A comprehensive approach to establishing a standard test method for evaluating insulated wall panel wythe connector performance

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- The main objective of this paper is to present research that is the basis for a standard test method for determining the performance of wythe connectors for partially composite, precast concrete insulated wall panels.
- This research investigated variables that may affect the results of the wythe connector's mechanical properties.
- The outcomes of this study will help design professionals, precast concrete producers, and connector manufacturers understand the behavior of partially composite wythe connectors and test such connectors with a certain level of confidence.

The precast concrete industry has used insulated wall panels for more than 70 years, although materials, means, and methods have evolved over time.[1] These panels have an insulation layer sandwiched between two concrete layers or wythes joined by a connector (often called the shear connector or wythe connector). By eliminating one layer of concrete in the middepth of the cross section, engineers make efficient use of materials, provide space for an insulating layer, and reduce the weight of the structural component. The wythe connector is then responsible for providing various levels of composite action between the two wythes, depending on the connector's mechanical properties, layout across the panel width, and number of connectors used.[2,3] Fully composite behavior represents the ideal condition where both wythes act integrally as a single component, resulting in a maximum moment of inertia and a continuous strain profile at the sectional level. Conversely, noncomposite behavior represents the case where the wythes act as individual bodies; thus, the moment of inertia is minimal. Partially composite behavior is in between the previous two conditions, where the moment of inertia falls in between the maximum and minimum values.

Contemporary insulated walls are often manufactured using flexible wythe connectors made from various fiber-reinforced polymer (FRP) composites or steel, resulting in partially composite insulated walls. This type of design normally provides the most efficient use of materials and connectors as well as smaller thermal deformations, often resulting in cost savings. Partially composite insulated concrete walls have become a large market for precast concrete producers; however, the connector engineering properties and the methods for obtaining such properties are not well established for specification and codification purposes. Thus, additional research is needed to provide a general design approach suitable for specifying partially composite insulated precast concrete walls, including their components. As jurisdictions adopt energy codes that disallow or penalize thermal bridging and advocate for more advanced behavioral analyses, the demand for precast concrete insulated walls will continue to increase because of their superior thermal and structural performance relative to other systems.[4,5]

Multiple methods are used to obtain the mechanical properties of wythe connectors. In the literature, double and single shear tests are the most popular forms of wythe connector testing. The mechanical properties of interest are ultimate or maximum force, stiffness, and maximum allowable slip or relative displacement between the wythes. Einea et al.[6] used the single shear methodology to test FRP truss connectors. Naito et al.[7] performed double shear tests on discrete proprietary connectors and tested full-scale panels for use in blast-resistant design applications, showing that double shear tests provide a reasonable estimate of the wythe connector properties. Several other research teams have investigated the mechanical properties of discrete or semicontinuous connectors by implementing both single and double shear testing.[8–12]

Recently, Syndergaard et al.[11] tested wythe connectors and compared test results from single and double shear tests based on modified versions of the International Code Council Evaluation Service (ICC-ES) acceptance criteria AC320[13] and AC422.[14] They determined that compared with single shear test results, double shear test results provide a more reasonable estimate of the mechanical properties of wythe connectors; however, they also emphasized that the sources of variability in those tests need additional study. The basis for ICC-ES AC32013 is ASTM E488, *Standard Test Methods for Strength of Anchors in Concrete Elements*,[15] which establishes guidelines for testing concrete anchors but is nonspecific in the details for testing wythe connectors. ICC-ES AC422[14] is explicitly developed for partially composite, semicontinuous grid connectors; it includes recent modifications to test discrete connectors.[16,17]

Although the literature contains several versions of tests that use either the single shear[6,18,19] or double shear method,[7,8,10,11] researchers and other industry stakeholders have not yet identified a universal form of testing suitable for determining the mechanical properties of wythe connectors. One obstacle to a universal testing method is the wide range of wythe connector shapes, types, and materials that are available. **Figure 1** shows various types of proprietary connectors commonly used in wall panel applications. Given the diversity of the connector options being marketed, designers have had to rely on bulk connector properties rather than dimensions and connector material models.

The previously mentioned testing methodologies can provide raw load–versus–slip curves for connectors; however, specifications and testing methods need to have values that connector manufacturers can reference to determine safe and reliable strength and stiffness properties for use in service and ultimate load design scenarios.[20–25] For the purposes of discussion, **Fig. 2** shows a single shear, two possible configurations of a double shear, and the resulting load versus

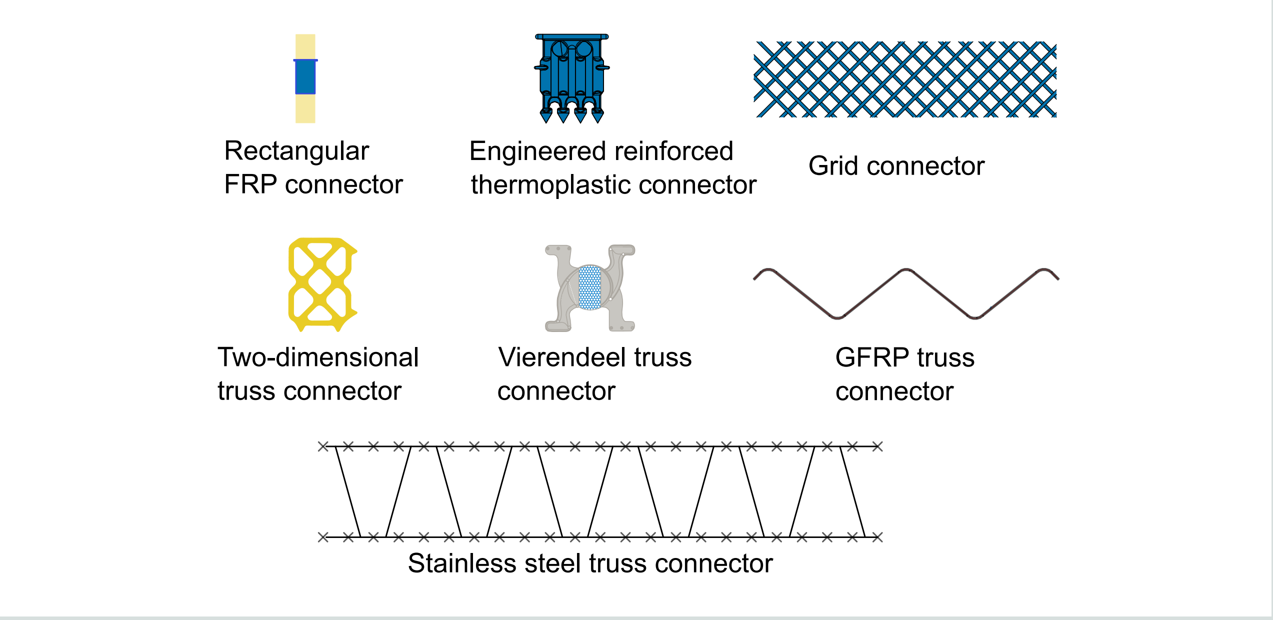


Figure 1. Examples of partially composite connectors. Note: FRP = fiber-reinforced polymer; GFRP = glass-fiber-reinforced polymer.

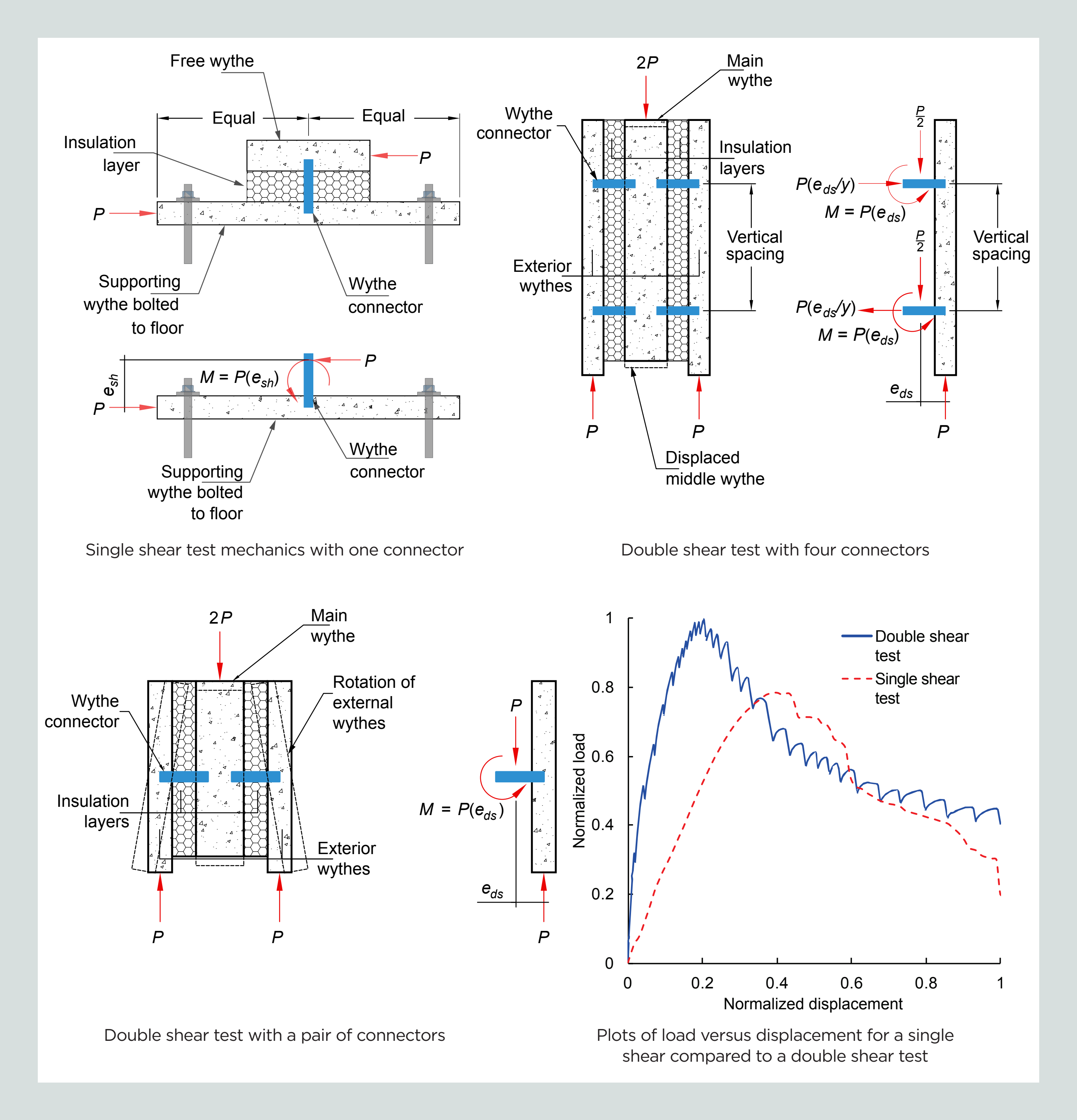


Figure 2. Two-dimensional single and double shear test mechanics. Note: e = eccentricity; e_{ds} = eccentricity of connector for the double shear testing; e_{sh} = eccentricity of connector for the single shear testing; M = flexural moment applied to the connector due to the eccentricity of the load; P = Applied load during the test.

displacement curve for a single and double shear test. The main difference between single and double shear test setups lies in the fixturing and the number of rows of connectors present in each specimen. Although single shear tests require external fixturing to hold the specimen such that the eccentric loads do not rotate the specimen, this testing method may require fewer materials and resources than double shear testing; however, single shear tests may not accurately reflect actual strength and stiffness in insulated wall panels due to the flexural moment (often called pinching action) in the test specimen. This effect exerts a moment on the connector that is not present in an insulated wall panel due to the interlayer slip mechanics of the panel (Fig. 2).

The specimens used in double shear tests are typically taller and have more rows than single shear specimens. Therefore, compared with single shear tests, double shear tests better replicate how connectors in large-scale panels behave, as the connector is tested with little flexural moment beyond that which would be present under normal panel physics (Fig. 2). Compared with single shear tests, double shear tests yield larger ultimate loads and higher stiffness values per connector for the same combination of concrete strength and connectors tested;[11] however, double shear tests, like single shear tests, may have a pinching action (Fig. 2), depending on the number of rows of connectors. This pinching action is reduced by the force couple acting on the specimen (Fig. 2). Therefore, that subtle difference in behavior produces a distinct curve for the connector's properties when single and double shear test results are compared (Fig. 2).

The main objective of this paper is to present research that is the basis for a standard test method for determining the performance of wythe connectors for partially composite, precast concrete insulated wall panels. This performance is studied using the maximum connector force F_{max}, stiffness at 50% of the maximum force $K_{0.5Fmax}$, and slip at maximum force δF_{max}. In addition, this research investigated variables that may affect the results of the wythe connector's mechanical properties during testing and how to interpret test results. Finally, we present a ruggedness investigation to assess the effects of testing parameters to enable the development of a draft standard.

The maximum force results presented in the following sections were normalized by dividing the strength results for a connector by the average maximum strength measured for that connector. This approach provides confidentiality regarding the proprietary connectors used in the study, deters relative performance comparisons between the connectors, and avoids any perceived endorsement of specific products. This approach also keeps the focus on the testing methods and their variability, rather than the characteristics of the connectors tested. The displacements reported in this paper were obtained from the tests, but they do not lead to the determination of mechanical properties. The outcomes of this study will help design professionals, precast concrete producers, and connector manufacturers understand the behavior of partially composite wythe connectors, test such connectors with a certain level of confidence, and understand the foundations of the suggested standard for testing wythe connectors.

Experimental program

The experimental portion of this research was devoted to testing multiple proprietary wythe connectors using different testing methodologies and specimen configurations. In total, 107 specimens were fabricated to evaluate the suitability of the testing methods. All concrete used to fabricate the specimens was normalweight concrete with a compressive strength that resembled that used for precast concrete applications.

The samples were separated into 29, 42, and 36 specimens for three rounds of testing. The first round involved testing double shear (braced and unbraced) and flexural test specimens, whereas the second and third rounds only used double shear test specimens. The specific goals for each round were as follows:

- Round 1: investigate three possible test configurations to obtain connector mechanical properties and select a general specimen configuration with which to proceed.
- Round 2: after the selection of the double shear configuration from round 1, investigate the influence of height on the specimen influences the occurrence of pinching action.
- Round 3: after selection of the minimum specimen height, investigate the ruggedness of testing parameters.

Table 1 shows the testing matrix implemented in the experimental program; this matrix is segmented into three rounds to provide an accurate understanding of the sizes of the specimens tested in each round, as well as which connectors were tested in each round.

To help maintain confidentiality about the proprietary connectors used in the investigation, the force was normalized for a given round and connector type to the average maximum force of a series of n samples. To give an extra layer of confidentiality to the connector manufacturers, letters of the alphabet (that is, letters A through G) were used instead of brands/models to identify connectors.

Double shear test specimens and setup

All of the double shear test specimens were 24 in. (610 mm) wide and had three concrete wythes and two insulation layers. The middle concrete wythe in each sample was 6 in. (150 mm) thick; the other wythes and the insulation layers were 3 in. (75 mm) thick. To ensure uniformity in the testing of all connector types, debonded extruded polystyrene (XPS) insulation was used on all specimens except one. The exception was because bonded expand polystyrene (EPS) insulation was an integral part of the system for one connector type. Identifying the kinds of insulation used for the specimens would reveal the brand of the connector that used EPS. Therefore, this parameter is excluded from Table 1. The concrete wythes were reinforced with Grade 60 (410 MPa), no. 3 (10 M) reinforcement spaced at 14 in. (360 mm) on the short face of the specimen and 19.5 in. (495 mm) on center on the long face of the panel. **Figure 3** shows the double shear test specimen, including the variables addressed in this paper. Table 1 includes the values for each variable contained in Fig. 3. The target 28-day concrete compressive strength of all specimens was 5000 psi (34 MPa). The precast concrete plant in charge of fabricating the specimens provided lifting anchors in the center of the middle wythe for each set of specimens. Table 2 and Fig. 3 contain information on all double shear specimens presented in this research.

Figure 4 shows the double shear test setup, variables, and instrumentation. The load was applied on the center wythe using a double-acting hydraulic ram, and its magnitude was monitored using a load cell sandwiched between two steel plates. The displacement sensors employed in the tests were linear variable displacement transducers (LVDTs) placed on

Table 1. Testing matrix for all specimens tested in the experimental program

Round	Connector label	Height, in.	Total thickness T, in.	Vertical connector spacing Y, in.	Transverse connector spacing S, in.	Edge distance W, in.	Edge distance Z, in.
1	A	26	18	12	12	6	12
	B	48	18	26	12	6	10
	C	39	18	24	12	6	8
	D	26	18	12	12	6	12
	E	n/a	n/a	n/a	n/a	n/a	n/a
	F	n/a	n/a	n/a	n/a	n/a	n/a
	G	n/a	n/a	n/a	n/a	n/a	n/a
2	A	n/a	n/a	n/a	n/a	n/a	n/a
	B	48, 72, 144	18	24	12	6	12
	C	n/a	n/a	n/a	n/a	n/a	n/a
	D	48, 72, 96, 144	18	12	12	6	2
	E	48, 96	18	24	12	6	12
	F	48, 144	18	24	12	6	12
	G	n/a	n/a	n/a	n/a	n/a	n/a
3	A	48	18	24	12	6	12
	B	n/a	n/a	n/a	n/a	n/a	n/a
	C	48	18	24	12	6	12
	D	n/a	n/a	n/a	n/a	n/a	n/a
	E	n/a	n/a	n/a	n/a	n/a	n/a
	F	n/a	n/a	n/a	n/a	n/a	n/a
	G	48	18	24	12	6	12

Note: In all cases, the width was 24 in., the exterior wythe thickness was 3 in., the center wythe thickness was 6 in., and the insulation thickness was 3 in. n/a = not applicable. 1 in. = 25.4 mm.

the surface of the concrete wythes. String potentiometers were used to measure out-of-plane displacement in flexural specimens, and to investigate pinching action in double shear test specimens. The reference for displacement was a steel angle attached halfway to the middle wythe, whereas the displacement sensors were located at four sites—two on each side of the front and back of the outer wythes. During rounds 1 and 2, the outer wythes rested on polytetrafluoroethylene (PTFE) pads to avoid friction between the supporting frame and the specimen.

Flexural test specimens and setup

The flexural test specimens were used to identify load versus displacement information for connectors under more native conditions that the connector would experience in a panel (that is, a panel undergoing bending). Figure 3 shows the cross section of the flexural test specimen, its dimensions, and reinforcement. All flexural specimens had two 3 in. (75 mm) thick wythes and 3 in. thick debonded XPS insulation. The specimens were 48 in. (1200 mm) wide and 96 in. (2400 mm) long. Flexural test specimens, which used connectors E and F, were previously designed with connector data from the manufacturers to achieve wythe connector rupture before specimen failure. The transverse reinforcement was Grade 60 (410 MPa), no. 3 (10 M) reinforcing bars spaced at 16 in. (410 mm) on center. The longitudinal reinforcement was either three ⅜ in. (9.5 mm) diameter, Grade 270 (1860 MPa) strands spaced at 18 in. (460 mm) on center or five Grade 60 (410 MPa), no. 4 (13 M) strands spaced at 11 in. (280 mm) on center on each wythe. The prestressed panels had a minimum precompression of 225 psi (1.55 MPa) per wythe. The 28-day target concrete compressive strength for all specimens was 5000 psi (34 MPa). The precast concrete plant in charge of fabricating the specimens provided lifting devices on the surface of one of the wythes for each set of specimens.

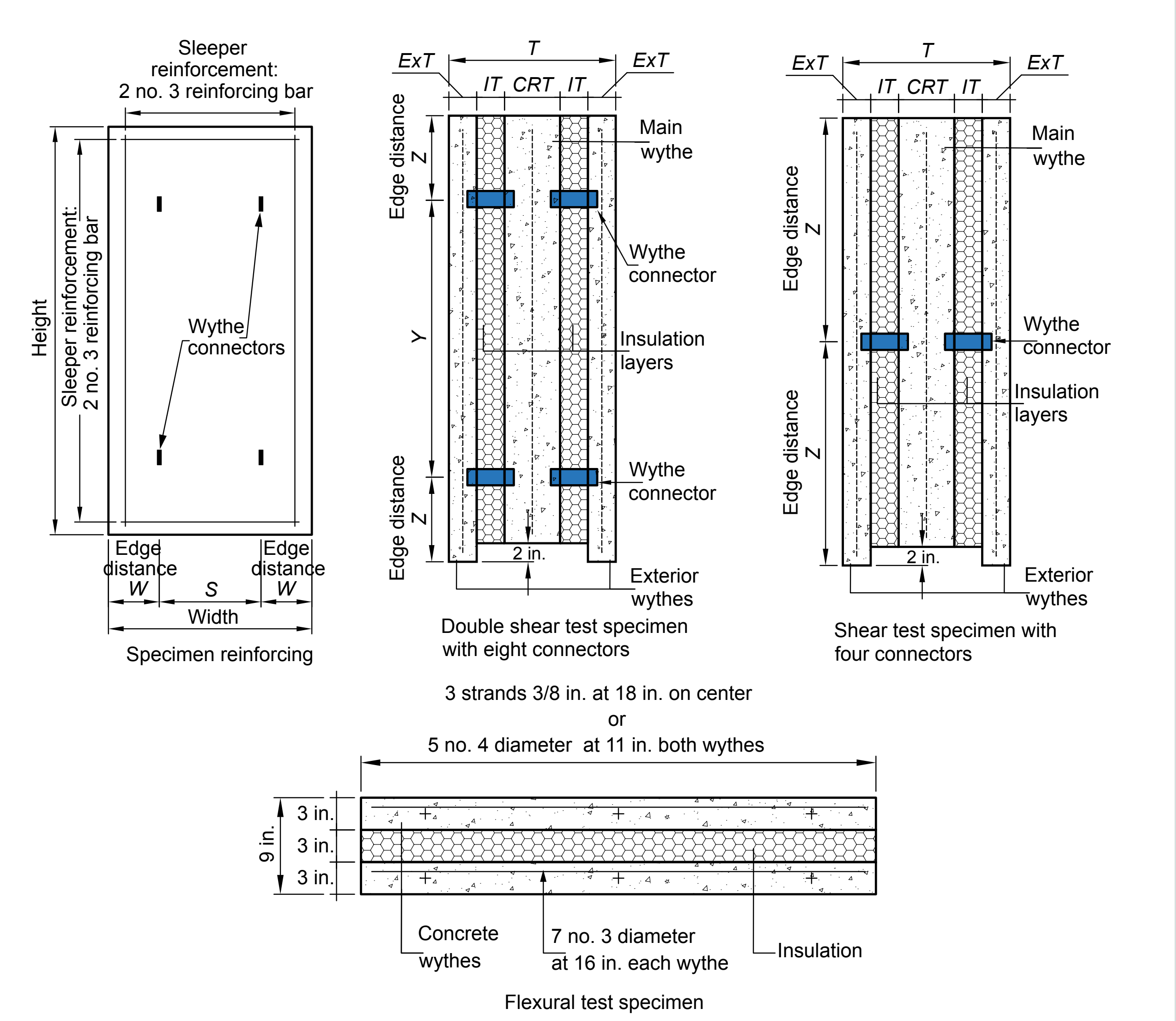


Figure 3. Typical test setup used in the experimental program. Note: *CRT* = center wythe thickness; *ExT* = exterior wyth thickness; *IT* = insulation thickness; *S* = transverse connector spacing; *T* = total thickness; *W* = edge distance; *Y* = vertical connector spacing; *Z* = edge distance. No. 3 = 10M; no. 4 = 13M; 1 in. = 25.4 mm.

Figure 4 shows the flexural test setup with the respective instrumentation. The loading scheme corresponds to three-point bending, with a pin in the middle and two rollers at the supports spaced at 72 in. (1830 mm). The load was applied using a hydraulic ram, and its magnitude was monitored using a load cell sandwiched between two steel plates. The displacement sensors used to measure relative wythe slip were LVDTs, and string potentiometers were attached to the surface of the concrete wythes to measure out-of-plane displacement. The panels, tested on their long edge, rested on top of PTFE pads to avoid friction between the supporting frame and the specimen.

Ruggedness test study

The ruggedness testing was performed as required by ASTM E1169-21, *Standard Practice for Conducting Ruggedness Tests*.[26] ASTM E1169 defines ruggedness as "the insensitivity of a test method to departures from specified test or environmental conditions." This standard details the procedures based on a statistical design of experiments and statistical tests to determine the influence of several conditions. Ruggedness study results help define the control required on the investigated criteria to ensure reliable and replicable tests. Given the support of the available precast concrete producer and connector supplier for this portion of the study, investigators selected three testing parameters to study across three different connectors (labeled *k* in ASTM E1169-21):

- the specimen boundary conditions
- the load placement tolerance
- the load rate/application

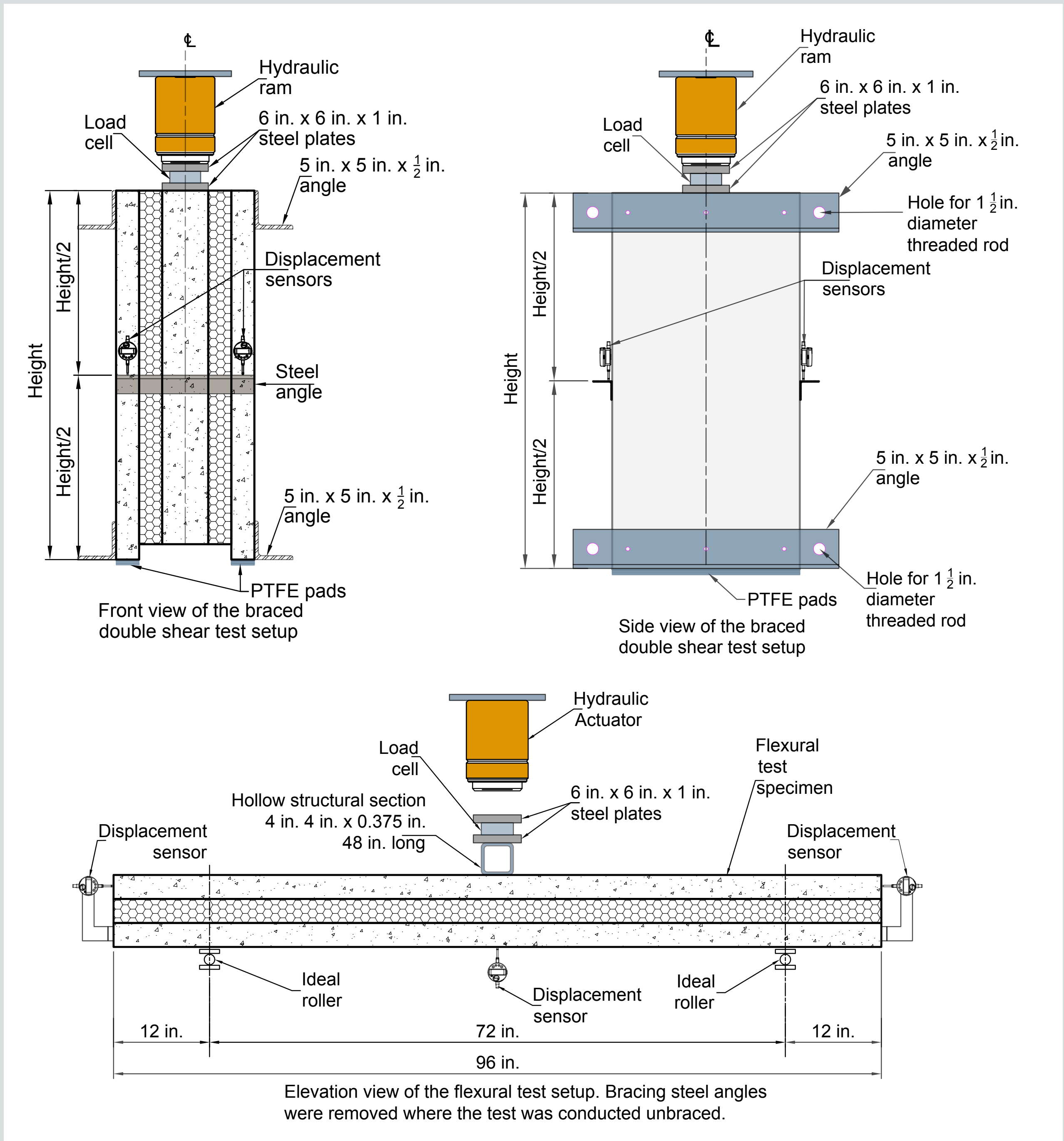


Figure 4. Illustration of the double shear test setup with instrumentation. Note: PTFE = polytetrafluoroethylene. 1 in. = 25.4 mm.

Each of the parameters was selected because they could be controlled and would be likely to have the most impact on testing efficiency. For this study, these factors are set to high and low, as described in the following subsections using the Plackett-Burman design.[26] Given the limited number of specimens, other factors, such as laboratory temperature, were considered but ultimately not selected as test parameters because the concrete and connector properties were expected to be minimally affected by typical laboratory temperature variations.

Load rate

The relationship between load rate and the behavior of wythe connectors is not well understood. The standard intends to determine the static properties of wythe connectors. If stringent controls are placed on the load rate, testing could require sophisticated equipment to control load and displacement, leading to increased testing costs; however, the load rate may need to be controlled to minimize variability. Two loading styles were selected to assess this issue. The high condition used a custom servo-hydraulic pump to provide a controlled load rate of 0.6 in./min (15 mm/min). This load rate caused failure between 5 and 10 seconds for the connectors tested in the ruggedness study, depending on the connectors' displacement capacity. The load rate specified in ICC-ES AC422 is 0.05 in./min (1.3 mm/min). The low condition used a simple hand hydraulic pump; the operator was kept constant throughout the testing program and was instructed to maintain a continuous pumping speed. In these low-condition tests, the specimen failure occurred between 5 and 10 minutes.

Boundary conditions

The boundary conditions are considered a categorical factor (a factor that has a noncontinuous, nonordered scale). Boundary conditions were thought to play a significant role in the performance of the specimens. ICC-ES AC422 specifically requires frictionless pads on the bottom surface of the outer, fixed wythes. The purpose of this requirement is unclear in the document, but it is likely intended to allow free movement and prevent the bottom treatment from influencing the test. ICC-ES AC422 does not specify a treatment for the load application point. In testing rounds 1 and 2, the load application point used a spherical bearing and load cell combination for the loading treatment and double layers of PTFE strips at the base (**Fig. 5**). This condition was considered the high condition for the boundary condition factor. For the low condition, the spherical plate and the PTFE strips were removed, leaving a concrete-on-steel condition. Removing the spherical plate could cause issues with

Spherical bearing and load cell sandwich

Polytetrafluoroethylene (PTFE) strip"++

Load cell sandwich without spherical bearing

Exterior wythe bearing directly on the testing machine platen without bottom PTFE strips

Figure 5. Boundary conditions for double shear tests.

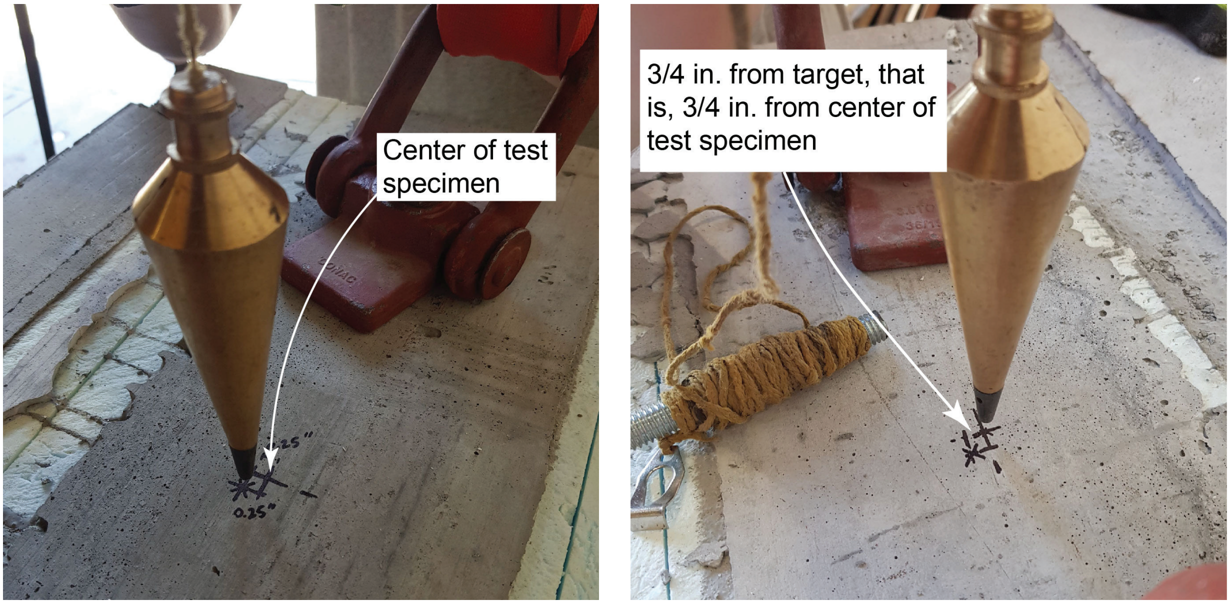
the load application being off center of the load cell and specimen, by an undetermined amount, due to inaccuracies in the testing frame or specimen plumbness. Removing the PTFE strips could cause similar problems and restrict some movement of the wythes during loading.

Load placement tolerance

The load placement tolerance is often controlled in mechanical testing standards (for example, section 8.4 of ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*,[27] or section 5.2 of ASTM C78, Standard Test Method for Flexural Strength of Concrete [Using Simple Beam with Third-Point Loading]28). During the first and second rounds of testing, feedback from the testing personnel indicated that the most tedious and often time-consuming part of the testing was accurately placing the specimen in the loading frame. During the first two rounds of this study and in past work, we used a tolerance of 0.125 in. (3.18 mm) as measured by a plum bob and tape measure from the center of the hydraulic actuator to the point of load application (**Fig. 6**). This condition was set to be the high condition for this factor. It is also considered the highest reasonable tolerance testing of such a large, difficult-to-move specimen. The low tolerance condition intentionally shifted the target by 0.75 in. (19 mm) in both longitudinally planar dimensions of the specimen. After 10 trial installations by the team, where a specimen was installed in a single attempt using a forklift without any fine adjustment, the distance from the hydraulic actuator center to the specimen's center was measured with a tape measure. The worst-case distance in both longitudinally planar dimensions was 0.75 in., while the average distance was 0.50 in. (13 mm). This average distance was selected as the new target, but an additional 0.125 in. tolerance was built in. Thus, the load placement could be between 0.625 and 0.875 in. (15.9 and 22.2 mm) from the center in either direction. For the specimens tested herein, as a fraction of the center wythe thickness, the load placement tolerance equates to ±12.5%, and as a fraction of the center wythe width, it equates to ±3.13%.

Summary of factors

The high and low conditions were then used in a Plackett-Burman design, defined by the number of runs. The standard requires the number of runs to be $k + 1 = 4$ runs. Because of the observed variability from previous rounds, three replicates r of each test were selected, resulting in 12 tests for each connector type. **Table 2** shows the Plackett-Burman design and indicates how many specimens (1 to 12) are tested. Each specimen was randomly labeled from 1 to 12 from the pool of specimens as delivered. The design provides equal low- and high-level runs for every factor. In other words, the design is balanced. Also, while any factor is at its high level, all other factors were run at equal numbers of high and low levels; similarly, while any factor is at its low level, all other factors will be run at equal numbers of high and low levels. In the terminology used by statisticians, the design is orthogonal.



Plumb bob and 0.25 in. tolerance

Plumb bob and 0.75 in. target plus 0.25 in. tolerance

Figure 6. Illustration of the tolerance study. Note: 1 in. = 25.4 mm.

Table 2. Plackett-Burman design for the three factors, four runs, and three replicates						
Run k + 1	Factors k			Replicates		
	Load rate	Boundary	Tolerance	1	2	3
1	+	+	+	1	2	3
2	+	–	–	4	5	6
3	–	+	–	7	8	9
4	–	–	+	10	11	12

Note: + = factor set to high; − = factor set to low. k = connector testing parameters.

Experimental results and discussion

Concrete cylinder testing

The compressive strength of concrete was determined in accordance with ASTM C39. In all cases, the concrete cylinders were 4 in. (100 mm) in diameter and 8 in. (200 mm) tall. Test specimens were retrieved from the precast concrete plant that fabricated them, and the cylinders were laboratory tested before the wythe connectors were sampled. The specimens were made of normalweight concrete with a target compressive strength of 5000 psi (34 MPa); however, many samples exceeded the required strength (**Table 3**). Reinforcing bars were not tested as part of the experimental procedure because the main point was to gather the mechanical properties of the connectors, and, in many samples, the reinforcing bars were not used for structural purposes. The strength of the reinforcing bars in the flexural specimens was 60 ksi (410 MPa), whereas the strength of the strands was 270 ksi (1860 MPa). None of the specimen failures were controlled by reinforcing bar or strand tensile rupture.

First-round testing results

All specimens fabricated for the first-round testing (braced and unbraced double shear testing and flexural testing) were monotonically loaded until the failure load was achieved. To uniformly test all specimens, the failure load was defined as the point where the connectors could not hold more than 20% to 40% of their peak load. **Figure 7** shows the normalized load–versus–slip relationship for all the tested specimens during the first round. The load was normalized by taking the average peak value for each connector type and dividing each curve value by the average value. The slip of the connectors for an individual test was the average displacement of the middle wythe measured relative to the exterior wythes. Specimens A, C, and F had a nearly linear force-displacement curve up to the maximum load. In contrast, connectors B, D, and E behaved almost elastically until they achieved 50% to 70% of the peak load; after that point, they behaved nonlinearly—that that is, they exhibited nearly bilinear behavior up to their maximum loading. After the peak load, the specimens exhibited stiffness degradation on the descending branch of the curve. In this round, only connector A was tested using a braced double shear test; it experienced a thin crack midway through the specimen and one row of connectors.

Connectors E and F were tested using a three-point flexural test. The force was taken as the horizontal shear acting on the connector, and the displacement was the measured slip at the connector location. This testing was intended to test a wythe connector in its native environment and provide a realistic understanding of the connector's behavior while the panel was subjected to flexure.

Table 3. Concrete compression testing results for the experimental program			
Specimen group	Round 1: average concrete compressive strength f'_c, psi	Round 2: average concrete compressive strength f'_c, psi	Round 3: average concrete compressive strength f'_c, psi
A	6127	n/a	5821
B	5154	5164	n/a
C	5154	n/a	5538
D	5330	5164	n/a
E	5980	5540	n/a
F	5154	5164	n/a
G	n/a	n/a	5769

Note: n/a = not applicable. 1 psi = 6.895 kPa.

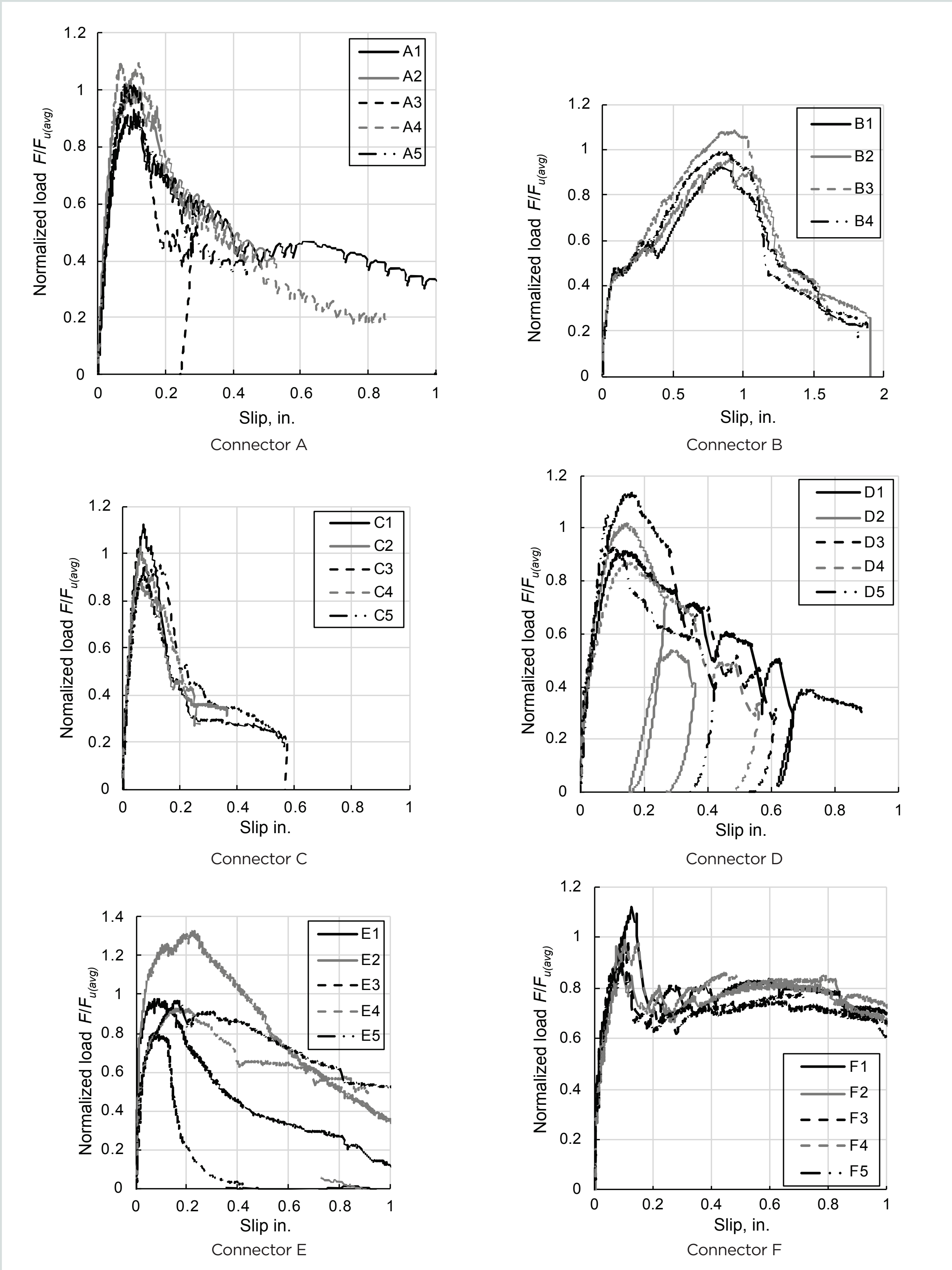


Figure 7. First-round normalized load–versus–slip plots. Note: F = applied load per connector; $F_{u(Avg)}$ = average of the ultimate force per connector. 1 in. = 25.4 mm.

Interpreting results and predicting flexural behavior with test data

Following the guidelines provided in Al-Rubaye et al.,[24] we developed a beam spring model to predict the load-displacement response of the full-scale flexural tests reported in the literature[29,33] and of a specimen tested in round 1. Because the beam-spring model requires the mechanical properties of the connectors, we used the shear load–versus–slip properties obtained from the first-round tests or those reported in Olsen et al.[29] **Table 4** lists the parameters we used in our modeling. We created the model using a structural analysis software framework, following the parameter recommendations of Gombeda et al.[23]

In the model, we represented the concrete wythes with a force-based beam-column element consisting of 40 discrete fibers. We assigned a uniaxial material with nonlinear compression behavior and linear tension softening to each fiber, using the compression curve from Kent and Park[30] and tension softening according to Schoenbrich.[31] For the structural analysis, we used default values of the ratio between the unloading slope at crushing and the initial slope of the concrete strain versus stress curve λ equal to 0.1, and a tension softening stiffness E_{ts} equal to 0.1. We incorporated the compressive strength f_c' and tensile strength f_t of concrete measured in our tests. We modeled the reinforcing steel with a truss element implementing a uniaxial elastic multi-linear material, assuming a linear stress–strain response from zero to yield and from yield to rupture.

We represented the wythe connectors as springs with calibrated strength and stiffness properties. For axial behavior, we used an elastic uniaxial material, and for shear behavior, we applied an elastic multi-linear material based on the slip–versus–load curves from the double-shear tests conducted in round 1 or as reported in the literature.[29,33] For further details on the beam-spring model, see Al-Rubaye et al.[24]

Figure 8 shows the linear portion of the panel behavior using a simple linear analysis and properties for connectors B and C. The panels from Naito et al.[33] using connector B double shear data from round 1 in Fig. 8 had bonded insulation, whereas the Fig. 8 panel from Olsen et al.[29] using connector C double shear test data from round 1 had unbonded insulation. In the two cases, the linear model closely followed the experimental linear stiffness of the panels, never deviating by more than 10%. Figure 8 also shows the predictions of large-scale behavior using load-displacement data from the experimental program and panels from Olsen et al.[29] for round 1, which included a nonlinear analysis. In both cases, the data obtained from the flexural tests either overestimated the peak load by approximately 30% or underestimated it by 30%. In contrast, when using double shear test data from Olsen et al.[29] to model the springs in the model, the maximum normalized load obtained during the first round was overestimated by about 17% or the model closely followed the load-displacement curve (Fig. 8), achieving nearly 100% accuracy for most of the tests. The ratio between the stiffness of the test in the literature[29,33] and the one modeled here was not included, as it would reveal the connector brand. Connectors D and E were excluded from this analysis because there were no tests available in the literature similar to those analyzed in this investigation.

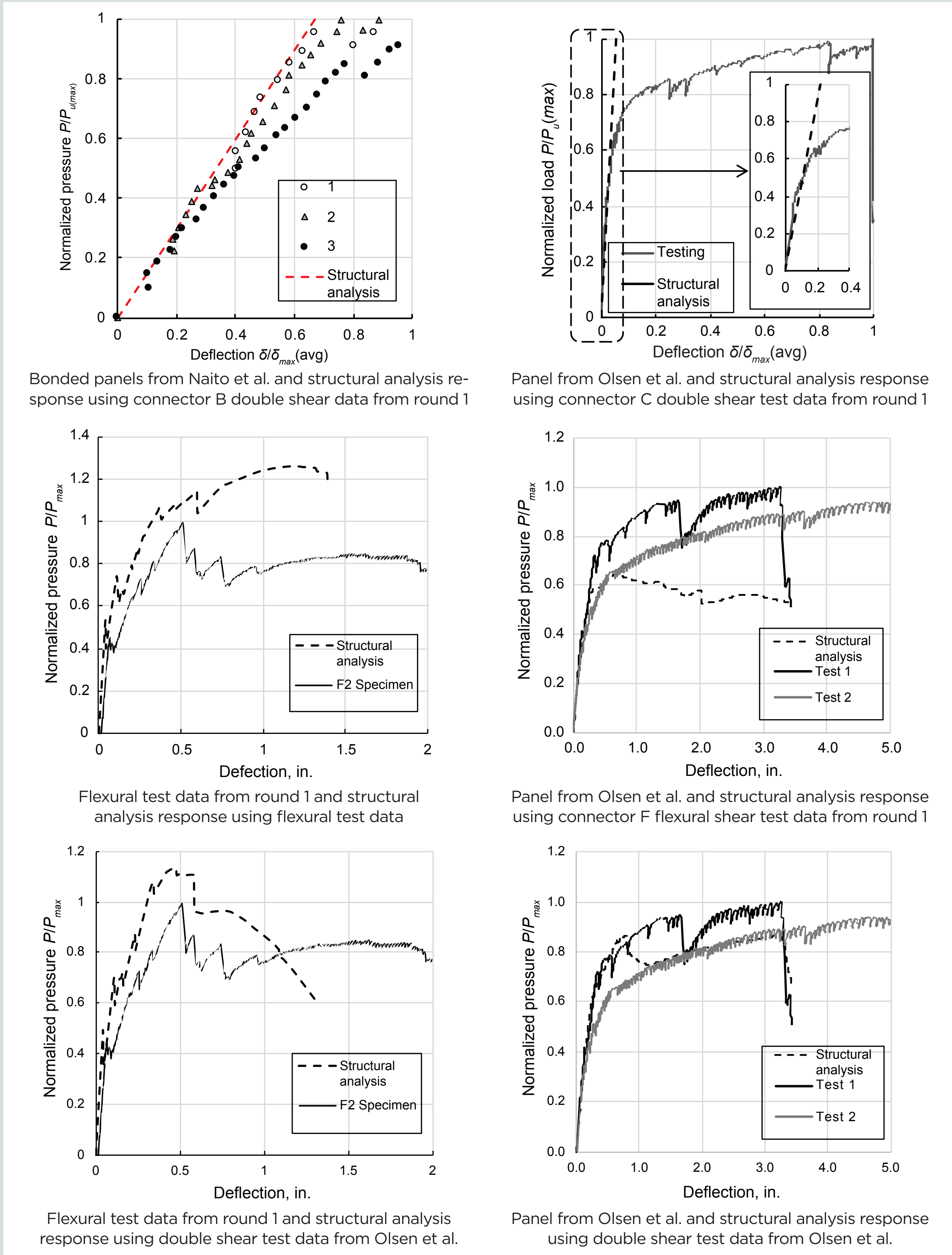
First-round findings

This subsection summarizes the findings related to variability across different specimen types. Double shear test specimens demonstrated an average coefficient of variation *COV* of 7.86% for the ultimate single connector shear force F_u. In ad-

Table 4. Parameters used in the modeling of flexural tests

Panel	Span, in.	Width, in.	t_1, in.	t_2, in.	t_{ins}, in.	f_c', ksi	E_c, ksi	f_t, ksi	Reinforcement	$F_{0.5}F_{max}$, kip	F_{max}, kip	$\delta_{0.5}F_{max}$, in.	δ_u, in.
Naito et al. (2011)	120	32	3	3	3	8.78	4403	0.702	three each ⅜ in. strands	2.50	4.99	0.13	0.833
Olsen et al. (2017)	192	26	3	3	2	10.8	5500	0.770	five no. 3	1.91	3.83	0.017	0.062
Panel F2	72	48	3	3	3	5.12	4078	0.536	five no. 4	1.88	3.92	0.02	0.073
Olsen et al. (2017)	168	36	4	4	3	9.23	5076	0.684	four no. 3	1.09	2.17	0.01	0.075
Panel F2	72	48	3	3	3	5.12	4078	0.536	five no. 4	1.09	2.17	0.01	0.075
Olsen et al. (2017)	168	36	4	4	3	9.23	5076	0.684	four no. 3	1.88	3.92	0.02	0.073

Note: E_c = modulus of elasticity of concrete; f_c' = compressive strength of concrete at testing; f_t = tensile strength of concrete; F_{max} = maximum force applied to a given wythe connector; $F_{0.5}F_{max}$ = 50% of the maximum force; t_{ins} = thickness of insulation on a flexural test from the literature; t_1 = thickness of first wythe on a flexural test from the literature; t_2 = thickness of second wythe on a flexural test from the literature; δ_u = slip when F_{max} is attained; $\delta_{0.5}F_{max}$ = slip when $F_{0.5}F_{max}$ is attained. No. 3 = 10M; no. 4 = 13M; 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 ksi = 6.895 MPa.



Bonded panels from Naito et al. and structural analysis response using connector B double shear data from round 1

Panel from Olsen et al. and structural analysis response using connector C double shear test data from round 1

Flexural test data from round 1 and structural analysis response using flexural test data

Panel from Olsen et al. and structural analysis response using connector F flexural shear test data from round 1

Flexural test data from round 1 and structural analysis response using double shear test data from Olsen et al.

Panel from Olsen et al. and structural analysis response using double shear test data from Olsen et al.

Figure 8. Predicting full-scale flexural behavior using double shear and flexural testing results from the first round and the literature. Note: P = applied load; P_{max} = maximum applied load; δ = out-of-plane displacement; $\delta_{max(avg)}$ = average of the maximum out-of-plane displacement.

dition, these specimens exhibited an average *COV* of 11.80% for the secant stiffness calculated at 50% of the ultimate shear force $K_{0.5}$. In contrast, flexural test specimens showed a higher average *COV* of 16.79% for F_u and an even greater average *COV* of 38.78% for $K_{0.5}$. The analysis of variability based on failure type revealed that connector-controlled failures produced less-scattered results. Specifically, connector-controlled failures yielded an average *COV* of 6.79% for F_u, while concrete breakout failures had an average *COV* of 12.70% for F_u. Additionally, shear-controlled failures exhibited an average *COV* of 10.80% for $K_{0.5}$, whereas concrete breakout failures experienced a significantly higher average *COV* of 31.24% for $K_{0.5}$. Overall, the connector properties of the backbone curve (F_u, $K_{0.5}$, and so forth) derived from the standardized flexural test style exhibited more variability than the double shear–derived properties, indicating that a flexural test will be less precise.

The shear stiffness and strength of the wythe connectors, as determined from our flexural tests, did not accurately predict the load–displacement response observed in the large-scale flexural tests reported in the literature.[29,33] This discrepancy was evident in the limited number of large-scale tests available that included connector configurations similar to those investigated here. When flexural test–derived properties were used, the panel strength was underestimated or overestimated by 30% or more. When using double shear–derived properties, the elastic stiffness did not deviate by more than 10% and the estimated maximum load capacity was not greater than 17%. These results indicated that the double shear test properties would perform more accurately for design.

The three-point bending test specimens, aside from having the largest scatter, had multiple components participating in the failure mechanics:

1. First, the specimens would crack under flexure.

2. Then, a single row or seemingly multiple connectors would fail.

3. Finally, depending on how the specimen was designed, its reinforcement might yield, which would degrade the stiffness of the entire assembly, including the connector itself.

Because this process involves three components—concrete tensile strength, connector ultimate strength, and stiffness—as well as the mechanical properties of the reinforcement, the obtained values may be scattered, with the degree of scattering depending on the connector failure type and strength. In addition, the design of specimens for three-point bending is difficult because the design relies a priori knowledge of the very properties of the connector that are being investigated. Therefore, the use of three-point bending requires the investigator to gather mechanical properties by trial and error or to estimate such properties via another type of testing, such as the double or single shear tests. Given these challenges, three-point bending was eliminated in the subsequent rounds.

Second-round testing results

The second round of testing (braced and unbraced double shear testing) was intended to identify the effect of the height of the specimens on the shear strength and stiffness of the connectors observed in the previous round of testing. ICC-ES AC422 requires an 8 ft (2.4 m) tall specimen for continuous connectors and a 4 ft (1.2 m) tall specimen for discrete connectors, although a reason for these requirements has not been published. Further, the braced double shear specimens were intended to prevent the pinching action that was observed in previous testing. [23] After investigators observed that resisting the pinching action with bracing—in an effort to minimize specimen height—resulted in wythe cracking that affected testing results, they determined that the height of the specimens and the bracing conditions would be the primary variables of interest in round 2. Other variables, such as the thickness of the wythes and the concrete strength, largely depend on the conditions of connector use and design. **Figure 9** displays the normalized load versus slip for connectors B, D, E, and F. The specimens ranged in lengths from 4 to 12 ft (1.2 to 3.6 m), with bracing condition (braced or unbraced) applied to all studied lengths. As can be observed from the plots in Fig. 9, both the bracing and the length factors had a minimal effect on the force versus displacement behavior of the wythe connectors for a fixed concrete strength and component thickness.

An analysis of variance performed on the data demonstrated that the bracing and unbracing and length factors are insignificant for the normalized force, the stiffness, and the slip of the connector. Therefore, adding bracing or increasing the length up to 12 ft (3.6 m) does not significantly influence the results for the range of connector strengths tested. On the contrary, these factors make the testing procedure more difficult and time consuming, translating into more costs associated with the testing standard.

Out-of-plane displacement effect

The final objective of the second round was to determine whether the point where the wythe slip reference point is taken affects the measured relative slip values. The sensors were placed at the bottom tenth, middle, and top tenth of the panel length, measured from the floor to the top of the panel. The results indicated no difference in average slip relative to the location of measurement, except for one case in which a sensor malfunction may have been present. Except for that case, all the load ascending lines are identical, which indicates that the relative wythe slip is not influenced by out-of-plane wythe displacement. Also, because the measurements show a nearly rigid-body movement from the middle wythe relative to the outer wythes, the relative wythe displacements should always be the same, except in those cases when a connector breaks and the applied load redistributes to one of the outer wythes.

A separate analysis was conducted to determine whether the out-of-plane displacements affected the normalized maximum load values for samples tested during the second round. A first

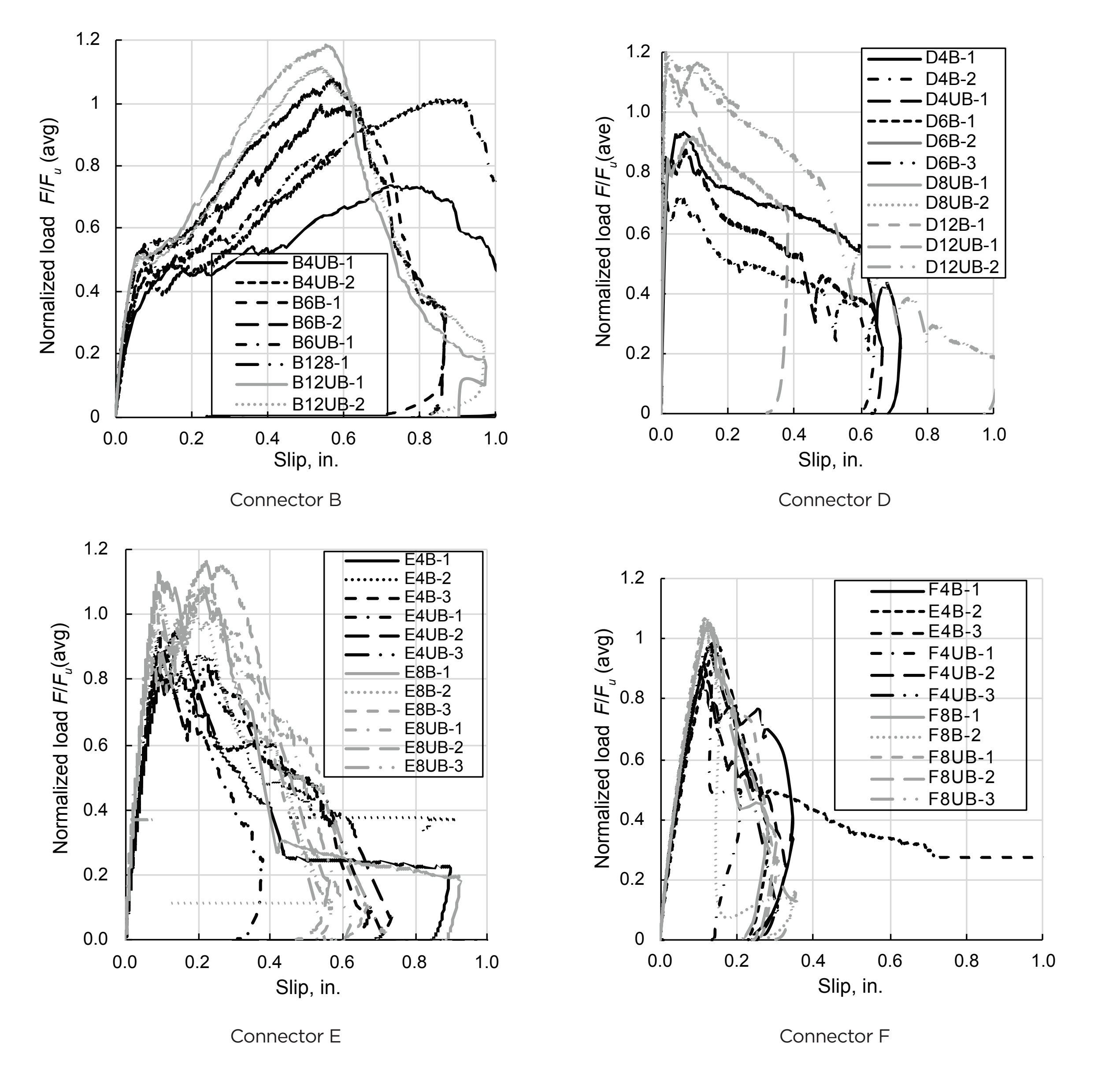


Figure 9. Second round double-shear test results for connectors. Note: The first letter is the connector label, the number is the height of the specimen in feet, the next letters are the bracing condition (B for braced and UB for unbraced), and the last number after the hyphen is the number of the sample. For example, B4UB is a 4 ft tall unbraced double shear test for connector B. P = applied load; P_{max} = maximum applied load. 1 in. = 25.4 mm; 1 kip = 4.448 N.

analysis involved determining whether the presence of bracing had any influence on the out-of-plane displacements either at the top or the bottom of the specimens. The results revealed no correlation between the normalized maximum force for the out-of-plane displacement at the top or the bottom of the specimen.

Third round of testing: Ruggedness testing

Figure 10 shows the test results for the third round of testing, which only sampled the connectors using double shear test specimens without bracing. This round only included connectors A, C, and G, and the results represent the values for the factors tested (Table 2). The following section on ruggedness test results and its subsections describes the analysis of each set of specimens and the factors considered in the ruggedness analysis.

Test results

As mentioned, three connectors—A, C, and G—were used in this final section of the testing program. Connectors A and C are discrete connectors, and connector G is a continuous connector. The selection of these connectors would allow investigators to make comparisons between the effects of continuous and discrete connectors if any effects were deemed

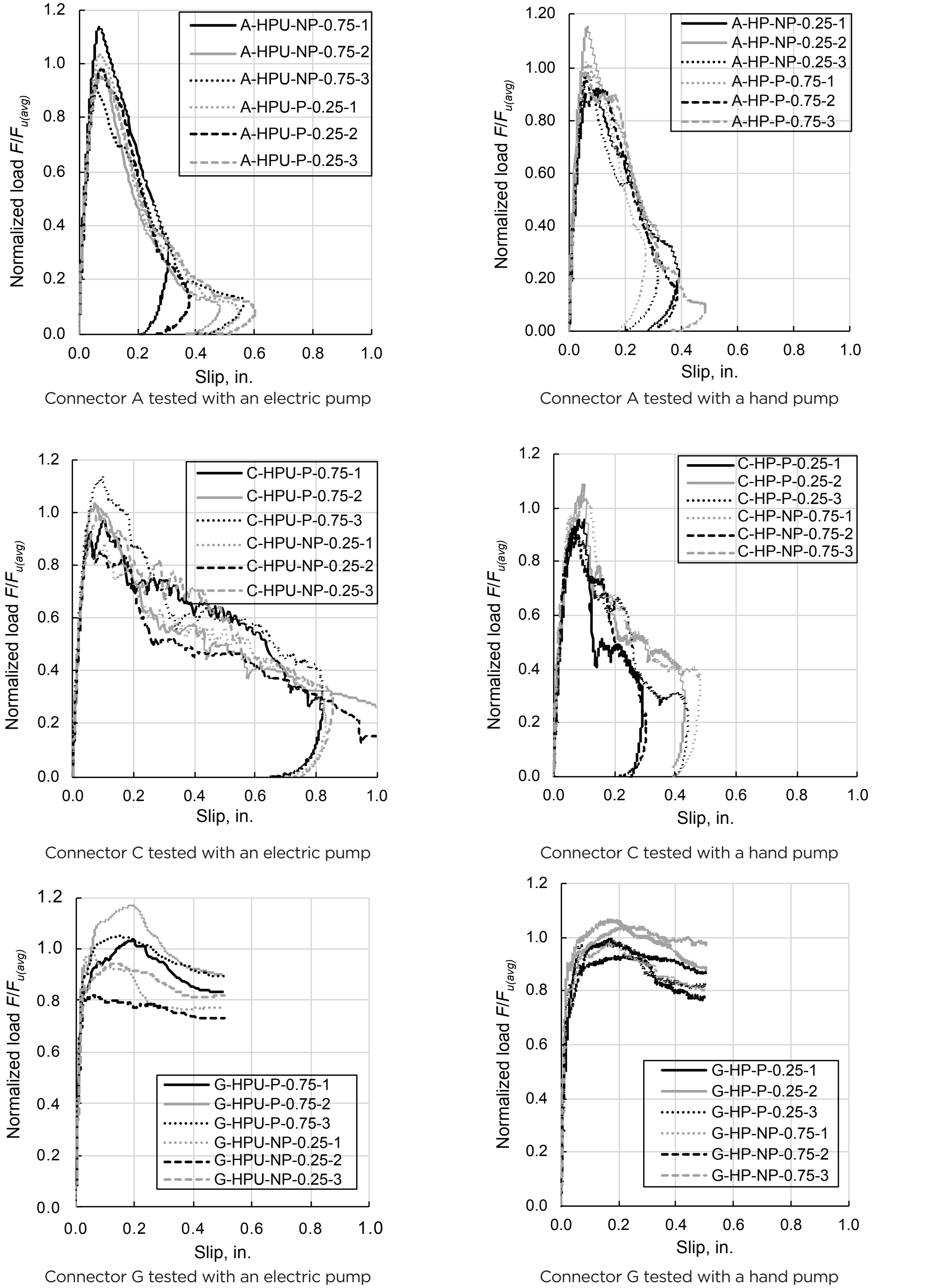


Figure 10. Third-round normalized strength–versus–slip plots. Note: F = applied load per connector; $F_{u(Avg)}$ = average of the ultimate force per connector. 1 in. = 25.4 mm.

significant. For each factor, the main effects are calculated by finding the average results from the high condition minus the average from the low condition. The variance of each run is calculated from the three repetitions from that run. Variances are added up from each run and then averaged. The standard deviation of the effects S_{effect} is then estimated from the following equation:

$$S_{effect} = \sqrt{\frac{4s_{rep}^2}{N \times r}}$$

where

N = number of runs in each design = 12

r = number of replicates of the design = 3

$s_{rep}^{\ 2}$ = average variance of the test results in this design

The main effects were all considerably smaller than the calculated standard deviation of the effects. Even without the analysis presented in the following subsections, this finding implies that the factors investigated will not be significant when compared to the scatter in the data.

Half-normal plots analysis

ASTM E1169-21[26] indicates two ways to assess whether the main effects are significant. The first is the half-normal plot, where the main effects are plotted against the half-normal plotting values (given in ASTM E1169-21 Annex A2). This method is semiqualitative in that one assesses whether a factor's main effect is far to the right of the reference line if the fitted points are nonlinear. The reference line in this work is plotted with a slope of the sample standard deviation for those samples tested in the ruggedness study for an individual connector. Another alternative, not selected herein, is to draw a reference line by eye to fit the effects. In both cases, if the data points are far from the reference or fitted lines, that indicates a significant factor. Appendix A presents the half-normal plots for connectors A, C, and G for F_{max} and $K_{0.5}$. All factors were tiny relative to the observed S_{effect} (**Table 5**). This type of analysis is better suited to investigating several factors, but it seems to indicate no statistically significant effects of those investigated.

Student's t-test

The second method in ASTM E1169-21 for determining whether a factor is significant is the Student's t-test. This test compares the means of two groups assumed to follow a t-distribution. In this case, the standard recommends a probability threshold p of 0.05, indicating a 95% probability that the main effect differs from the group's mean. Appendix A presents the values for the Student's t-test for each connector in this study phase, revealing that none of the calculated values of p are close to the standard recommended threshold of 0.05. The lowest value of p was 0.33, much higher than the threshold, for load placement tolerance for $K_{0.5}$. The results of this analysis strongly corroborate the semiqualitative analysis of the half-normal plots described in the previous subsection, which found no significant effects among the factors investigated.

Summary and discussion

This section presents a summary and discussion of the test results for rounds 1 through 3. Round 1 consisted of testing double shear and flexural specimens to determine the most appropriate test to continue the research. The double shear test specimens had one or two connector rows, whereas the flexural specimens had two rows of connectors placed longitudinally. Flexural specimens produced highly variable results, influenced by the specimen reinforcement and configuration, and did not produce accurate large-scale predictions for the studied dataset. Double shear specimens with one row of connectors performed poorly in testing, as the outer wythe cracked and deformed considerably postcracking, even after bracing was added to some of the specimens. The third specimen group, double shear specimens with two rows of connectors, produced results with low variability for both displacement and force of the connectors. Because that group outperformed the other two in terms of data quality and uniformity of results, the research team and the committee decided to use a double shear test specimen with two connector rows for the second round of testing.

The second round of testing consisted of evaluating how the specimen length, bracing condition, and out-of-plane displacement affected the strength and stiffness of the wythe connectors. It was determined that in specimens with lengths between 4 and 12 ft (1.2 and 3.6 m), none of those parameters significantly affected the mechanical properties of wythe connectors, so investigators decided to exclude them from the final round of testing.

During the third round, the significance of the factors was investigated using half-normal plots and the Student's t-test. The half-normal plots are more suited to investigating several factors, but the findings indicate no statistically significant effects of the factors studied. For the Student's t-test, the lowest value of p was 0.33, much higher than the threshold for load placement tolerance for $K_{0.5}$. The results of this analysis strongly corroborate the semi-qualitative analysis of the half-normal plots, which found no significant effects among the factors investigated.

These findings shaped the testing protocol developed by the research team and the PCI Research Advisory Committee (Appendix B). The selection of the specimen for use in the testing protocol was based on the first-round findings showing excessive cracking in single-row double shear test specimens and flexural test specimens. A minimum specimen length of 4 ft (1.2 m) was adopted to simplify logistics without affecting the observed connector behavior. The boundary conditions and treatment (PTFE pads and bearings), along with load placement tolerance, were defined through statistical analysis, ensuring consistent and repeatable measurements. More details about the experimental program and data analysis can be found in Pozo-Lora et al.[32]

Table 5. Connectors A, C, and G main effects and variance estimates*

Connector	Run	Maximum force Fmax					Stiffness at 50% of the maximum force $K_{0.5}$				
		Factor			Average	Variance	Factor			Average	Variance
		Load rate	Boundary	Tolerance			Load rate	Boundary	Tolerance		
A	1	+	+	+	1.06*	0.047	+	+	+	29.1*	26.6
	2	+	–	–	0.99*	0.028	+	–	–	28.6*	96.6
	3	–	+	–	0.97*	0.06	–	+	–	23.9*	8.1
	4	–	–	+	1.01*	0.033	–	–	+	28.1*	64.7
	average +	1.02*	1.01*	1.03*	total variance	0.168	28.9*	26.5*	28.6*	total variance	195
	average –	0.99*	1*	0.98*	average variance	0.042	26*	28.4*	26.3*	average variance	49
	main effect	0.085	0.043	0.138	S_{effect}	0.237	7.47	-4.84	6.12	S_{effect}	6.983
C	1	+	+	+	0.97*	0.94	+	+	+	24.45*	1160
	2	+	–	–	0.99*	0.05	+	–	–	29.16*	336
	3	–	+	–	1*	0.79	–	+	–	27.34*	231
	4	–	–	+	1.04*	0.12	–	–	+	27.54*	148
	average +	0.98*	0.98*	1*	total variance	1.89	26.8*	25.9*	26*	total variance	1879
	average –	1.02*	1.02*	1*	average variance	0.47	27.4*	28.4*	28.3*	average variance	470
	main effect	-0.29	-0.27	0.05	S_{effect}	0.79	-0.6	-2.5	-2.3	S_{effect}	25
G	1	+	+	+	1.02*	0.019	+	+	+	53.54*	3.78
	2	+	–	–	0.98*	0.019	+	–	–	40.46*	21
	3	–	+	–	1.05*	0.006	–	+	–	40.37*	249
	4	–	–	+	1.05*	0.134	–	–	+	43.91*	309
	average +	1*	1.03*	1.03*	total variance	0.179	47*	47*	48.7*	total variance	583
	average –	1.05*	1.01*	1.01*	average variance	0.045	42.1*	42.2*	40.4*	average variance	146
	main effect	-0.01	0.15	-0.06	S_{effect}	0.24	11	10.8	18.8	S_{effect}	16.1

Note: S_{effect} = standard deviation of the effects.

* Value was normalized by the mean of the F_{max} average in this set of 12 experiments.

Conclusion

The research presented in this paper involved the testing of 107 specimens fabricated to evaluate multiple aspects of the properties of commercially available wythe connectors. The study consisted of testing flexural and double shear specimens during the first round and testing double shear specimens during the second and third rounds. The variables studied in this research were the testing method, the number of connectors per specimen, specimen length, bracing condition, load application point tolerance, boundary conditions, and load treatment. The following conclusions were drawn from the investigation:

- Double shear test specimens can provide consistent results with low variability compared with flexural test specimens, which produce scattered results and have many variables interacting during testing. Double shear test specimens with one row of connectors also tend to develop cracks in the middle of the specimen when bracing is used.

- The length, bracing condition, and measured out-of-plane displacement do not significantly affect wythe connector shear mechanical properties for specimens greater than or equal to 4 ft (12 m) in length. Specimens with lengths less than 4 ft produced scattered results. Observed out-of-plane displacements did not consistently reflect differences in the connector shear mechanical properties among connector types.

- The ruggedness study indicates that the boundary condition, load placement tolerance, and displacement rate have no statistically significant effects within the bounds provided. Therefore, it can be concluded that the double shear test is not sensitive to the studied variables when the tolerances and conditions outlined previously are implemented.

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Notation

COV = coefficient of variation

e = eccentricity

e_{ds} = eccentricity of connector for the double shear testing

e_{sh} = eccentricity of connector for the single shear testing

E_c = modulus of elasticity of concrete

E_{ts} = ratio between the unloading slope at crushing and the initial slope of the concrete strain versus stress curve

= compressive strength of concrete at testing

f_t = tensile strength of concrete

F = applied load per connector

F_{max} = maximum force applied to a given wythe connector

F_u = ultimate single connector shear force

$F_{u(Avg)}$ = average of the ultimate force per connector

$F_{0.5}F_{max}$ = 50% of the maximum force

k = connector testing parameters

K_X = elastic slope of the load versus relative displacement curve

$K_{0.5}$ = stiffness of the wythe connector calculated at 50% of the ultimate shear force

M = moment applied to the connector due to the eccentricity of the load

N = number of runs in each design

p = probability threshold

P = applied load

P_{max} = maximum applied load

r = replicates of the design

s_{rep2} = average variance of the test results in this design

S = transverse connector spacing

S_{effect} = standard deviation of the effects

t_{ins} = thickness of insulation on a flexural test from the literature

t_1 = thickness of first wythe on a flexural test from the literature

t_2 = thickness of second wythe on a flexural test from the literature

T = total thickness

W = horizontal edge distance

Y = vertical connector spacing

Z = vertical edge distance

δ = out-of-plane displacement

δ_u = slip when F_{max} is attained

δF_{max} = slip at maximum force

$\delta_{max(avg)}$ = average of the maximum out-of-plane displacement

$\delta_{0.5}F_{max}$ = slip when $F_{0.5}F_{max}$ is attained

λ = tension softening stiffness

Appendix A: Half-normal plots and the Student's t-test

ASTM E1169, *Standard Practice for Conducting Ruggedness Tests*, indicates two methods to assess whether the main effects are significant. The first method uses the half-normal plot, plotting the main effects against the half-normal plotting values (given in ASTM E1169-21 Annex A2), and compares the main effects to a reference line. ASTM E1169 provides little guidance regarding reference line construction when using small sample sizes. Section 5.2.2.2 implies that the line is formed by fitting some number of the smaller effects, but it is nonspecific about the number. Section 5.2.2.3 indicates that this line can be plotted with a slope of the inverse of the experimental error (that is, the standard deviation of the error). The latter method was selected in this investigation because only three main effects were investigated, but the reader can envision a fitted line to the lower two points, resulting in similar conclusions in the subsequent half-normal plots.

This method is semiqualitative in that it is an assessment of whether a factor's main effect is far to the right of the reference line or if the fitted points are highly nonlinear, the latter being difficult to establish when only three effects are investigated. The reference line in this half-normal plot is a graph with a slope of the sample standard deviation for the samples tested in the ruggedness study for an individual connector. Another alternative, not selected in this study, is to draw a reference line by eye to fit the effects. In both cases, if the data points are far from the reference line or the fitted line, that indicates a significant factor.

Figure A.1 presents the half-normal plots for connectors A, C, and G for the maximum force applied to a given wythe connector F_{max} and the stiffness of the wythe connector calculated at 50% of the maximum force $K_{0.5}$ (stiffness at half of ultimate). Figure A.1 has a few points to the right of the reference line. Another option (not shown) would be to fit a least-squares line to the three data points, which the reader can imagine would also indicate that all points are near the reference line. Thus, all factors were small relative to the observed standard deviation of the effects S_{effect}. This type of analysis is better suited to the investigation of several more factors that could influence the behavior, but that would require a larger number of tests and the project budget could not sustain more testing. The graphs in Fig. A.1 seem to indicate there are no statistically significant effects associated with the variables investigated. Examples of half-normal plots that indicate significant effects can be found in ASTM E1169 Fig. 1 and 2, which seem to further indicate that the effects observed herein are not significant, given how far to the right of the reference line significant effects are expected. These example figures are not reproduced here for brevity, but the reader is encouraged to read ASTM E1169.

The second method in ASTM E1169 for determining whether a factor is significant is the Student's t-test. This test compares the means of two groups that are assumed to follow a t-distribution. In this case, a probability threshold p of 0.05 is recommended in ASTM E1169, which would then indicate a 95% probability that the main effect is different than the mean of the group. Table A.1 presents the values for the Student's t-test for each of the connectors in the round 3 testing. None of the calculated values of p are close to the standard recommended threshold of 0.05. The lowest value of p is 0.33 (the bold number in **Table A.1**), which is higher than the threshold for load placement tolerance with respect to K0.5. The results of this analysis strongly corroborate the semiqualitative analysis of the half-normal plots, where no significant effects were found among the factors investigated.

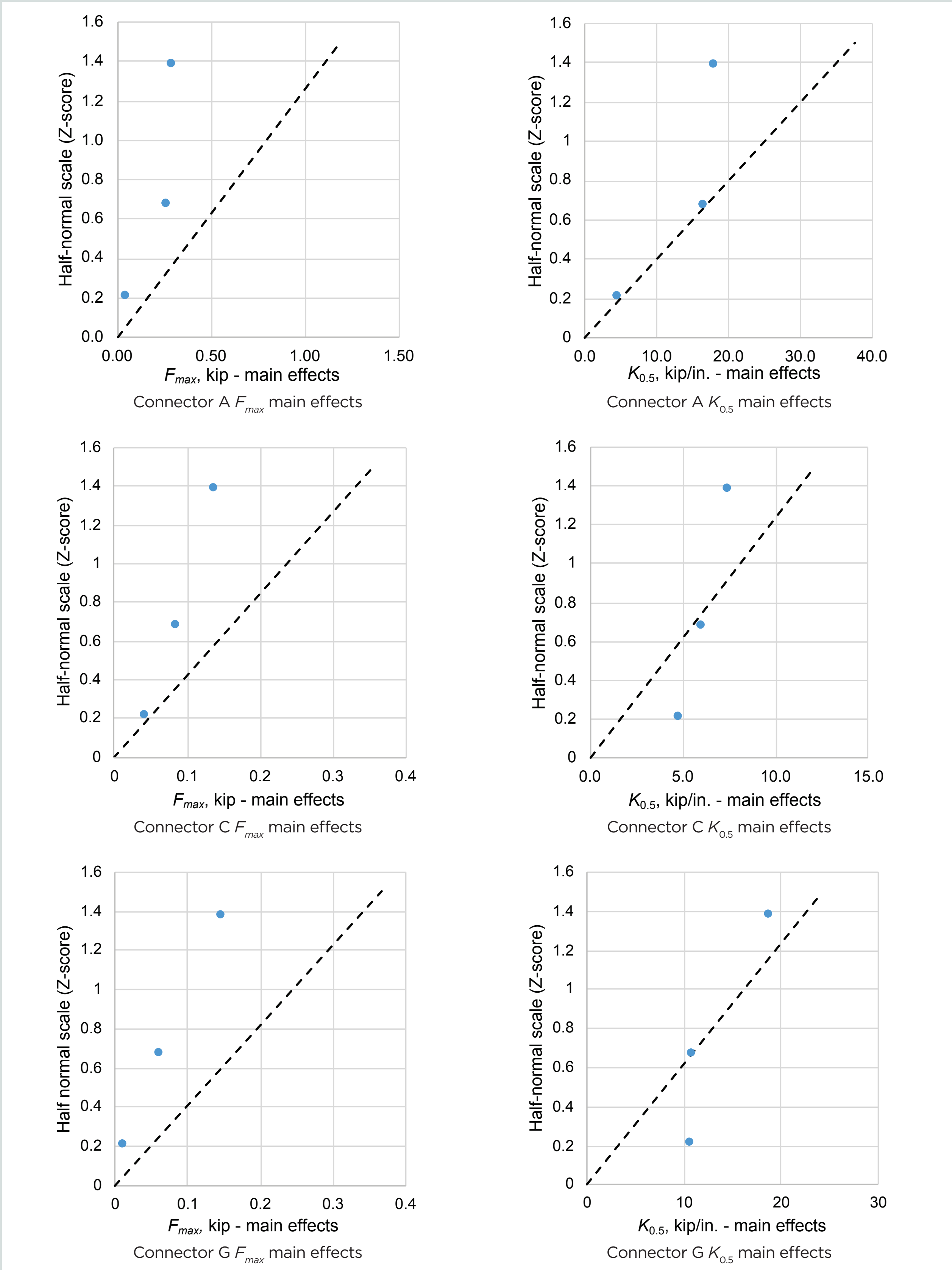

Figure A1. Half-normal plots for connectors. Note: F_{max} = maximum force applied to a given wythe connector; $K_{0.5}$ = stiffness of the wythe connector calculated at 50% of the maximum force.

Table A.1. Student's t-test for F_{max} and $K_{0.5}$ main effects					
Connector	**Value**	**Effect (ordered)**	**Estimated effect**	**Student's t-test value**	**Probability threshold *p***
A	F_{max}	tolerance	0.14	0.58	0.57
		load rate	0.08	0.36	0.73
		boundary	0.04	0.18	0.86
	$K_{0.5}$	load rate	7.47	0.92	0.42
		tolerance	6.12	0.76	0.50
		boundary	4.84	0.60	0.59
C	F_{max}	load rate	0.29	0.37	0.74
		boundary	0.27	0.34	0.76
		tolerance	0.05	0.07	0.95
	$K_{0.5}$	boundary	18.05	0.72	0.52
		tolerance	16.58	0.66	0.56
		load rate	4.67	0.19	0.86
G	F_{max}	boundary	0.15	0.60	0.59
		tolerance	0.06	0.25	0.82
		load rate	0.01	0.04	0.97
	$K_{0.5}$	tolerance	18.80	1.17	0.33*
		load rate	11.00	0.68	0.54
		boundary	10.79	0.67	0.55

Note: F_{max} = maximum force applied to a given wythe connector; $K_{0.5}$ = stiffness of the wythe connector calculated at 50% of the maximum force.
* The lowest probability threshold *p*.

Appendix B: Laboratory test protocol outline

Based on the test performed in rounds 1, 2, and 3, the authors have developed a test protocol to evaluate the shear characteristics of wythe connectors. This test protocol consists of testing wythe connectors in double shear. The standard length of the specimens should be 4 ft (1.2 m). The other specimen dimensions should be taken as the sum of the variables involved in the specimen sizing, such as the external wythe thicknesses, connector spacing, connector edge distance, insulation thickness, insulation bonding condition (bonded or debonded), and concrete strength; all of those variables should be representative of the design and construction application for which the connector is commercially used. The testing protocol consists of the required materials, the step-by-step testing process, and the expected results and interpretation. **Figure B.1** shows an isometric view of the test parts and the specimen.

Materials

The materials used in the testing of double shear specimens should consist of the following:

- a test specimen that is fabricated to emulate the construction environment of the connector and has an embedded lifting anchor in the center wythe
- attachment hardware for displacement instrumentation
  - two L3 in. × 3 in. × ⅛ in. (L75 mm × 75 mm × 3 mm) steel angles
  - wood plate beneath the angles attached to the middle wythe measuring at least ½ in. (13 mm) in thickness to provide a gap between the middle wythe and the steel angle
  - a generic battery-powered hammer drill
  - concrete or masonry screws to attach the steel angles to the exterior wythes
- bearing plates and pad hardware for loading specimens
  - two 6 in. × 6 in. × 1 in. (150 mm × 150 mm × 25 mm) steel plates are to be placed on either side of the load cell to ensure even load distribution when load is applied to the middle wythe
- a nylon strap of at least 2 in. (50 mm) in width to keep the exterior wythes specimen from completely falling off the specimen as the specimen fails
- a testing load frame or testing machine
  - a hydraulic ram that can apply a load greater than the connector group's anticipated rupture load
- four calibrated displacement sensors with enough range to cover the total anticipated deformation range of the connectors
- a calibrated load cell capable of recording the maximum expected load
- a data logger with a minimum sampling frequency of 10 Hz

Step-by-step testing procedure

The following is a step-by-step guide for testing wythe connectors in normalweight concrete. Although the list of steps is complete, it is only for educational purposes. Moreover, all testing samples must be tested after the specimen concrete has reached the desired compression strength.

1. Place the polytetrafluoroethylene (PTFE) pads on the bottom testing platen where the external wythes would be bearing against during the specimen testing.
2. Bring the test specimen into the laboratory and position the test specimen on top of the PTFE pads under the load frame.
3. Attach the steel angles to the front and back of the middle wythe, including the washers.
4. Attach the displacement sensors to the exterior wythes with the tip (digital gauges, linear variable differential transformers, or string potentiometers) attached to the steel angle as a reference point.
5. Place a loose nylon strap around the specimen to prevent the specimen's sudden split after failure.
6. Center the load cell at the top center of the panel, sandwiched between the two steel plates under the load frame. Alternatively, if a universal testing machine is used, center the loading head at the top center of the panel.
7. Plug into the data acquisition system and test all of the sensors. Substitute the faulty ones with new calibrated sensors.
8. Load the double shear test specimens using the hydraulic ram until the applied load decreases to 20% to 40% of the peak load. The test can be stopped once the specimen response enters the negative stiffness branch of the load-displacement curve.
9. Stop the data acquisition and then retract the hydraulic ram.

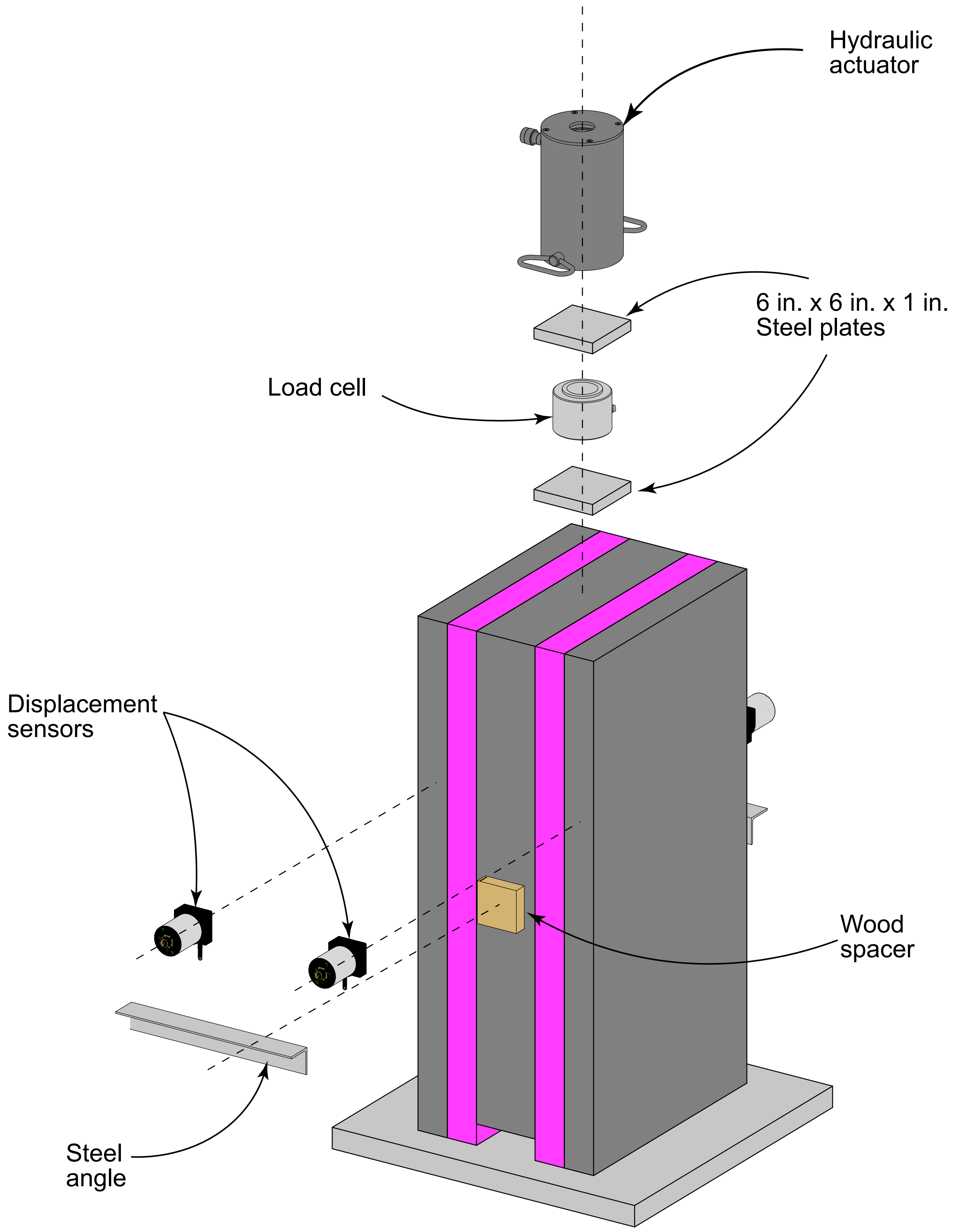

Figure B1. Isometric view of the parts of the proposed test setup. Note: F_{max} = maximum force applied to a given wythe connector; K_x = elastic slope of the load versus relative displacement curve; 1 in. = 25.4 mm.

10. Remove all sensors and store them securely, free of dust and moisture.

11. Transport the specimen to a clean area and carefully separate the three layers of concrete to identify the wythe connector failure type. Conduct an autopsy of the failure, noting the type of wythe connector failure (that is, concrete breakout, connector shear rupture, or a combination of the two).

Expected results

After the results from the data acquisition system are transferred to a computer, the test results are plotted to show the load versus the average of the middle wythe displacement relative to the exterior wythes. There are two ways of reporting the test results: divide the total load by the number of connectors (discrete connectors) or divide the total load by the length of the connectors (continuous connectors) and report the connector capacity load per foot per the total area of the connector at any given section.

After the results are plotted, the mechanical properties can be obtained depending on the behavior type. If the connector tested has a linear portion of the load-displacement curve, the stiffness should be computed at half the maximum load (**Fig. B.2**). If there is evidence of a bilinear load-displacement behavior, note the point where the elastic behavior stops and measure the stiffness for the bilinear segment (Fig. B.2). If the connector has a ductile-like behavior (Fig. B.2), the authors recommend computing the unloading stiffness possibility using a bilinear relationship to represent the descending branch of the curve. If the behavior is deemed brittle, the load-displacement curve should terminate at the peak load or model the descending branch of the curve as a steep curve.

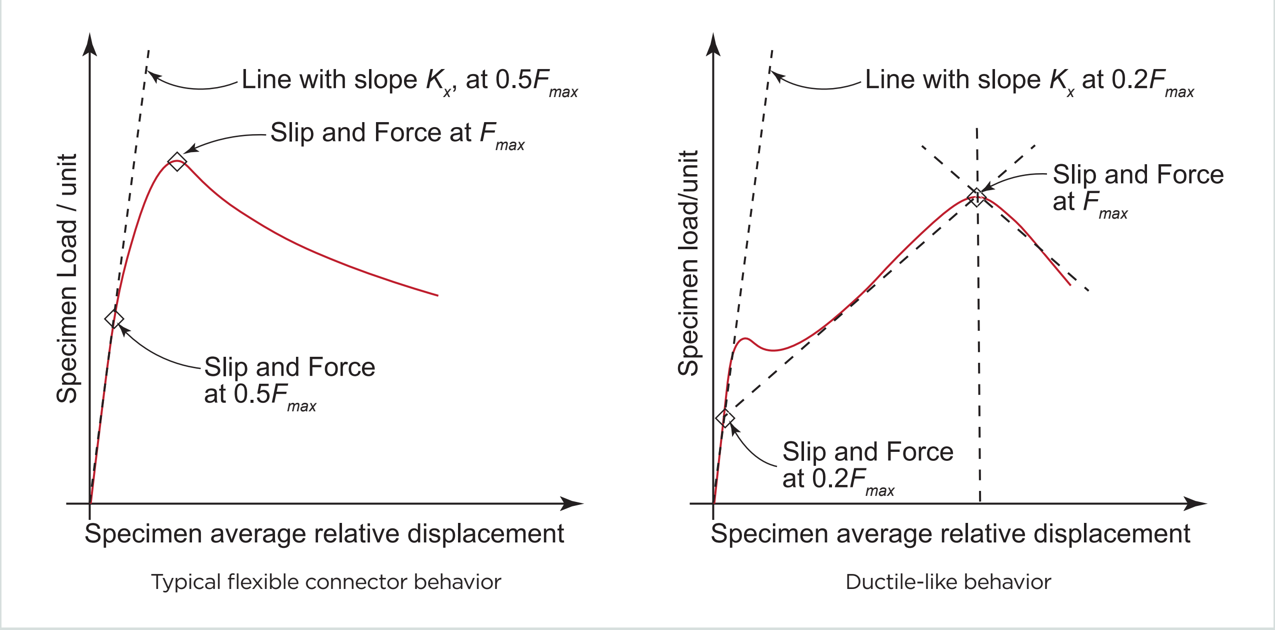

Figure B2. Specimen load/unit versus specimen average relative displacement

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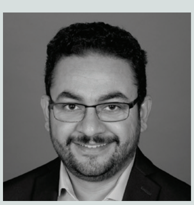

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Abstract

The precast concrete industry has implemented insulated wall panels for more than 70 years in various applications worldwide; however, there has yet to be a standardized form of testing their wythe connectors, which may prevent engineers from taking advantage of the full potential of partially composite insulated wall panels. This research addresses this issue by presenting a comprehensive approach for developing a testing standard that tests braced and unbraced double shear and flexural specimens, typically implemented in the literature, to obtain the mechanical properties of partially composite wythe connectors. To devise a standard test method, 107 specimens were fabricated and tested to investigate the variables affecting the connector shear and stiffness testing results. The results showed that double shear tests provide more accurate mechanical properties than flexural test specimens. Moreover, bracing or increasing the length of the specimen up to 12 ft (36 m) showed no significant impact on the mechanical properties of the wythe connectors compared with 4 ft (12 m) long specimens. The outcomes of this study will help the precast concrete community better understand the behavior of wythe connectors, test them with a certain level of confidence, and understand the foundations of the standard for testing wythe connectors.

Key words

Connector, fiber-reinforced polymer, FRP wythe connector, insulated wall panel, shear, standard development, precast concrete, wythe connector testing.

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