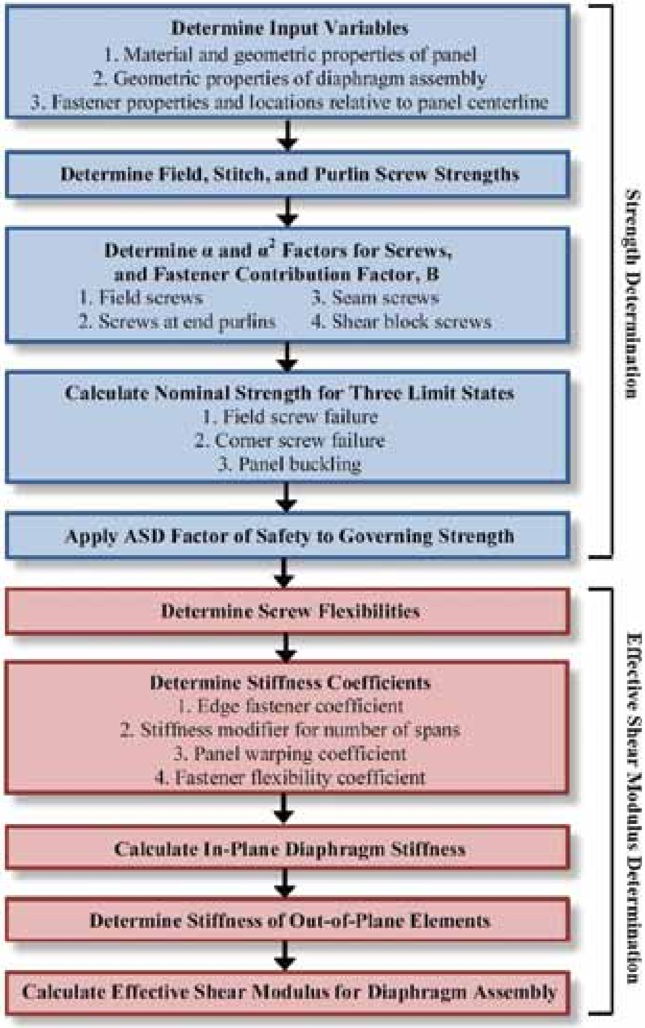

Figure 2. Flowchart for the Modified MCA Procedure

With regard to stiffness predictions, one of the most sensitive input values in the modified MCA procedure is the flexibility of screws through the overlap seams. Connection tests were conducted to determine the flexibility of the screws used in diaphragm tests. Measured load-displacement curves were nonlinear, and therefore stiffness values vary at different points on the load-deflection curve. The stiffness value for the seam screws was taken at screw design loads. **Table 2** tabulates the screw flexibilities for seam screws as determined from testing and predicted by modified MCA equations for comparison.

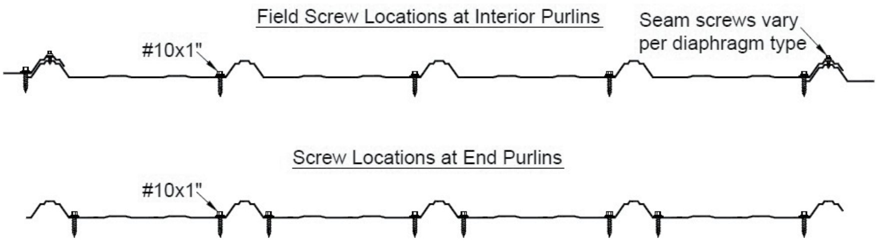

Figure 3. Screw pattern for test panels

Table 1. Cladding, Screw Type, and Spacing Used for Each Diaphragm

Diaphragm Type	Cladding Type	Seam Screw	On-Center Spacing (in)
1	Grandrib 3	#12x1.5" purlin screw	24
2	Grandrib 3	#12x.75" stitch screw	8
2A	Wick Panel	#12x.75" stitch screw	8
3	Grandrib 3	#12x.75" stitch screw	24
3A	Wick Panel	#12x.75" stitch screw	24
5	Grandrib 3	#12x.75" stitch screw	8
6	Grandrib 3	#12x.75" stitch screw	12

Table 2. Comparison of Seam Screw Flexibilities

Profile	Screw	Tested Flexibility (in/kip)	Flexibility per Modified MCA Procedure (in/kip)
Grandrib 3	#12x3/4"	0.054	0.034
Grandrib 3	#12x1.5"	0.043	0.025
Wick	#12x3/4"	0.036	0.033

Table 3. Comparison of Allowable Design Unit Shear Strength

Diaphragm Type	Sample Size	Average Test Value (min, max) (lb/ft)	Predicted per Modified MCA Procedure (lb/ft)	Ratio: Predicted/Test
1	3	119 (115, 123)	122	1.03
2	3	217 (212, 222)	213	0.98
2A	1	223	191	0.85
3	2	131 (129, 132)	122	0.93
3A	1	117	107	0.92
5	2	214 (209, 219)	213	1.00
6	1	179	174	0.97
			Average =	0.95
			COV =	6%

Note. A 2.5 factor of safety was applied to tested and predicted values in all cases.

Screw flexibilities from testing were used in place of modified MCA predictions for the validation because they represent true connection flexibilities for the diaphragms tested.

Results and Discussion

Leflar (2008) validated the modified MCA procedure by comparing tested values for 26 diaphragm constructions with modified MCA model predictions. The strength value calculated using the modified MCA procedure averaged 98 percent of tested strength with a 16 percent coefficient of variation (Leflar, 2008). The calculated stiffness value averaged 97 percent of the tested stiffness with a 23 percent COV. The COVs were judged to be consistent with those observed in diaphragm testing (Anderson, 2011).

The study herein provided further independent validation of the modified MCA procedure by comparing predicted unit shear strength and effective shear modulus values to those obtained from recent diaphragm tests sponsored by NFBA (Bender & Aguilera, 2013). **Table 3** presents a comparison of average tested and predicted design unit shear strength. The predicted design unit shear strengths are in good agreement with average test values, with only slight conservative differences in all but one diaphragm. For diaphragms with more than one repetition, predicted values fell within the range of tested minimum and maximum values for all but one diaphragm. Predicted design unit shear strength averaged 95 percent of the tested strength with a COV of 6 percent.

Table 4 provides a comparison of tested and predicted effective shear modulus. With use of tested seam screw stiffness, the ratio of predicted effective shear modulus to tested value averaged 1.04, with a COV of 18 percent. In the computation of effective shear modulus, deflections from chord splice slip and bending were removed to produce a stiffness value using only shear deflections.

The modified MCA procedure provides insight into how changes in geometry, material properties and placement of screws can affect diaphragm performance. After an in-depth evaluation of the modified MCA procedure, several important observations were made.

The model shows a decrease in unit shear strength as the length (eave-to-ridge distance) increases. This effect is largely due to different screw configurations being used for end purlins and interior purlins. Often screws are placed on both sides of the major rib at end purlins, while only a single screw is placed on one side of major ribs at interior purlins as depicted in Figure 3. The screws at an end purlin contain twice as many screws as an interior purlin, thus providing approximately twice the strength.

Lukens (1988) conducted cantilever tests on 6-, 8-, 12-, 16-, and 20-foot diaphragm lengths with a 9-foot rafter spacing. The screw pattern was the same as shown in Figure 3, except that stitch screws were not used at panel overlaps. Results showed that the design unit shear strength decreased as diaphragm length increased. A comparison of tested and predicted design unit shear strength using the modified MCA procedure is shown in **Table 5**. Although the modified MCA procedure may have underestimated the design strength, it is important to note that the ratio of predicted to tested strength is similar. **Table 6** shows the decrease in tested and predicted values expressed as a ratio of the design strength of a 6-foot panel to the design strength of larger panel lengths. The percent decrease predicted by the modified MCA method is consistent with the percent decrease in test values. The decrease in unit shear strength from a 6-foot panel to a 20-foot panel is 35 percent, and the modified MCA method predicts a 34 percent decrease.

Table 4. Comparison of Effective Shear Modulus

Diaphragm Type	Sample Size	Average Test Value* (min, max) (kips/in)	Calculated per Modified MCA Procedure (kips/in)	Ratio: Predicted/Test
1	3	6.8 (6.2, 7.9)	8.5	1.24
2	3	13.0 (10.9, 14.7)	11.9	0.92
2A	1	13.6	13.1	0.97
3	2	7.1 (6.8, 7.4)	7.7	1.09
3A	1	7.3	9.0	1.24
5	2	8.4 (8.1, 8.8)	N/A**	N/A**
6	1	13.4	10.5	0.79
			Average =	1.04
			COV =	18%

COV = coefficient of variation.
*For tested diaphragms, deflections from bending and chord slip were removed in the calculation of the effective shear modulus; therefore, shear modulus values differ from those in Bender and Aguilera (2013).
**Effective shear modulus could not be computed because connection stiffness for recessed purlins supported by hangers was not known.

Table 5. Comparison of Tested and Predicted Design Unit Shear Strength for Lukens Diaphragm Tests

Diaphragm Length (ft)	Sample Size	Average Test Value (lb/ft)	Predicted per Modified MCA Procedure (lb/ft)	Ratio: Predicted/Test
6	1	143	124	0.86
8	2	120	109	0.91
12	2	110	94	0.86
16	2	99	86	0.88
20	2	93	82	0.88
			Average =	0.88
			COV =	2%

The shear strength values obtained from testing small-scale panels (typically 12 feet in length) may overestimate design unit shear strengths for diaphragms of longer length. This issue needs to be resolved to determine at what length the additional end screws are considered negligible to the overall strength of the diaphragm.

The modified MCA procedure also shows a significant increase in effective shear modulus when blocking is used. When small-scale diaphragms are tested in a laboratory, blocking is used, with additional screws placed through the cladding to ensure that applied loads are getting into and out of the diaphragm. However, it is common practice in the post-frame industry to use blocking only at end/shear wall locations, while leaving interior purlins unblocked. Effective shear modulus values derived from blocked diaphragms can yield effective shear modulus values higher than those from actual diaphragms being constructed without the use of blocking. Since post design is a function of eave deflections, overestimating diaphragm stiffness could lead to nonconservative post design.

Further, the modified MCA procedure shows that the use of additional screws through the cladding into blocking can increase unit shear strength. When diaphragms are *unblocked*, using shear

Table 6. Normalized Values for Tested and Predicted Design Unit Shear Strength

Diaphragm Length (ft)	Normalized Value for Test	Normalized Value for Predicted
6	1.00	1.00
8	0.84	0.88
12	0.77	0.76
16	0.69	0.70
20	0.65	0.66

strength values obtained from *blocked* diaphragm tests may be nonconservative.

Summary and Conclusions

An independent validation of the modified MCA procedure was made by comparing predicted strength and stiffness values of SCWF diaphragms to those obtained from testing. The comparison in Table 2 shows that unit shear strength was in good agreement with tested values. The effective shear modulus had larger differences in predicted and tested values, but they are within reason when one considers that some diaphragm types had only one replication, and large variability of stiffness results is typical from testing.

The modified MCA procedure predicted that small-scale diaphragm tests may overestimate unit shear strengths for diaphragms with longer length because of different screw patterns being used at interior and end purlins. Comparison with tests showed that the modified MCA method closely predicted the percent decrease in design unit shear strength for longer test panels. Further, diaphragm tests using blocking with additional screws through the cladding may overestimate unit shear strength for unblocked diaphragms. The use of blocking in tested diaphragms causes significant increases in effective shear modulus values and may not be representative of unblocked diaphragms commonly used in industry. Further research is needed to validate and compare predicted diaphragm *component* response versus actual building *system* response.

Although the modified MCA procedure provides an accurate means to analytically predict design values, the time investment to learn the procedure and its complexity are significant barriers to implementation.

As a means of simplifying the implementation of the modified MCA procedure, Washington State University is working closely with NFBA to develop diaphragm design tables for the post-frame industry. Our next step is to develop tabulated design values with accompanying adjustment formulas to provide a simpler, flexible and economical approach to diaphragm design. After input and acceptance from the NFBA Technical and Research Committee have been given, design values will be submitted for possible inclusion in a revised edition of the ANSI/ASAE EP484.2 standard to promote safe and economic design of post-frame buildings.

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