The slip modulus between cold formed steel and timber sheathing based on fastener spacing increment

by

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Abstract

The combination of cold formed steel (CFS) with structural wood panels exhibits a degree of partial composite action behavior. In the current design and construction codes, CFS and wood sheathing systems are considered separate, in a non-composite manner, due to the absence of sufficient supporting experimental and research data**.** The problem with previous research is the lack of information to fully define the composite action between CFS and wood sheathing. The scope of this study is to check fundamental information provided in previous research. The approach adopted to solve the problem follows previous experimental procedures conducted at Kansas State University. The objective of the research is to determine the slip modulus with various fastener spacing. Additional results obtained in this study are compared to previous research results.

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Acknowledgements

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Chapter 1 – Introduction

The widespread usage of Cold-formed Steel (CFS) is getting closer attention in the present building construction from engineers and contractors and is being more valued as a result of its high strength-to-weight ratio. In 1946, AISI published the first specification named "Specification for the Design of Light Gauge Steel Structural Members", and in 1956, the AISI specification was adopted into building codes for the first time.

Composite action exists when two or more types of material are bound together so that they act as a single unit. This phenomenon is commonly applied in engineering construction. Previous research explained one of the growing areas of application of CFS is in repetitive member assemblies. A composite member of wood panels connected to an array of CFS members spaced closely together had been chosen to generate the test members. Previous researches had been reviewed and summarized in this report, and a Shimadzu 10,000-lb machine was found suitable to conduct a series of compression tests.

Chapter 2 - Background

It is important for understanding the phenomenon of composite action to study the mechanism of various types of composite member collocation.

Composite Action

Composite action is obtained when two or more different types of material, with certain type of connection, are assembled so that some of their behaviors are complementary, and they act as a single unit. Because a certain level of shear force must be developed between two elements when flexural or other external forces are applied onto the connecting surface, the path to transfer shear forces and to counteract possible detachment is required to be provided, and various methods were developed and applied by engineers. To best understand the significance of providing shear metastasis mechanism Figure 2-1 shows a steel beam topped with a concrete slab, which present no composite action, loaded in flexure. It is obvious to expect that the steel beam and the concrete slab act as two separate elements because a horizontal slip is developed at the contact surfaces between the steel and the concrete, and different strains are generated in the two elements.

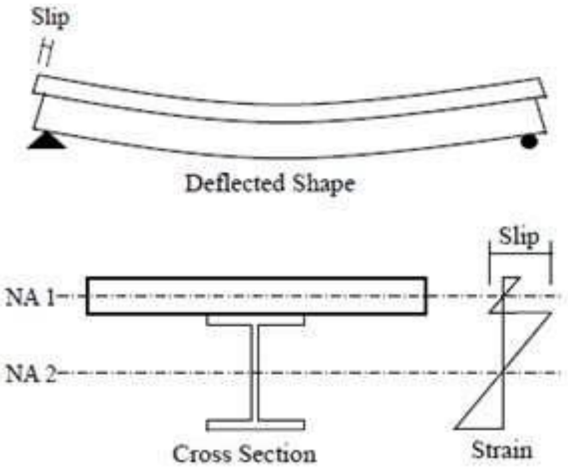

Figure 2-1 Beam in Flexure with No Composite Action, Adapted from Martin (5)

Conversely, the composite behavior exists when shear metastasis mechanism is provided. Figure 2-2 shows that the same elements, when assembled with connectors, exhibit full composite action. When the steel beam and concrete slab are joined together with adequate connectors, the connectors provide shear transfer and ensure the continuity of the strain generated in the two elements. This path of connection results in the two element deforming together and acting as a single unit.

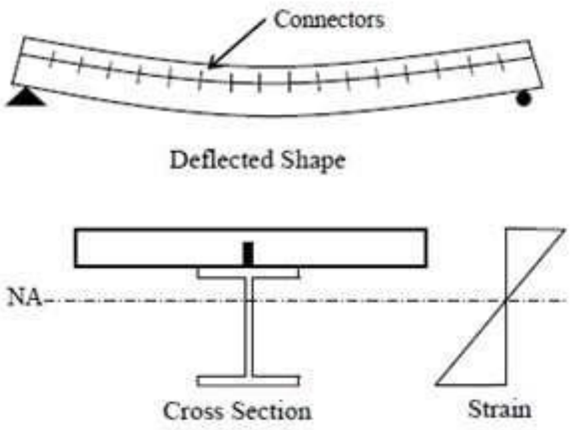

Figure 2-2 Beam in Flexure with Full Composite Action, Adapted from Martin (5)

In fact, partially composite system is often used in construction practice. The shear force generated at the connection surface is partially transferred by the fasteners, and a certain level of movement between two elements is allowed to happen.

Composite members are acknowledged and widely applied in modern construction. A common type of composite member is concrete-steel system. Reinforced concrete is often used for beams and columns as structural elements because of its strength quality and low cost. Reinforced concrete shows composite action by adding steel reinforcement into concrete to resist tension to compensate for the relatively low tensile strength of concrete. When the concrete-steel composite system is used to carry compressive load, the concrete take the majority of the compression. If flexure is applied to the system, the steel reinforcing bars on the tensile side of bending carry the majority of the tension.

Cold-Formed Steel-Timber Composites

Cold-Formed Steel (CFS) channel sheathed with structural wood is recommended as a replacement to traditional timber wall studs, floor joists, or roof rafters because of its high strength-to-weight ratio and the efficiency of timely construction. To determine the incentives of composite action between CFS and timber sheathing, previous study was reviewed and summarized.

In 2012, Amy Northcutt conducted compression tests to determine the slip modulus between CFS and wood sheathing by following ISO 6891 **(2).** Equation 2-1 is used to determine the slip modulus of CFS-Timber sheathing system, and Equation 2-2 is used to normalize the slip modulus with the number of fasteners and fastener spacing. The elements dimensions and test result are surmised in Table 2-1.

Equation 2-1 Slip Modulus

$$\boldsymbol{K = \frac{0.4P_u}{V_{0.4}}}$$

where

$0.4P_u$ = 40% of the expected ultimate load (lbs)

$V_{0.4}$ = the displacement or slip at $0.4P_u$ (in.)

Equation 2-2 Normalized Slip Modulus

$$\boldsymbol{K_N = \frac{K}{n\,s}}$$

where:

$\boldsymbol{K}$ = the slip modulus (lbs/in.)

$\boldsymbol{n}$ = number of fasteners

$\boldsymbol{s}$ =fastener spacing (in.)

Table 2-1 Northcutt Slip Modulus and Recommended Normalized Slip Modulus Values (6)

Test Series	**Steel Thickness** (gauge)	**Plywood Thickness** (in.)	**Recommended Normalized Slip Modulus** (lbs/in./in.)
T1	20	½	140
T2	16	½	560
T3	14	½	N.A.
T4	12	23/32	640

The results illustrate that partial composite action between CFS and structural wood exists because the normalized slip modulus varies when changing elements thickness.

In 2014, Geoff Martin conducted compression tests focusing on the effect of changing CFS thickness has on slip modules of CFS-Timber sheathing system (5). At that time, the influence of fastener spacing was brought up for the first time. Martin's test results are summarized in Table 2-2. In this study, the number of "T" series tests considered the thickness of steel, and the number of "TF" series considered the fastener spacing in inch.

Table 2-2 Summary of Martin's Results

Test Series	**Steel Thickness** (Mils)	**Slip Modulus** (lbs/in)	**Normalized Slip Modulus** (lbs/in/in)
T43	43	22442	468
T54	54	17659	368
T97	97	32470	676
TF6	43	28338	787
TF8	43	25933	540
TF10	43	16029	401
TF12	43	22442	468

In 2015, the idea of a tensile test was brought up to resolve the instability issues associated with the end conditions, and the high level of variance in test results. This idea, however, did not reduce the level of variance, and the test results were not published. At the Imperial College of London (ICL) in that same year, Kyvelou, Gardner, and Nethercot provided their experimental results that indicated that changing fastener spacing has an influence on composite action between CFS and timber sheathing. The ICL results, shown in Table 2-3, proved a positive correlation between fastener spacing and level of composite action **(3).**

Table 2-3 Summary of ICL Results (3)

	Experimental vs. Bare Steel		Experimental vs. Theoretical	
Test No.	Moment Capacity	Flexural Stiffness	Moment Capacity	Flexural Stiffness
1	1.00	1.00	0.43	0.58
2	1.05	1.07	0.45	0.62
3	1.45	1.14	0.61	0.66
4	1.50	1.41	0.64	0.82
5	1.99	1.42	0.85	0.82

In 2016, Weston Loehr conducted a series of compression tests to investigate the fastener spacing-slip modulus relationship **(4).** He modified the test setup to avoid previous construction issue. Loehr's modified test setup and procedure are summarized in this report.

Chapter 3 – Test Setup and Procedure

The main objective of this study is to determine the slip modulus between CFS and timber sheathing while changing the spacing between fasteners. To accomplish this, an adequate number of tests is required to achieve a confident level of 85% or greater **(5)**. This study focused on compression test only.

Approach

To determine and compare the slip modulus with Loehr's test results, fastener spacing of 6 inches, 8 inches, 10 inches, and 12 inches were selected. At the meantime, CFS thickness, timber sheathing thickness, fastener diameter, and all the other variables were held constant. To accomplish the requirement of confidence level, 15 tests of each fastener spacing were conducted. This was defined in Loehr's research.

Test Setup

To conduct the compression test, Loehr had improved the traditional test setup. A total of 12 preliminary tests were conducted to examine setup modification **(4)**. In traditional test setup, the CFS channel and timber sheathing are assembled with a short distance so that the first fastener from the bottom of the specimen is 7.5 inches from the timber sheathing end, and the composite specimen is compressed as a column. Figure 3-1 shows the compression test setup with steel end at the top and the timber sheathing end at the bottom.

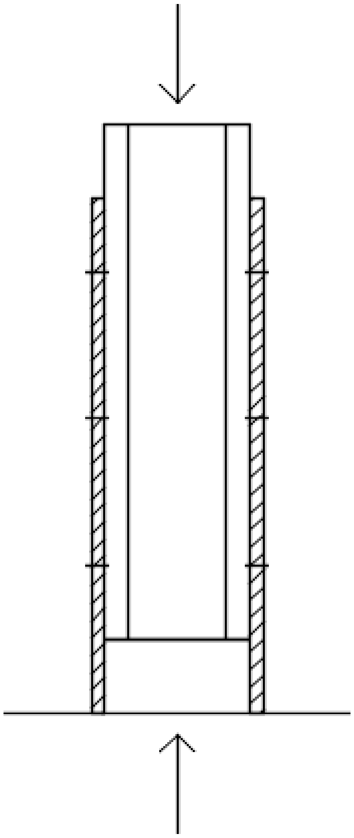

Figure 3-1 Compression Test Setup (4)

Modified Test Setup

In the previous researches, a buckling failure happened at timber sheathing end because the wood panels at the bottom were directly put on the base of the machine to support the compressive load. To avoid the buckling issue, a base support was applied at the bottom of the specimen, and the distance between the first fasteners from the bottom of the specimen to the timber sheathing end was reduced by 1.5 inch. Figure 3-2 shows the dimensions of all four test series.

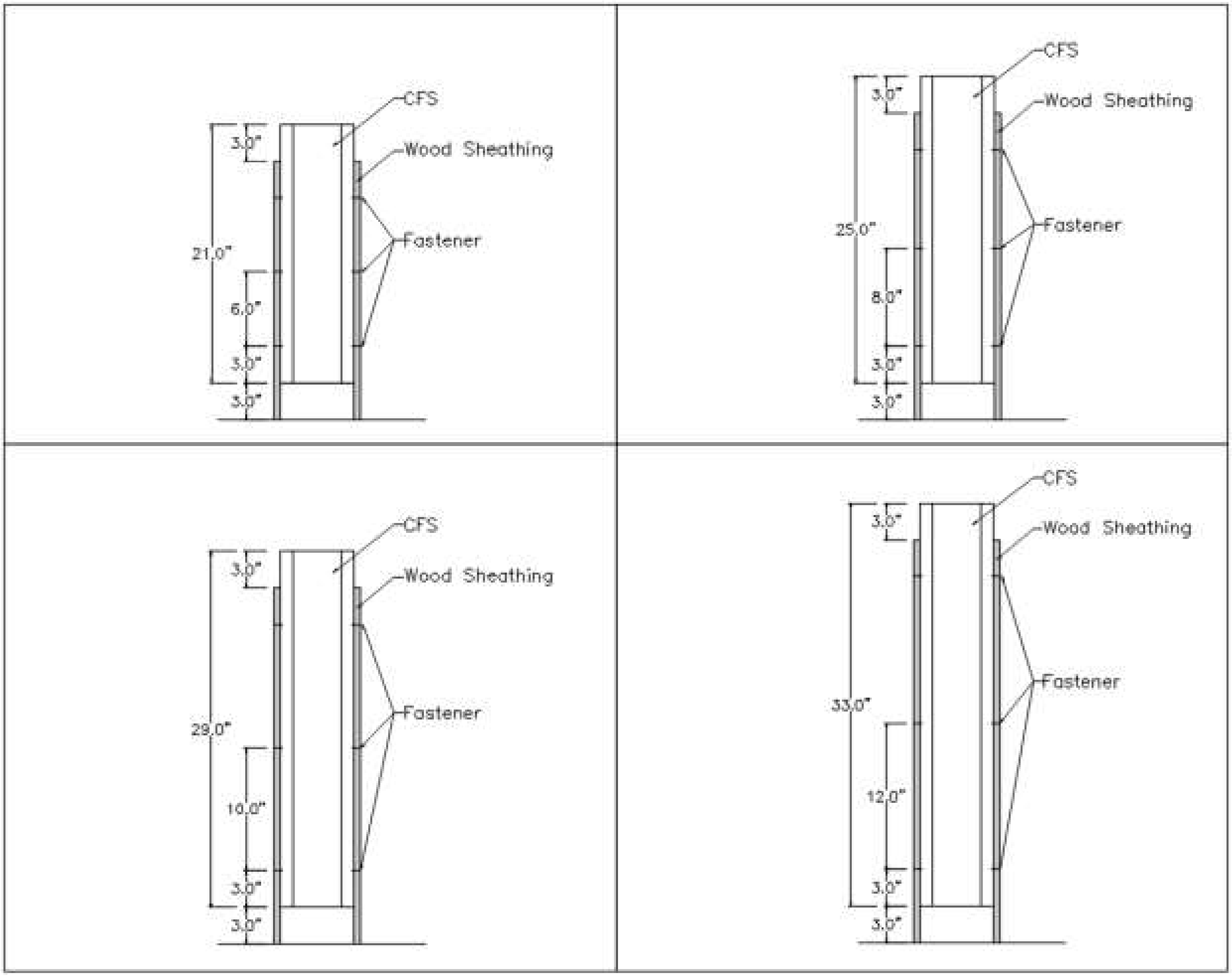

Figure 3-1 Specimen Dimensions of Loehr's Modified Setup (4)

Base Plate

A special wooden base plate was used as the base plate to hold the test specimen at the timber sheathing end. The plate has two slots 6 inches away to hold two wood panels from the bottom of the test specimen. Each slot was fabricated with an additional 1/8 inch over the timber sheathing thickness which allows a small rotation up to 2° to prevent moment generated at the base plate **(4)**. A new base plate was fabricated in this study to best center the specimen directly under the loading ram during the entire test. Four holes were drilled at the middle span, and the base plate was then bolted to the testing machine as shown in Figure 3.

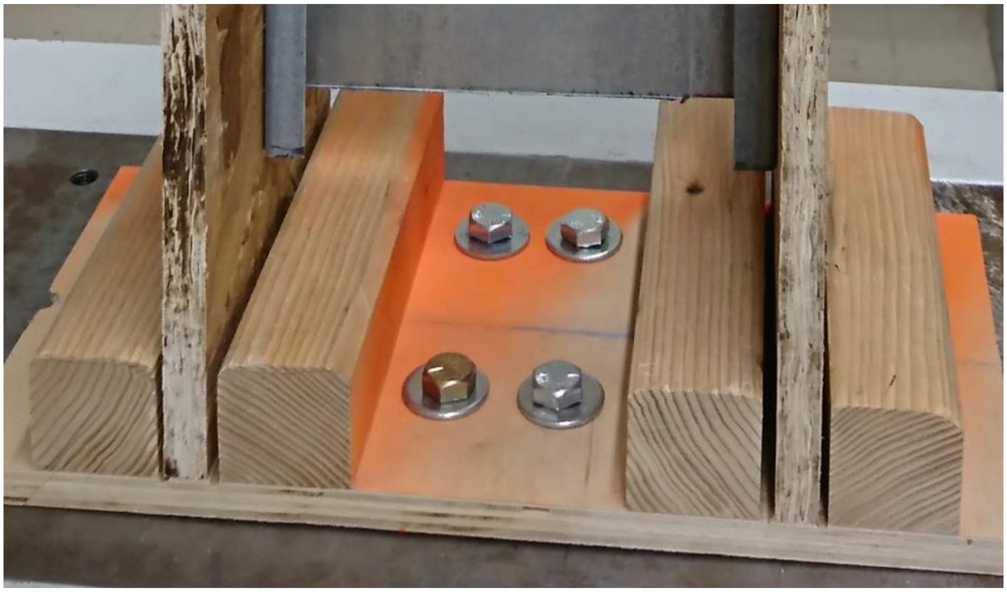

Figure 3-3 Base Plate Bolted to the Testing Machine

Load Distribution System

A load distribution system was placed on the top of the steel end for each test to uniformly distribute the load applied onto the specimen. A 6 inch × 2 inch × 0.5 inch (width × depth × thickness) aluminum plate was supported by a 6.5 inch x 2.5 inch x 0.25 inch aluminum plate to ensure the compressive load was centered, and a 1/8 inch rubber mat was glued and taped to the bottom plate to prevent slip between the aluminum plate and the CFS. The rubber mat was replaced for each loading series to maintain the roughness. Figure 3-4 shows the load distribution system following a series of compression tests after which the rubber mat had cracked.

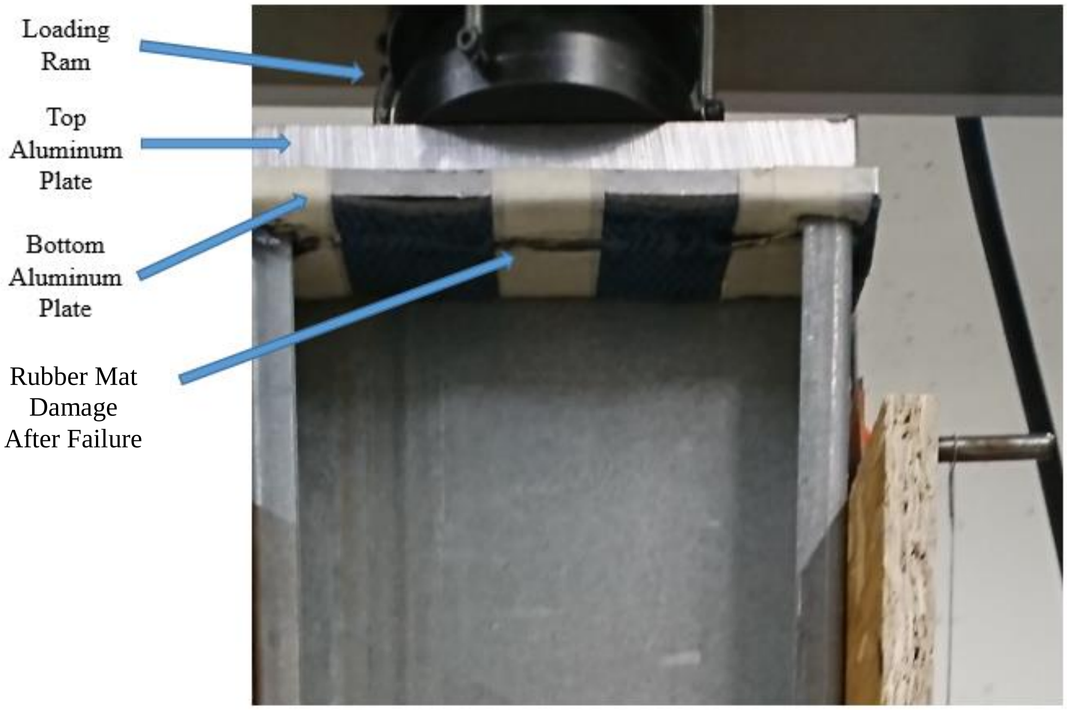

Figure 3-4 Load Distribution System after Test

Slip Displacement Sensors

The relative displacement of the steel compared to the timber sheathing was measured with two Celesco SP2-12 Compact String Potentiometers (Pot sensors) on each side of the specimen. A U-shaped metal bracket was fixed to the CFS at the top of the specimen by using an Eclipse Magnet so that the bracket hugged the back and the flanges of the CFS. The magnetic force of the Eclipse Magnet was tested and proved that it was able to sustain its self-weight. A steel wire was used to connect the U-shaped metal bracket and the eyelet at the end of each sensor. Each string pots was fastened to an L shaped, metal bracket, and a metal clamp was used to bind the metal bracket. Thus the body of the string pot and the timber sheathing were firmly connected, and the steel wire was stretched along the direction of displacement. Figure 3-5 shows the setup of one String Pot sensor.

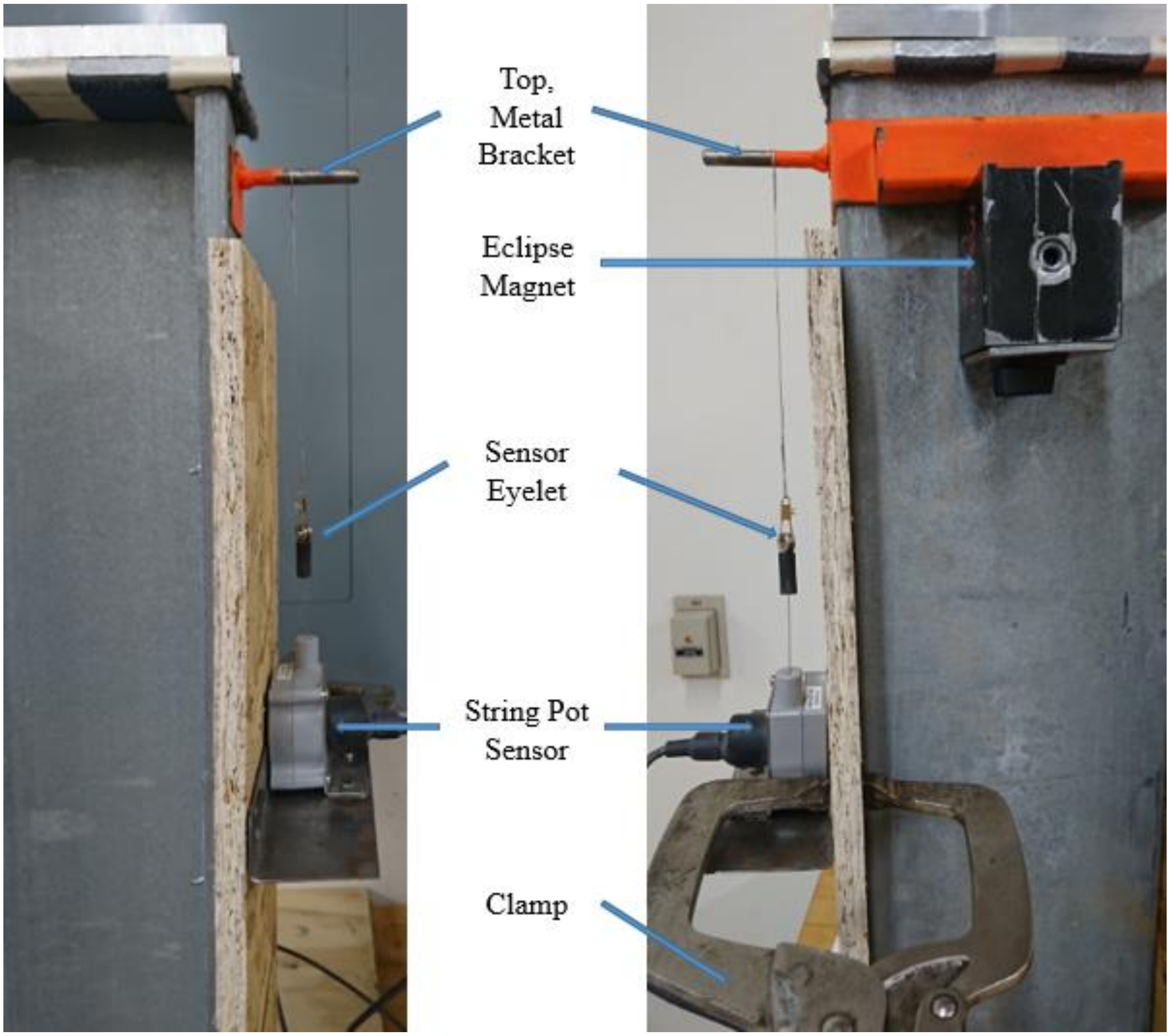

Figure 3-5 String Pot Sensor Setup

Test Procedure

Using a Shimadzu 10,000-lb machine with a compression ram device installed was suggested to conduct the tests. The Shimadzu machine was connected to a computer and run by a software named Trapezium X, which controlled the Shimadzu machine through the entire test once it has been programed. As mentioned earlier in this report, 12 preliminary tests were conducted in the previous research, and a conservative loading pattern was determined as follows:

1. Load the specimen at a rate of 800 pounds per minute
2. At 1600 pounds, hold stroke for 30 seconds
3. Release load at a rate of 800 pounds per minute
4. At 800 pounds, hold stroke for 30 seconds
5. Reload specimen at a rate of 800 pounds per minute until failure

The preliminary tests also demonstrated that failure occurred when the ram stroke reached 0.6 inch. This amount of displacement ensured the peak strength, capacity reduction, and failure were graphically recorded **(4)**. Loading rate and stopping point were determined and programed into Trapezium X, and the Shimadzu machine loaded the specimen automatically once a test started. Figure 3-6 shows a graph of the loading pattern.

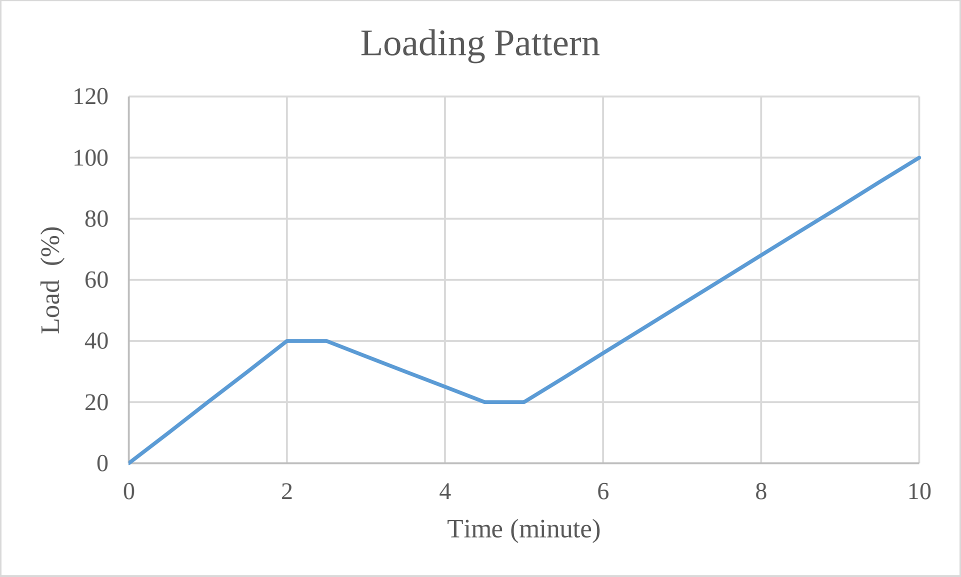

Figure 3-6 Test Loading Pattern

Chapter 4 – Test Specimens

A CFS–Timber sheathing system was built by centering a CFS channel and placing a piece of wood panel onto each flange of the channel. The CFS and timber elements were fastened together as a single unit. To best prepare the test specimens, two aspects were considered. First, the test material must be locally available and commonly produced by industry. Second, the installation method must be feasible with current conditions, and all inconvenience must be predicted. The test material and the assembly method are provided in this chapter.

Material Selection

Timber

Oriented strand board (OSB) was fabricated to be the sheathing. OSB is commonly used as a wood structural sheathing in floor, wall, and roof systems. The 19/32 inch thickness with a 40/20 span rating was selected based on its flexural properties. With this thickness and span rating, OSB can have maximum support spacing of 20 inch **(7)**, but a 16 inch spacing is more likely in a residential setting **(4)**.

CFS

Cold-formed steel with section of 600S162-43 was used as the web of the specimens. The 600S162-43 CFS has stud section of 6 inches with 1.625 inch wide flanges and 0.5 inch stiffener lips. The thickness is 43 mils (0.043 inch), and the specified yield stress is 33 ksi. The cold-formed steel was provided by Hi-Tech Interiors.

Fastener

“It is necessary to assure the proper performance of the connections used in cold formed steel construction” **(1)**. Thus fastener selection need to be carefully conducted. In brief, fastener point type, head style, and fastener dimensions need to be considered.

Eliminating unnecessary steps could prevent slip issue for specimen installation. Self-drilling screws enable drilling without first creating a pilot hole, and this type of fastener is commonly used to join sheet metal like CFS. #3 point screws was chosen based on availability and the thickness of the CFS.

A smooth surface is normally required for timber sheathing. Therefore, flat head fasteners were recommended because of their applicability and universality in construction.

The fasteners diameter was selected to be consistent with previous research. Thus # 10-24 screws were selected, and a length of 1-1/2 inch was used to achieve at least three threads be exposed past the connected materials **(1)**.

Assembly

Inconvenience and avoidable error must be predicted, which highlights the necessity to insure consistency in the assembly process of the test specimens. This required the installation tools to be consistent. Extra devices were fabricated for stability and consistency.

The first step was to cut the CFS. The CFS channels were cut with specified length for each test series by Hi-Tech Interiors.

The next step was to cut the OSB to fabricate the side panels of the test specimens. A table saw with scale was used to cut the timber to exact length. An assist rubber pusher was used to level the OSB during cutting. Figure 4-1 shows the OSB cut by the table saw. The fabricated panels then were marked with screw locations.

Figure 4-1 OSB Cut by the Table Saw

Figure 4-2 Marking Screw Locations on Timber Panel

After all element pieces were cut, the assembly proceses was conducted. A wood jig was built to regulate the CFS by placing one end of the CFS chanel into the slot of the jig. A steel angle was fixed along one leg at the end of the work table, and the other leg was used to level the CFS by placing one side of the jig so that it touches against the steel angle. A small piece of wood was put between the CFS and the steel beam to provide a 3 inch offset. Thus the CFS and the steel angle were perfectly parallel. Figure 4-3 shows process of regulating CFS.

Figure 4-3 CFS Regulated by Wood Jig and a Piece of Wood

Each wood panel was placed on the top of the CFS with one of the long edge of the panel touching the outstanding leg of the angle so that the screws could drill through the CFS at the center line of the flanges. A ½ in thick wood piece was used to adjust the panels to have an exact 3 inch offset with the CFS. Three metal clamps were used to prevent the panels from moving during drilling, and the lateral clamps were supported and leveled by a solid wood block. Then a drywall screw-gun was used to drive the screws into the wood panels and the CFS flanges. Figure 4-4 shows how the wood panel were clamped with the flange of the CFS.

Figure 4-4 Wood Panel Clamped on the Top of the CFS flange

Avoidance of Installation Issues

The assembly process is very important and must be carefully conducted, otherwise problems will occur and results could be harmfully affected. One of the possible issues that could occur is detachment between the CFS and the timber sheathing. Figure 4-5 depicts the timber sheathing breaking away from the CFS, and permanent test specimen damage was obtained not only in the sheathing but also in the CFS and fastener. This type of damage was generated due to over drilling during the composite assembly. When a fastener head is drilled beyond the sheathing surface, the timber would be considered already damaged. Such specimens were discarded.

Figure 4-5 Separation of the Sheathing

In order to prevent pre-damage of timber sheathing, a Hitachi screw driver was used to tight fasteners instead of regular screw driver. The advantage of using a Hitachi screw driver is that it controls the depth that fastener reaches. In other words, it prevents over drill of the fasteners and protects the timber sheathing from pre-damage. A shear capacity reduction of almost 10% can occur if a fastener is overdriven by as little as 1/16 inch **(8)**. The depth adjustment feature was essential to set the screws to the correct depth each time.

Another possible issue is pre-deformation. The fasteners were planned to be installed at 90˚. If the fasteners are installed non-perpendicularly to the sheathing and CFS flanges, it is nonconservative to confirm the failure occurs at the 0.6 inch compression ram stoke; however, it is difficult to control the drilling angle to ensure that the fasteners are installed at 90˚. Figure 4-6 shows that the screws on the right side of the specimen were installed with a small angle upward. Preventing pre-deformation as much as possible requires not only precise drilling skills but also assisting tools. Clamps were placed on each end of the specimen to prevent the member from shaking and shifting during the installation of the fasteners once the wood panel was placed properly on top of the CFS.

Figure 4-6 Specimen with Screws installed Non-Perpendicular to the Sheathing

Chapter 5 – Results

The experimental results for each spacing distance were collected and summarized in Table 5-1. The slip modulus is calculated by using Equation 2-1 and the normalized slip modulus is calculated by using Equation 2-2. Instead of the 40% maximum load for each test, the rounded average value of 40% maximum load for all samples, 1,900 lbs, and its corresponding displacement for each test are used for slip modulus computation. Samples 6-8 and 8-4 were excluded from the result calculation because of their abnormal results.

Table 5-1 Test Results Summary

Spacing (in)	**Statistic**	**P Max** (lbs.)	**D Max** (in.)	**P 40%** (lbs.)	**D 40%** (in.)	**D @1900** (in.)	**Slip Modulus** (lbs. /in.)	**Normalized Slip Modulus** (lbs./in./in.)
6	Average	4,773	0.3248	1,909	0.0112	0.0111	194,134	5,392
	Standard Deviation	109	0.0397	44	0.0038	0.0043	29,671	824
	C.O.V	2%	12%	2%	18%	17%	15%	15%
	Maximum	4,939	0.4288	1,976	0.0192	0.0206	249,415	6,928
	Minimum	4,480	0.2809	1,792	0.0052	0.0048	129,833	3,606
8	Average	4,693	0.3306	1,877	0.0117	0.0122	163,872	3,414
	Standard Deviation	130	0.0422	52	0.0031	0.0028	38,787	808
	C.O.V	3%	13%	3%	26%	23%	24%	24%
	Maximum	4,981	0.3839	1,992	0.0181	0.0217	256,901	5,352
	Minimum	4,505	0.2491	1,701	0.0064	0.0074	87,757	1,828
10	Average	4,621	0.3352	1,849	0.0167	0.0156	132,382	2,206
	Standard Deviation	303	0.0786	121	0.0084	0.0081	68,909	1,148
	C.O.V	7%	27%	7%	51%	46%	52%	52%
	Maximum	4,990	0.3712	1,996	0.0362	0.0352	327,383	5,456
	Minimum	3,990	0.0390	1,596	0.0034	0.0058	53,916	899
12	Average	4,604	0.3368	1,842	0.0139	0.0154	131,436	1,825
	Standard Deviation	216	0.0303	87	0.0035	0.0038	35,081	487
	C.O.V	5%	9%	5%	25%	25%	27%	27%
	Maximum	4,963	0.4007	1,985	0.019	0.0224	202,657	2,815
	Minimum	4,108	0.2906	1,643	0.0082	0.0094	84,697	1,176

Discussion of Results

To obtain test results and compare with Loehr's research, the graphical response of the CFS-Timber sheathing system was required. Providing a load-slip relationship is the best strategy to illustrate the composite action of CFS-Timber sheathing system. Figure 5-1 graphically present the behavior of five samples of 6 inch spacing specimens. All samples demonstrate a similar behavior with same shape of the load-slip relation. Even though the curves start diverging after achieving a load of 1600 lbs, they still present the same pattern. A slight reduction in compression force was obtained after reaching the peak value and before failure. An assumed failure point of 0.6 inch in displacement was proved as a conservative value to include the peak strength and the reduction. This diagram follows the same shape as that of Loehr's test results.

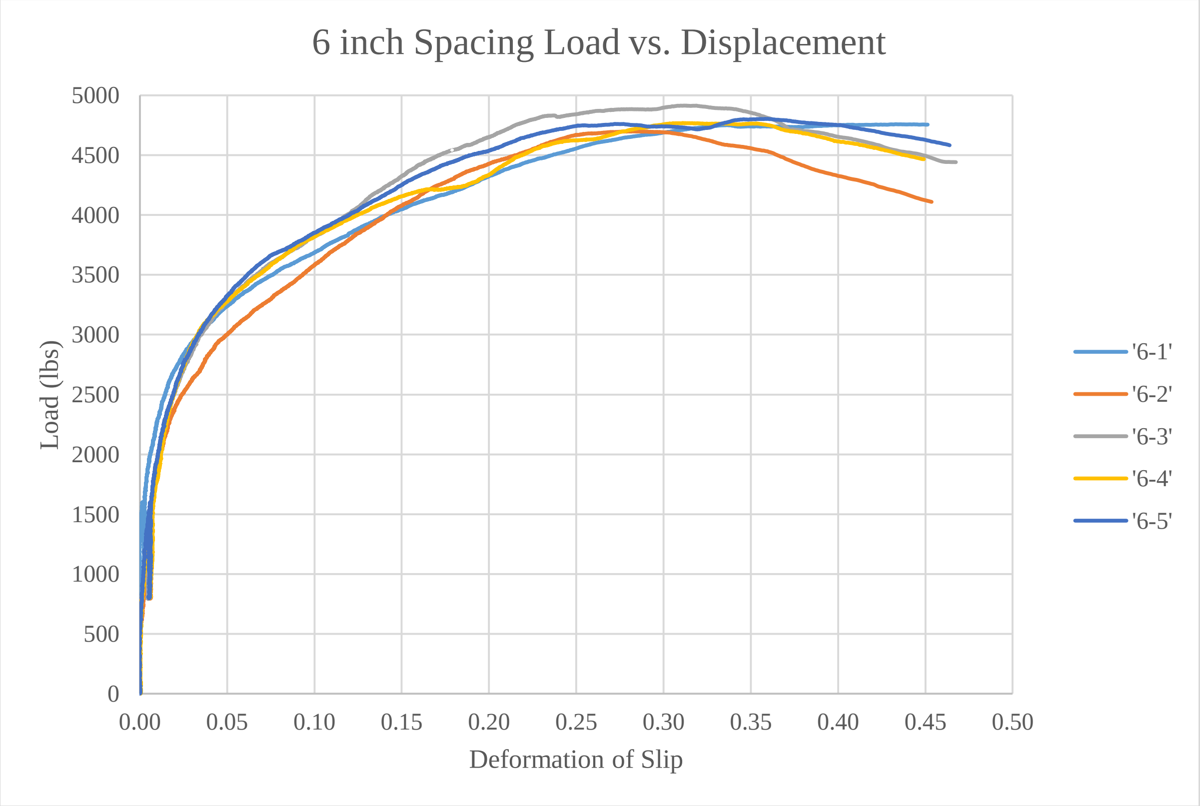

Figure 5-1 Load Displacement Diagram Obtained from Five Samples of 6 inch Spacing

An averaged load-slip diagram was created and is shown in Figure 5-2 for 6 inch spacing test samples before reaching the ultimate compressive loads. The curve shows a trend of gradually leveling off as the load increases. This “yielding” phenomenon is the result of the crushing of the timber. The damage to the wood panels increased with the increase of the compression force applied to the specimens, and the resistance to additional load and deformation was reduced. Similar results were obtained in Loehr’s research, and a point of closer view before the load reached 2000 lbs was proposed.

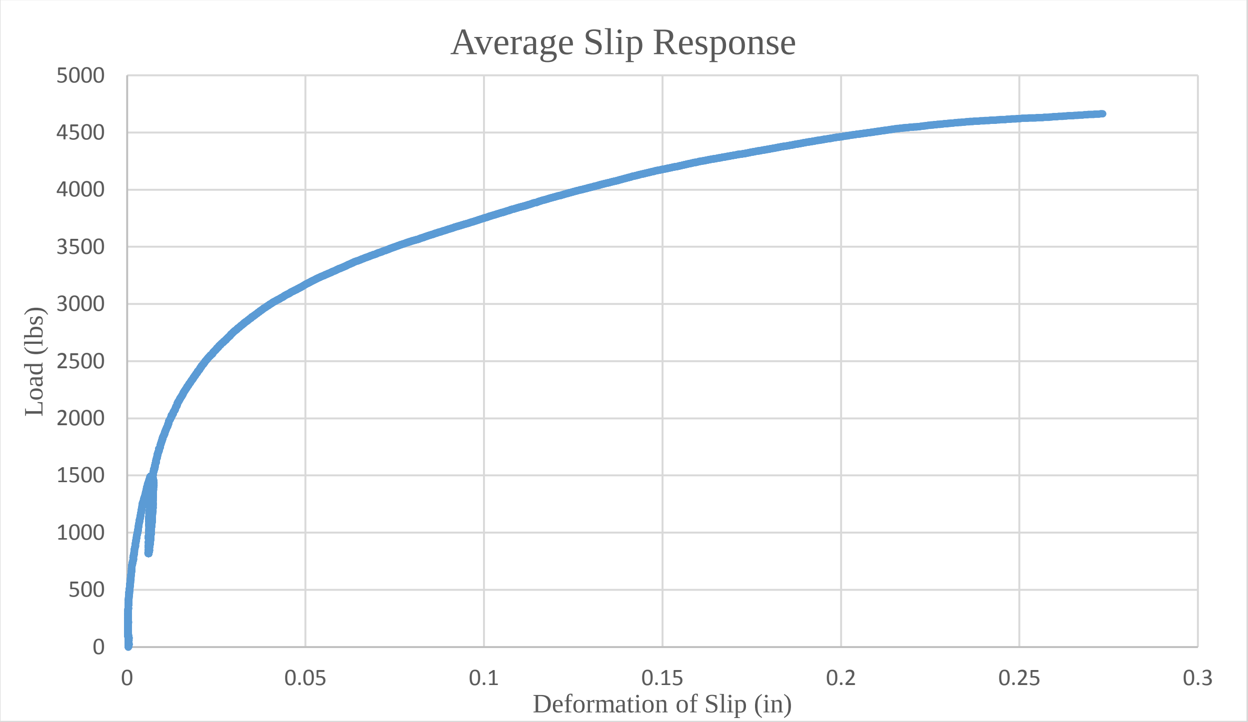

Figure 5-2 Average Slip Response of 6 inch Spacing Test

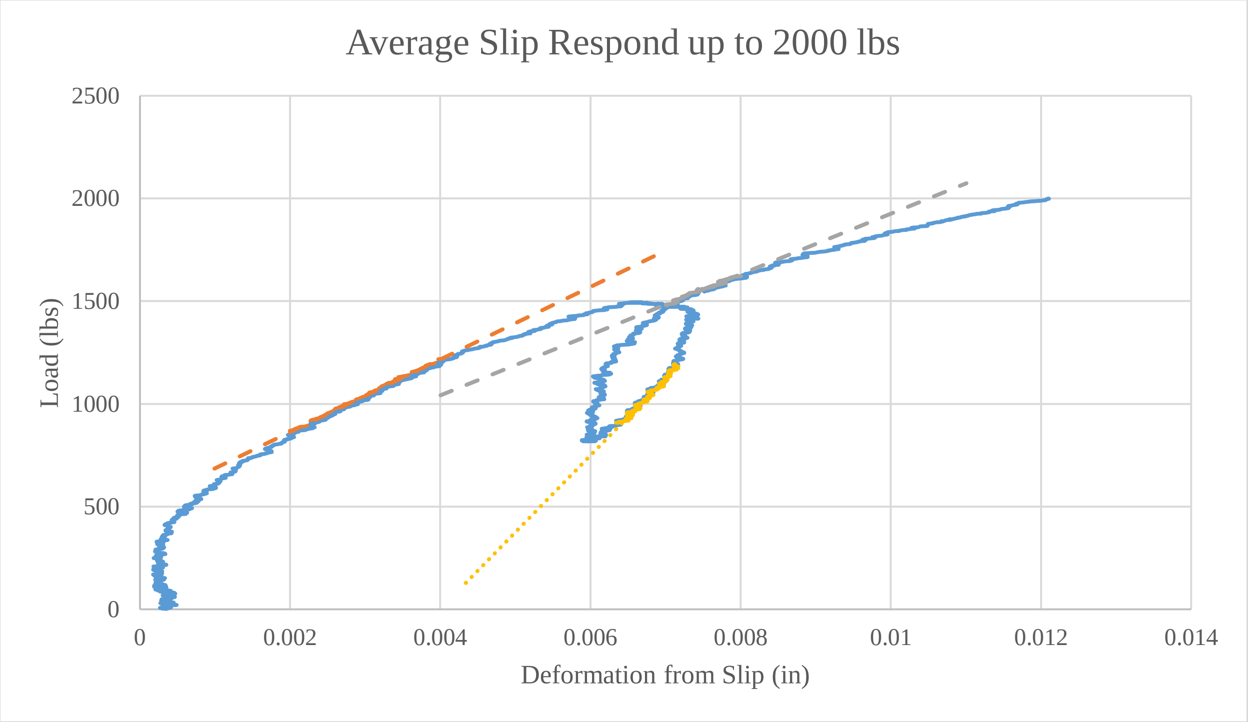

Figure 5-3 Average Slip Response of 6 inch Spacing Test up to 2000 lbs

Figure 5-3 magnifies the average slip response curve to show the change in slope. The slope of the curve is steep at the beginning of the test until the load reaches about 500 lbs. The specimen shows a relatively higher stiffness during this period, and this is considered to be caused by the friction between the wood panels and the CFS channel flanges. After overcoming the friction, the majority of the load is transferred through the fasteners to the wood panels. At this time, the curve trends to level off. A loop is obtained from this magnified curve, and this feature represents the pause, unloading, and reloading cycle generated in the test. Strikingly, the loop does not reach the pause point of 1,600 lbs based on the loading pattern. It is because not all of the specimens experienced that amount of load with the same amount of slip. The average slip responses (such as the one shown in Figure 5-2) are taken as the average of the data for the number of specimens in each group. Currently the only thing the tests have in common in the data is the time steps (which is a function of the data acquisition capabilities of the equipment). To obtain an better average of the load-slip curves, some algorithm will be needed to double-interpolate within each test data set to compute the slip at fixed load step and average them. Although, the average slip response curve was slightly off the expectation, this curve is able to show the slip response of the specimens. As mentioned in Loehr's research, a type of circle is obtained from the curve instead of an overlapping path, which shows that the system does not recover in a perfectly elastic manner **(4)**. The yellow dotted line shows some permanent slip occurs. Loehr proposed that overcoming friction and transition into fastener bearing might be the incentives.

Failure Mechanism

Screw tilting was considered as the failure mechanism of the specimens. Figure 5-4 reviews the idealized diagram of the movement at failure and the applied forces of the screws. The forces induced in the screw can be idealized as a force acting at the centroid of the steel, and an opposite triangular stress distribution from the wood **(4)**. The crush of the wood occurs at the holes and is caused by both compression and rotation of the screws.

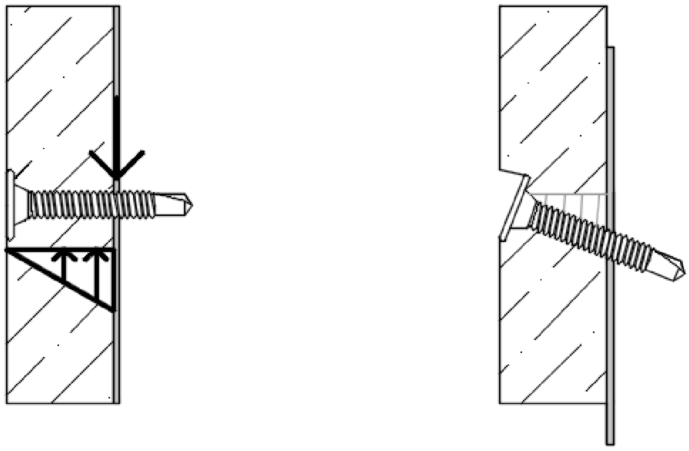

Figure 5-4 Screw Tilting Mechanism and Failure (4)

Figure 5-5 shows the orientation of the screw after failure of the specimen occurred, and Figure 5-6 shows the final angle of the screw head.

Figure 5-5 Screw Tilting

Figure 5-6 Screw Head after Failure

Slip Modulus and Normalized Slip Modulus

The maximum load of each test series with similar fastener spacing was averaged, and the results showed a decrease in maximum load with larger spacing between fasteners. This was because longer length allows the increase in fasteners rotation and accentuates the crushing of the sheathing. For the same reason, a larger spacing between fasteners caused a larger amount of slip between the wood sheathing and CFS. Consequently, the slip modulus and the normalized slip modulus decreased as the distances between fasteners increased. Figure 5-7 and Figure 5-8 display the slip modulus and normalized slip modulus with different fastener spacing.

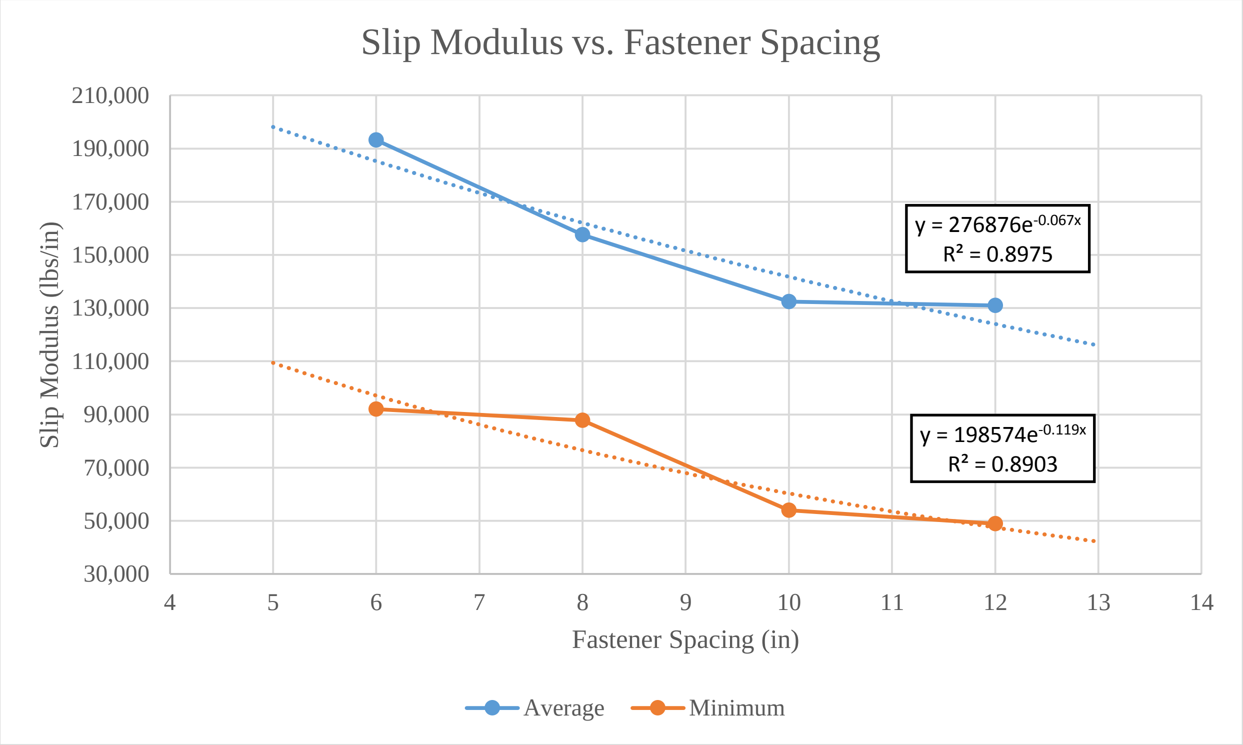

Figure 5-7 Slip Modulus Compared to Fastener Spacing

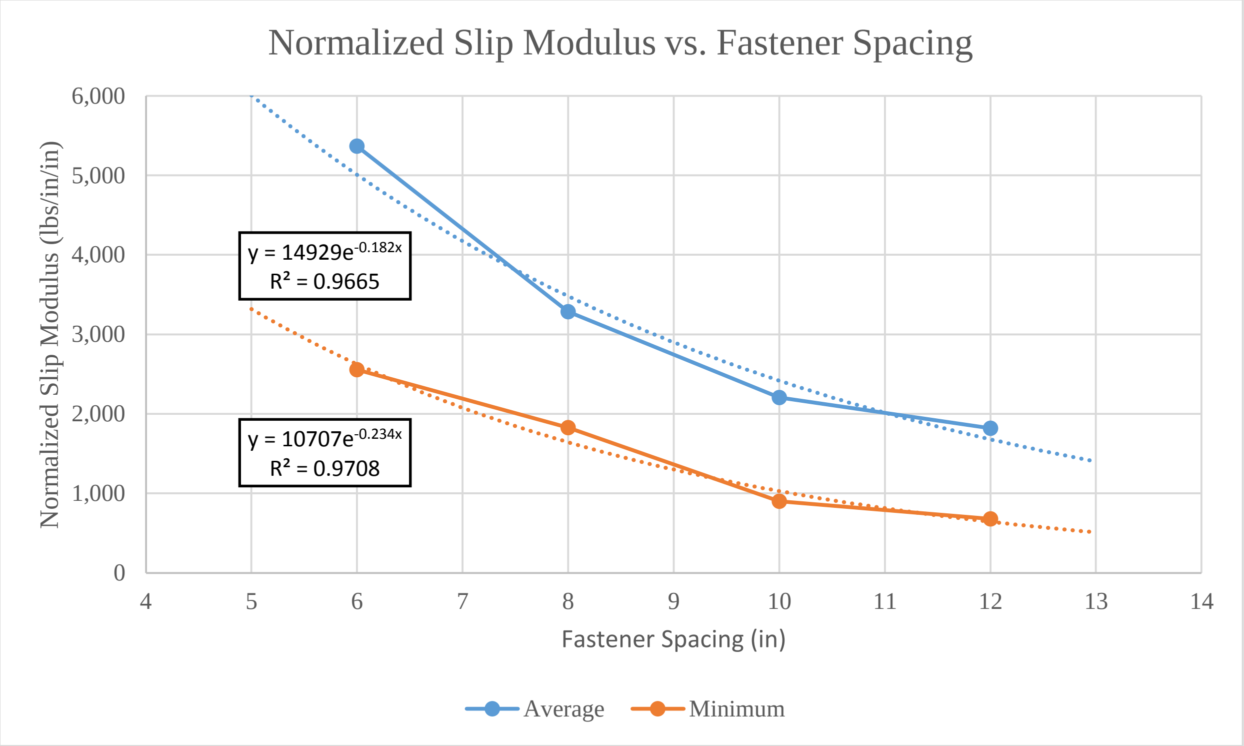

Figure 5-8 Normalized Slip Modulus Compared to Fastener Spacing

Test Matrix

A summary of all tests conducted in the experimental program described in this report is given in the test matrix shown in Table 5-2. The dimensions of the specimens were provided in a previous chapter. As described before, the 600S162-43 CFS has stud section of 6 inches with 1.625 inch wide flanges and 0.5 inch stiffener lips. The thickness is 43 mils (0.043 inch). For each spacing between fasteners, 15 specimen were fabricated and tested (total 60 specimen).

Table 5-2 Test Matrix of Test Specimens

	Spacing (in.)	6	8	10	12
Timber Sheathing	Length (in.)	21	25	29	33
	Width (in.)	6	6	6	6
	Thickness (in.)	19/32	19/32	19/32	19/32
CFS	Length (in.)	21	25	29	33
	Stud (in.)	6	6	6	6
	Thickness (in.)	0.043	0.043	0.043	0.043

Comparison of Results to Loehr’s Research

It is very important to compare test results with previous research completed by Loehr to observe the composite action behavior of CFS-Timber sheathing system. Table 5-2 and 5-3 review the results of this study and Loehr’s research. The results were summarized with average and standard deviation of maximum amount of load and slip, the amount of slip when the load reached 1,900 lbs, calculated slip modulus, and normalized slip modulus. The averaged maximum compressive loads from both studies are close. However, while the averaged maximum amount of slip results of this study are slightly lower than previous research, the results of slip modulus and normalized slip modulus are found to be close because the slip modulus and normalized slip modulus are calculated for individual test and concluded as averaged numbers. A reduction of standard deviations of this study illustrates that a serious of tests with higher stability were conducted, and the avoidance of potential error was effective.

Table 5-3 Summarized Results

Spacing (in)	**Statistic**	**P Max** (lbs.)	**D Max** (in.)	**D @1900** (in.)	**Slip Modulus** (lbs. /in.)	**Normalized Slip Modulus** (lbs./in./in.)
6	Average	4,784	0.3186	0.0100	194,134	5,393
	Standard Deviation	115	0.0262	0.0017	29,672	824
8	Average	4,693	0.3306	0.0122	163,871	3,414
	Standard Deviation	130	0.0422	0.0028	38,787	808
10	Average	4,621	0.3352	0.0156	132,382	2,206
	Standard Deviation	303	0.0786	0.0081	68,909	1,148
12	Average	4,604	0.3368	0.0154	131,436	1,825
	Standard Deviation	216	0.0303	0.0038	35,081	487

Table 5-4 Summarized Results of Loehr's Research (4)

Spacing (in)	**Statistic**	**P Max** (lbs.)	**D Max** (in.)	**D @1900** (in.)	**Slip Modulus** (lbs. /in.)	**Normalized Slip Modulus** (lbs./in./in.)
6	Average	4,836	0.462	0.0118	182,043	5,057
	Standard Deviation	372	0.0202	0.0046	61,258	1,702
8	Average	4,757	0.4459	0.0127	158,902	3,310
	Standard Deviation	317	0.0287	0.0035	40,854	851
10	Average	4,744	0.4710	0.0150	149,754	2,496
	Standard Deviation	391	0.0304	0.0054	78,333	1,306
12	Average	4,590	0.4507	0.0153	135,480	1,882
	Standard Deviation	257	0.0222	0.0048	42,817	595

Chapter 6 – Conclusion

The main objectives of this study include to determine the slip modulus with fastener spacing influence and to compare with previous research completed by Weston Loehr in 2016. Slip modulus and normalized slip modulus are the main indexes for comparison. Compression tests were completed on CFS-Timber sheathing system with fastener spacing of 6 inch, 8 inch, 10 inch, and 12 inch. 15 tests were conducted for each spacing. The specimens were composed of 18 gauge stud section CFS and 19/32 inch thick OSB attached to each flange as sheathings. # 10-24 self-tapping screws were used to fasten the specimen. Possible error and installation issues were predicted, and solution were provided.

Test sample 6-6 and 8-4 were eliminated from the calculations due to their vastly different results. The results show that the slip modulus and normalized slip modulus increase as fastener spacing decreases. The results of this study present similar features as the previous study and relative constancy of the test procedures.

Recommendations for Future Research

There are several recommendations for future research concerning the composite action in CFS-Timber sheathing systems.

1. Different thickness of the wood panel should be considered for sheathings, and different test setup must be analyzed.
2. Different types of fasteners should be concerned in future tests, and the fastener dimensions also need to be adjusted.
3. Applying cyclic loading to the test specimens may be considered in experimental program. Such loading pattern needs to be determined by running a set of preliminary tests.
4. Full scale tests of CFS-Timber sheathing system should be conducted to review the amount of partial composite action between CFS and wood.
5. To improve the average slip response curve, some important time points of the loading process should be determined for the raw data of load of 15 test specimens to align with each other so that the deviation of the curve can be avoided.

References

1) CFSEI, (2011). Screw Fastener Selection for Cold-Formed Steel Frame Construction. (Tech Note F102-11). Washington, D.C.

2) ISO, (1983). Timber Structures – Joints Made With Mechanical Fasteners. (Ref. No. ISO 6891-1983). International Organization for Standardization.

3) Kyvelou, P., Gardner, L., & Nethercot, D. A. (2015). Composite Action Between Cold-Formed Steel Beams and Wood-Based Floorboards. *International Journal of Structural Stability and Dynamics, 15*(08), 1540029. Retrieved September 10, 2015.

4) Loehr, W. (2016). *The Influence of Fastener Spacing On the Slip Modulus between Cold Formed Steel and Wood Sheathing.* (Master's Thesis) Retrieved from K-State Research Exchange.

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6) Northcutt, A. (2012). *Slip modulus of cold-formed steel members sheathed with wood structural panels* (Master's Thesis). Retrieved from K-State Research Exchange.

7) *OSB Design and Application Guide* (Publication). (n.d.). Retrieved December 12, 2015, from TECO website: http://www.tecotested.com/techtips/pdf/osbdesignapplicationguide=

8) *Reduction In Shear Capacity Due To Overdriven Fasteners* (Tech.). (2008, January). Retrieved February 23, 2016, from TECO website: http://www.tecotested.com/techtips/pdf/tt_overdrivenfasteners

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1) AISI, (2008). Cold-Formed Steel Design Manual. AISI S905-13. American Iron and Steel Institute.

2) ASTM Standard D6555 – 03 (2014), “Standard Guide of Evaluating Systems Effects in Repetitive-Member Wood Assemblies,” ASTM International, West Conshohocken, PA, www.astm.org.

Appendix A - Individual Test Results

The individual sample tests are resulted in Table A-1, Table A-2, Table A-3, and Table A-4. A plot of the amount of slip at 40% of ultimate load compared to the average, one standard deviation interval, and two standard deviation interval is produced for each test serious of different fastener spacing. The slip modulus is calculated by using Equation 2-1 and the normalized slip modulus is calculated by using Equation 2-2. Instead of the 40% maximum load for each test, the rounded average value of 40% maximum load for all samples, 1900 lbs, and its corresponding displacement for each test are used for slip modulus computation. Samples 6-6 and 8-4 were excluded from the result calculation because of their abnormal results.

Table A-1 6 Inch Fastener Spacing Test Results

Sample	P Max (lbs)	D Max (in.)	P 40 (lbs)	D 40 (in.)	D @ 1900 (in.)	Slip Modulus (lbs/in)	Nominalized Slip Modulus (lbs/in.)
6-1	4480	0.3029	1792	0.0082	0.010648	178,437	4,957
6-2	4698	0.2809	1879	0.0098	0.010033	189,375	5,260
6-3	4914	0.3101	1966	0.0102	0.009632	197,259	5,479
6-4	4769	0.3092	1908	0.0116	0.011676	162,727	4,520
6-5	4803	0.3564	1921	0.0092	0.008821	215,395	5,983
6-6	4915	0.2993	1965	0.0082	0.0076	249,415	6,928
6-7	4752	0.3544	1901	0.0100	0.010023	189,564	5,266
6-8	*	*	*	*	*	*	*
6-9	4724	0.3093	1890	0.0084	0.008642	219,857	6,107
6-10	4722	0.3093	1889	0.0084	0.00862	220,418	6,123
6-11	4821	0.3067	1928	0.0150	0.014634	129,835	3,607
6-12	4939	0.3576	1976	0.0104	0.00882	215,420	5,984
6-13	4820	0.2832	1928	0.0098	0.009572	198,496	5,514
6-14	4835	0.3402	1934	0.0108	0.010605	179,161	4,977
6-15	4780	0.3405	1912	0.0110	0.011035	172,179	4,783
Average	4784	0.3186	1913	0.0101	0.0100	194,134	5,393
Std Dev	115	0.0262	46	0.0018	0.0017	29,672	824

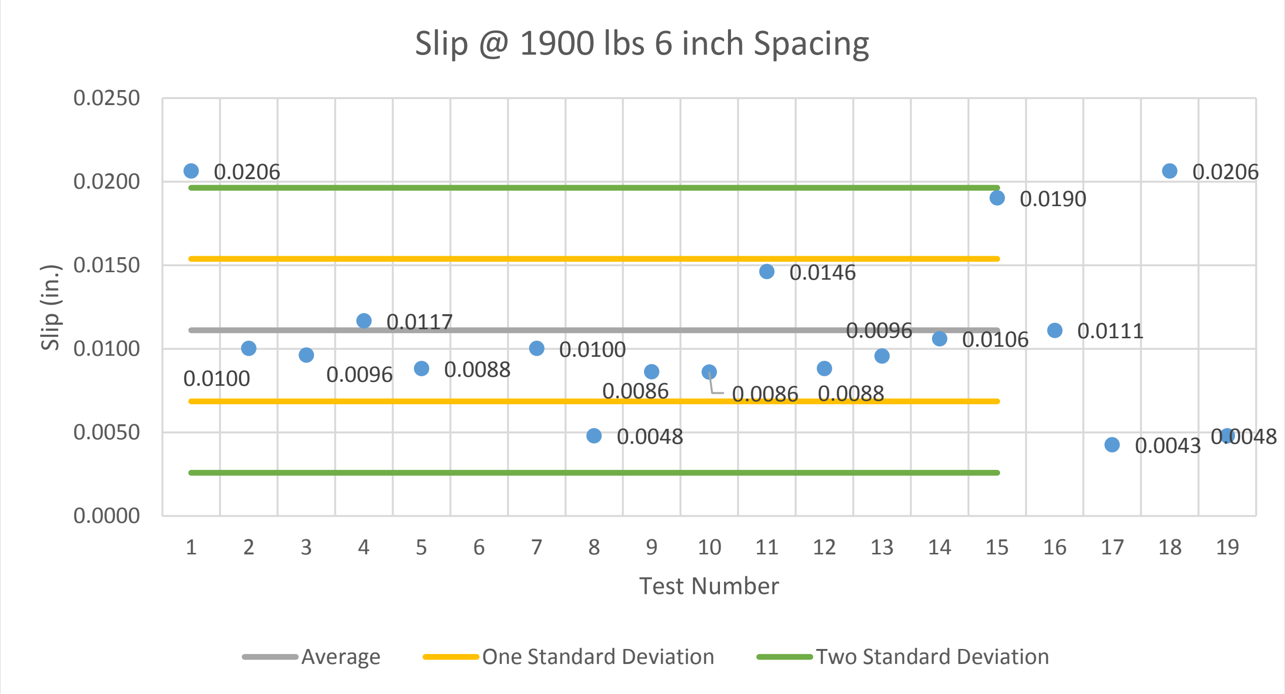


Figure A-1 6 Inch Fastener Spacing Slip at 1900 lbs

Table A-2 8 Inch Fastener Spacing

Sample	P Max (lbs)	D Max (in.)	P 40 (lbs)	D 40 (in.)	D @ 1900 (in.)	Slip Modulus (lbs/in)	Nominalized Slip Modulus (lbs/in.)
8-1	4597	0.3534	1799	0.0106	0.0118	161,385	3,362
8-2	4777	0.3142	1911	0.0105	0.0109	173,916	3,623
8-3	4665	0.3778	1866	0.0113	0.0127	149,044	3,105
8-4	*	*	*	*	*	*	*
8-5	4730	0.3839	1892	0.0098	0.0098	194,314	4,048
8-6	4576	0.3386	1831	0.0096	0.0098	192,941	4,020
8-7	4725	0.3247	1890	0.0126	0.0124	153,302	3,194
8-8	4505	0.2491	1802	0.0103	0.0121	157,061	3,272
8-9	4860	0.2495	1944	0.0094	0.0096	198,884	4,143
8-10	4531	0.3287	1812	0.0130	0.0148	128,078	2,668
8-11	4660	0.3019	1864	0.0110	0.0114	166,284	3,464
8-12	4701	0.3731	1880	0.0168	0.0172	110,207	2,296
8-13	4619	0.3302	1848	0.0064	0.0074	256,901	5,352
8-14	4981	0.3374	1992	0.0181	0.0165	115,410	2,404
8-15	4775	0.3662	1910	0.0142	0.0142	133,683	2,785
Average	4693	0.3306	1877	0.0117	0.0122	163,871	3,414
Std Dev	130	0.0422	52	0.0031	0.0028	38,787	808

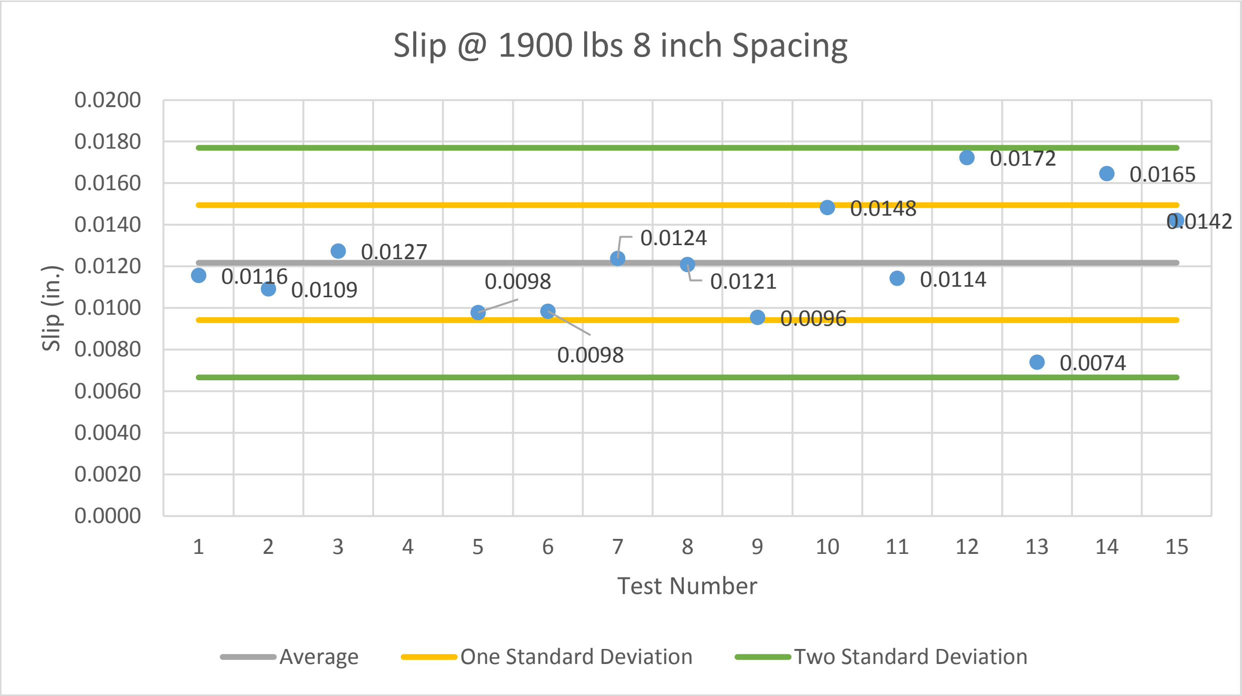


Figure A-2 8 Inch Fastener Spacing Slip at 1900 lbs

Table A-3 10 Inch Fastener Spacing

Sample	P Max (lbs)	D Max (in.)	P 40 (lbs)	D 40 (in.)	D @ 1900 (in.)	Slip Modulus (lbs/in)	Nominalized Slip Modulus (lbs/in.)
10-1	4907.509	0.3231	1963.003	0.017018	0.015615	121,677	2,027
10-2	4915.145	0.3300	1966.058	0.00947	0.008668	219,197	3,653
10-3	4307.633	0.3604	1723.053	0.013659	0.017869	106,329	1,772
10-4	4923.977	0.2913	1969.591	0.012283	0.012082	157,254	2,620
10-5	4738.132	0.3356	1895.253	0.030006	0.030046	63,237	1,053
10-6	4736.445	0.3309	1894.578	0.013632	0.013632	139,379	2,322
10-7	4735.213	0.3309	1894.085	0.013632	0.01303	145,812	2,430
10-8	4602.191	0.3329	1840.876	0.01579	0.016391	115,917	1,931
10-9	3990.452	0.3557	1596.181	0.012747	0.016756	113,391	1,889
10-10	4516.341	0.3328	1806.536	0.010345	0.011748	161,727	2,695
10-11	4275.57	0.3269	1710.228	0.015595	0.02161	87,924	1,465
10-12	4621.853	0.3275	1848.741	0.026459	0.027662	68,687	1,144
10-13	4852.295	0.3712	1940.918	0.036242	0.03524	53,915	898
10-14	4989.636	0.2945	1995.854	0.01969	0.018287	103,900	1,731
10-15	4209.11	0.3153	1683.644	0.003398	0.005804	327,383	5,456
Average	4621.433	0.3311	1848.573	0.01564	0.017629	132,382	2,206
Std Dev	303.0743	0.0216	121	0.008443	0.008063	68,909	1,148

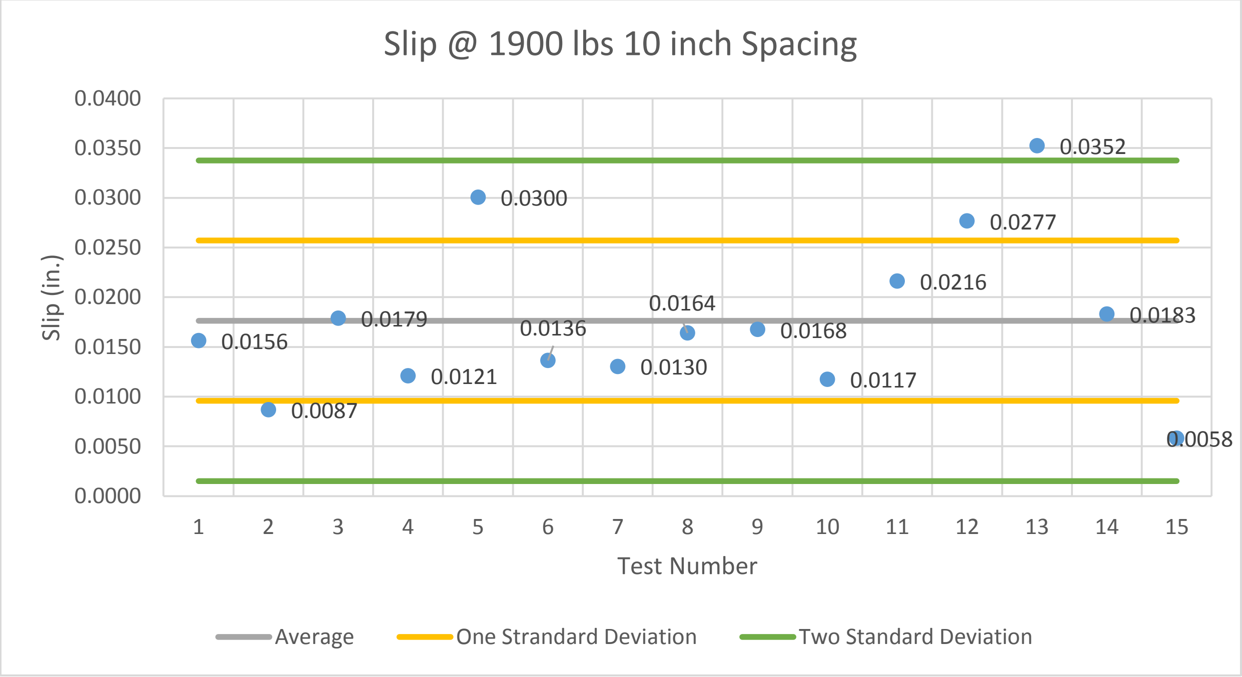


Figure A-3 10 Inch Fastener Spacing Slip at 1900 lbs

Table A-4 12 Inch Fastener Spacing

Sample	P Max (lbs)	D Max (in.)	P 40 (lbs)	D 40 (in.)	D @ 1900 (in.)	Slip Modulus (lbs/in)	Nominalized Slip Modulus (lbs/in.)
12-1	4529	0.4007	1812	0.0178	0.0202	93,844	1,303
12-2	4229	0.3439	1692	0.0097	0.0135	140,882	1,957
12-3	4827	0.3216	1931	0.0172	0.0162	117,009	1,625
12-4	4511	0.3622	1804	0.0126	0.0140	135,736	1,885
12-5	4744	0.3450	1898	0.0190	0.0192	99,008	1,375
12-6	4650	0.3085	1860	0.0122	0.0136	140,066	1,945
12-7	4108	0.3157	1643	0.0146	0.0224	84,697	1,176
12-8	4679	0.3536	1872	0.0148	0.0160	118,647	1,648
12-9	4759	0.3044	1903	0.0177	0.0179	106,065	1,473
12-10	4547	0.3697	1819	0.0127	0.0145	131,035	1,820
12-11	4590	0.3181	1836	0.0365	0.0189	48,898	679
12-12	4747	0.3112	1899	0.0141	0.0141	134,984	1,875
12-13	4574	0.3676	1830	0.0082	0.0094	202,657	2,815
12-14	4963	0.3394	1985	0.0102	0.0102	232,056	3,223
12-15	4605	0.2906	1842	0.0092	0.0106	179,606	2,495
Average	4604	0.3368	1842	0.0151	0.0154	131,436	1,825
Std Dev	216	0.0303	87	0.0068	0.0038	35,081	487

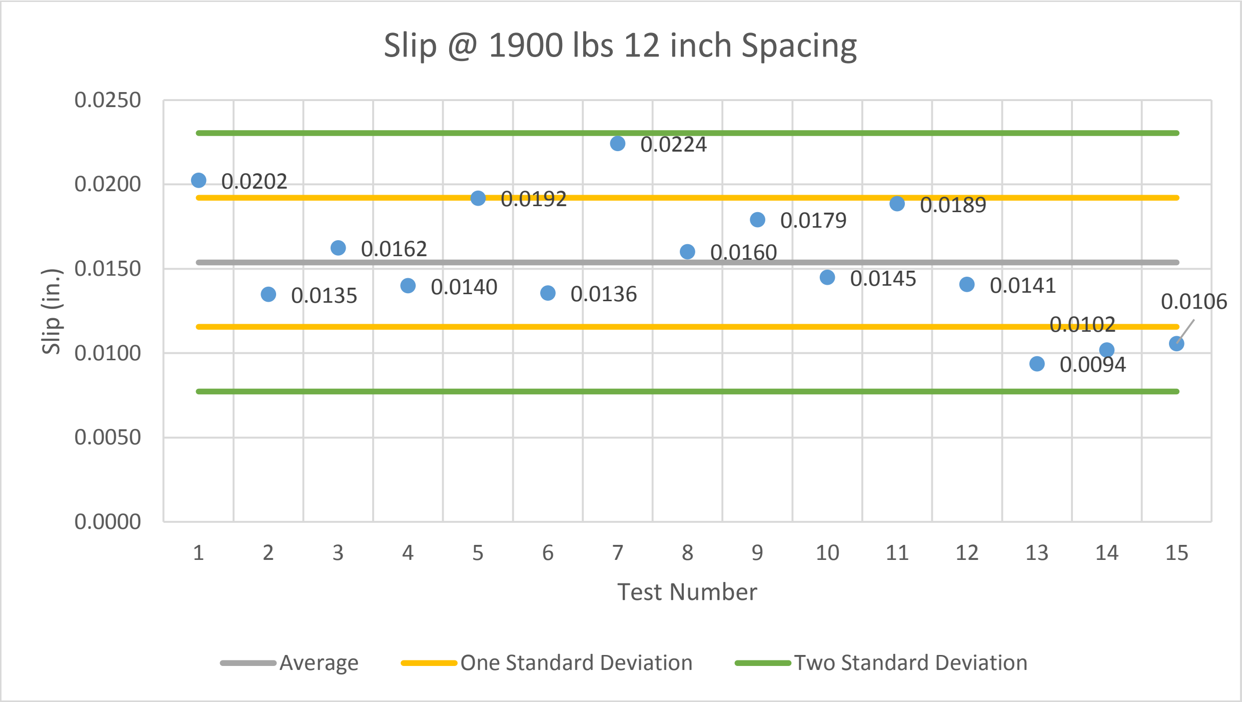
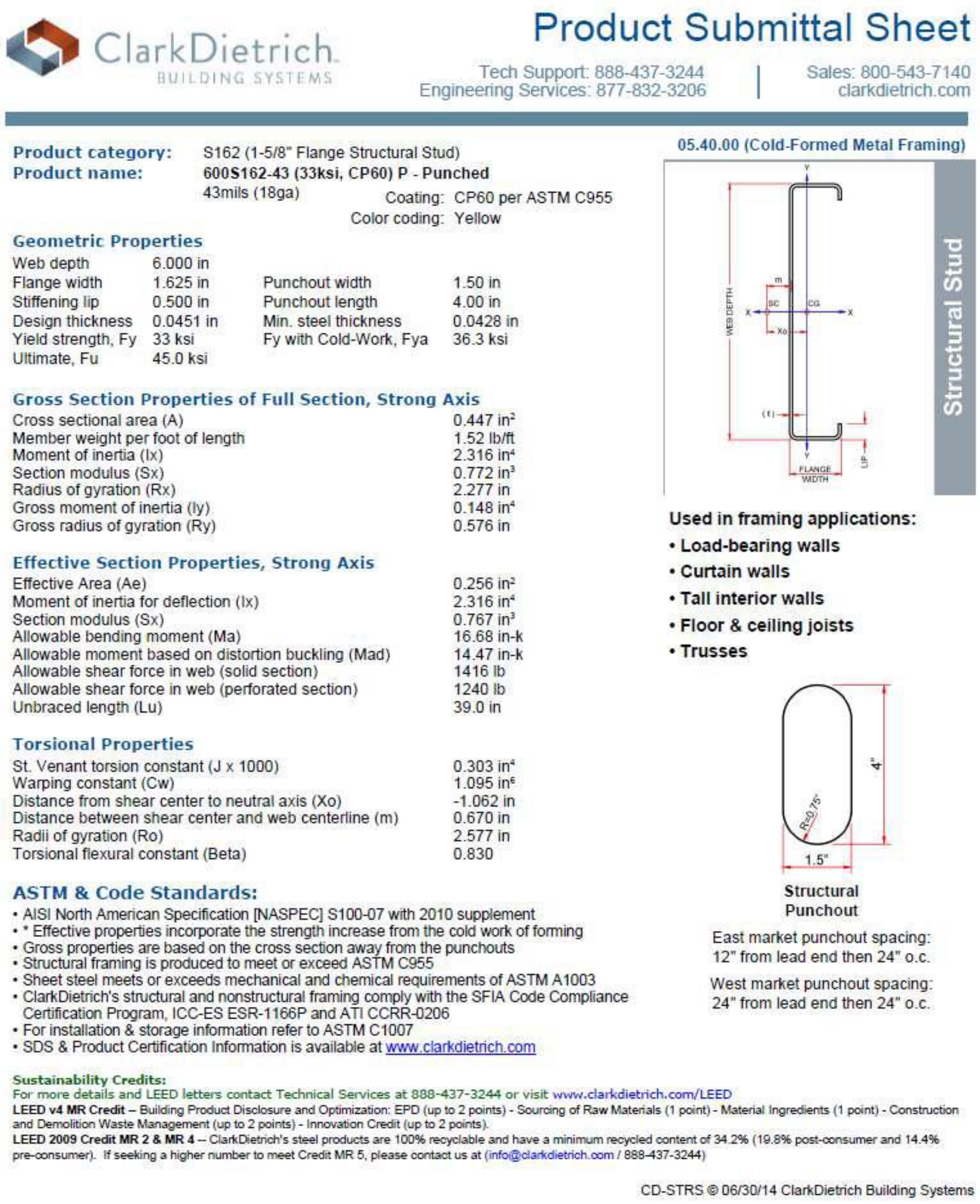


Figure A-4 12 Inch Fastener Spacing Slip at 1900 lbs

Appendix B - CFS Specifications Sheet



ClarkDietrich
BUILDING SYSTEMS

Product Submittal Sheet

Tech Support: 888-437-3244
Engineering Services: 877-832-3206
Sales: 800-543-7140
clarkdietrich.com

05.40.00 (Cold-Formed Metal Framing)

Structural Stud

Product category: S162 (1-5/8" Flange Structural Stud)
Product name: **600S162-43 (33ksi, CP60) P - Punched**
43mils (18ga)
Coating: CP60 per ASTM C955
Color coding: Yellow

Geometric Properties

Web depth	6.000 in		
Flange width	1.625 in	Punchout width	1.50 in
Stiffening lip	0.500 in	Punchout length	4.00 in
Design thickness	0.0451 in	Min. steel thickness	0.0428 in
Yield strength, Fy	33 ksi	Fy with Cold-Work, Fya	36.3 ksi
Ultimate, Fu	45.0 ksi		

Gross Section Properties of Full Section, Strong Axis

Cross sectional area (A)	0.447 in^2
Member weight per foot of length	1.52 lb/ft
Moment of inertia (Ix)	2.316 in^4
Section modulus (Sx)	0.772 in^3
Radius of gyration (Rx)	2.277 in
Gross moment of inertia (Iy)	0.148 in^4
Gross radius of gyration (Ry)	0.576 in

Effective Section Properties, Strong Axis

Effective Area (Ae)	0.256 in^2
Moment of inertia for deflection (Ix)	2.316 in^4
Section modulus (Sx)	0.767 in^3
Allowable bending moment (Ma)	16.68 in-k
Allowable moment based on distortion buckling (Mad)	14.47 in-k
Allowable shear force in web (solid section)	1416 lb
Allowable shear force in web (perforated section)	1240 lb
Unbraced length (Lu)	39.0 in

Torsional Properties

St. Venant torsion constant (J x 1000)	0.303 in^4
Warping constant (Cw)	1.095 in^6
Distance from shear center to neutral axis (Xo)	-1.062 in
Distance between shear center and web centerline (m)	0.670 in
Radii of gyration (Ro)	2.577 in
Torsional flexural constant (Beta)	0.830

Used in framing applications:

- **Load-bearing walls**
- **Curtain walls**
- **Tall interior walls**
- **Floor & ceiling joists**
- **Trusses**

Structural Punchout

East market punchout spacing:
12" from lead end then 24" o.c.

West market punchout spacing:
24" from lead end then 24" o.c.

ASTM & Code Standards:

- AISI North American Specification [NASPEC] S100-07 with 2010 supplement
- * Effective properties incorporate the strength increase from the cold work of forming
- Gross properties are based on the cross section away from the punchouts
- Structural framing is produced to meet or exceed ASTM C955
- Sheet steel meets or exceeds mechanical and chemical requirements of ASTM A1003
- ClarkDietrich's structural and nonstructural framing comply with the SFIA Code Compliance Certification Program, ICC-ES ESR-1166P and ATI CCRR-0206
- For installation & storage information refer to ASTM C1007
- SDS & Product Certification Information is available at www.clarkdietrich.com

Sustainability Credits:
For more details and LEED letters contact Technical Services at 888-437-3244 or visit www.clarkdietrich.com/LEED

LEED v4 MR Credit – Building Product Disclosure and Optimization: EPD (up to 2 points) - Sourcing of Raw Materials (1 point) - Material Ingredients (1 point) - Construction and Demolition Waste Management (up to 2 points) - Innovation Credit (up to 2 points).

LEED 2009 Credit MR 2 & MR 4 -- ClarkDietrich's steel products are 100% recyclable and have a minimum recycled content of 34.2% (19.8% post-consumer and 14.4% pre-consumer). If seeking a higher number to meet Credit MR 5, please contact us at (info@clarkdietrich.com / 888-437-3244)

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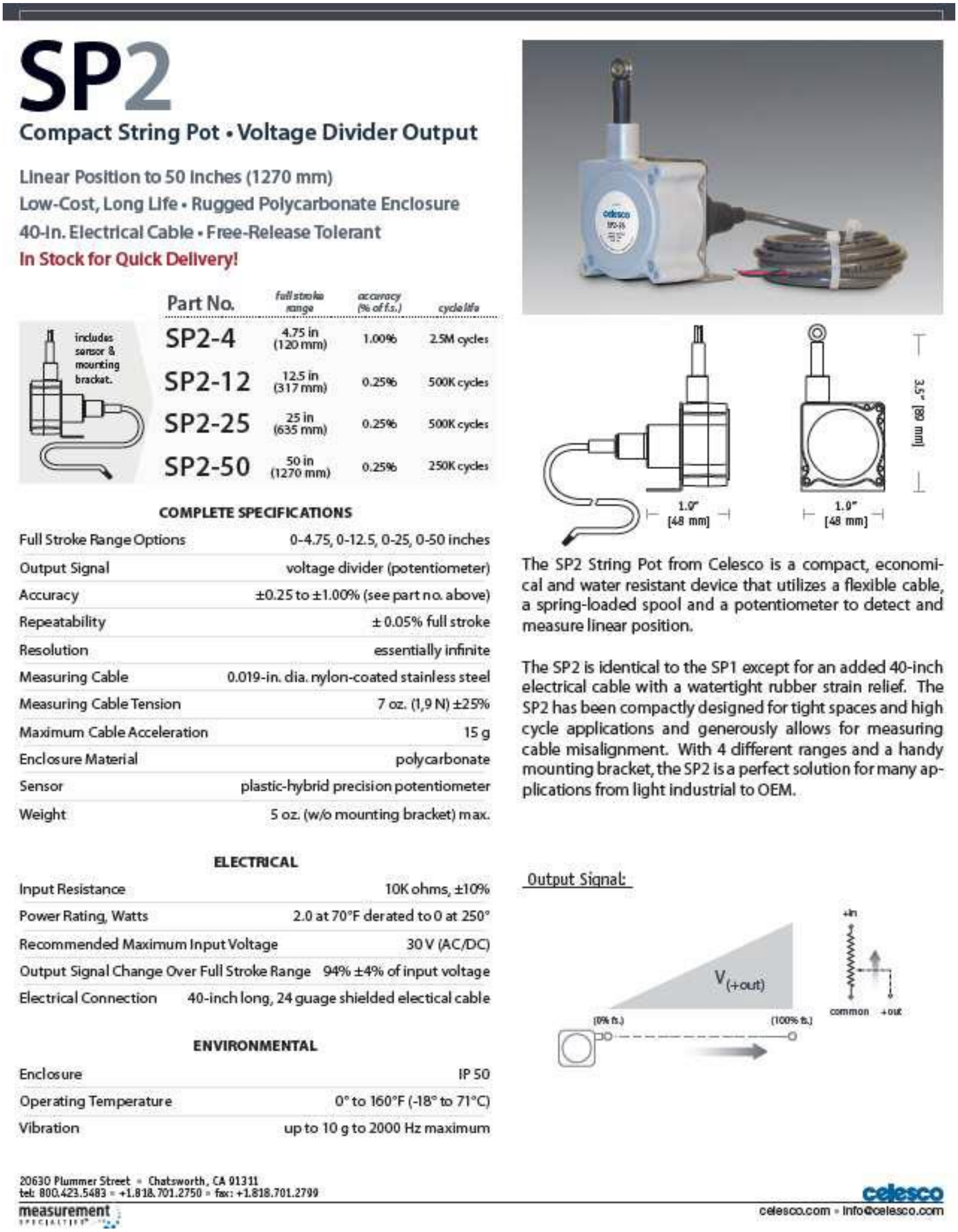
Appendix C - Celesco SP2-12 Specifications Sheet



SP2

Compact String Pot • Voltage Divider Output

Linear Position to 50 Inches (1270 mm)
Low-Cost, Long Life • Rugged Polycarbonate Enclosure
40-In. Electrical Cable • Free-Release Tolerant
In Stock for Quick Delivery!

Part No.	*full stroke range*	*accuracy (% of f.s.)*	*cycle life*
SP2-4	4.75 in (120 mm)	1.00%	2.5M cycles
SP2-12	12.5 in (317 mm)	0.25%	500K cycles
SP2-25	25 in (635 mm)	0.25%	500K cycles
SP2-50	50 in (1270 mm)	0.25%	250K cycles

COMPLETE SPECIFICATIONS

Full Stroke Range Options	0-4.75, 0-12.5, 0-25, 0-50 inches
Output Signal	voltage divider (potentiometer)
Accuracy	±0.25 to ±1.00% (see part no. above)
Repeatability	± 0.05% full stroke
Resolution	essentially infinite
Measuring Cable	0.019-in. dia. nylon-coated stainless steel
Measuring Cable Tension	7 oz. (1,9 N) ±25%
Maximum Cable Acceleration	15 g
Enclosure Material	polycarbonate
Sensor	plastic-hybrid precision potentiometer
Weight	5 oz. (w/o mounting bracket) max.

ELECTRICAL

Input Resistance	10K ohms, ±10%
Power Rating, Watts	2.0 at 70°F derated to 0 at 250°
Recommended Maximum Input Voltage	30 V (AC/DC)
Output Signal Change Over Full Stroke Range	94% ±4% of input voltage
Electrical Connection	40-inch long, 24 guage shielded electical cable

ENVIRONMENTAL

Enclosure	IP 50
Operating Temperature	0° to 160°F (-18° to 71°C)
Vibration	up to 10 g to 2000 Hz maximum

The SP2 String Pot from Celesco is a compact, economical and water resistant device that utilizes a flexible cable, a spring-loaded spool and a potentiometer to detect and measure linear position.

The SP2 is identical to the SP1 except for an added 40-inch electrical cable with a watertight rubber strain relief. The SP2 has been compactly designed for tight spaces and high cycle applications and generously allows for measuring cable misalignment. With 4 different ranges and a handy mounting bracket, the SP2 is a perfect solution for many applications from light industrial to OEM.

Output Signal:

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